Review Article

Maximizing Crop Resilience: Exploring Stay-Green Traits for Sustainable Agriculture and Crop Research

Abstract

The "stay-green" trait, distinguished by detained aging, sustain photosynthetic activity , nutrient use efficiency, offering critical advantages in drought, heat, and nutrient-deficient conditions. This review examines how "stay-green" traits can help crops better withstand the challenges of climate change, ensuring food security for a growing global population while conserving resources in the face of scarcity. This phenomenon is crucial in promoting yield stability, biomass production, and improved grain filling, thereby addressing the global demand for sustainable agriculture. This provides a detailed analysis of stay-green traits in various crop species, emphasizing their genetic basis, physiological mechanisms, and practical applications. It delves into hormonal regulation, reactive oxygen species scavenging, and nutrient remobilization as underlying mechanisms. This paper also underscores advancements in phenotyping technologies and molecular breeding approaches, such as marker-assisted selection and CRISPR-Cas gene editing, for effectively incorporating stay-green traits into crop breeding programs. Real-world examples from cereals such as wheat, maize, and sorghum highlight the significant impact of stay-green traits on crop improvement. The potential of these traits is not limited to agricultural crops; they can also enhance the quality and marketability of horticultural produce. The document discusses emerging biotechnological tools, including nanotechnology and omics-based breeding, as future directions for enhancing stay-green traits and overall crop resilience. By integrating stay-green traits with broader stress tolerance strategies, this review advocates for a sustainable agricultural system that balances productivity and ecological conservation. The insights provided lay the groundwork for future research and innovation in developing resilient crop varieties to ensure climate variability presents concerns to global food security.

1. Introduction

1.1. Overview of Global Agricultural Challenges

The world's population is predicted to reach 10,000 million by 2050, with the majority of this rise occurring in emerging areas. Addressing the future food needs sustainably, both environmentally and economically, is one of humanity's greatest challenges. The global agricultural sector is grappling with numerous challenges that complicate efforts to improve crop productivity and resilience (Mohanty *et al.,*2024). To feed a growing global population, agricultural productivity must increase significantly by 2050. However, climate change exacerbates the difficulty (Janni *et al.,*2024). Agriculture faces increasing problems as the population expands and the effects of climate change worsen. At this crucial moment, it is vital to achieve sustainable agriculture to secure food supplies, preserve ecological balance, and foster economic growth. Effective water

40   management is vital, particularly as agriculture demands more water and water shortages intensify. Maintaining healthy soil

41   is crucial for sustainable agricultural practices and is receiving increasing focus. Soil forms a vital part of the ecosystem,

42   intricately linked with water, plants, and animals in a complex and interdependent web. As global temperatures rise and

43   climate patterns shift, traditional planting seasons may be disrupted, presenting challenges for crop growth. Both research

44   groups highlight that changes in climate, including the rise in extreme weather events, pose a significant threat to food

45   security by disrupting the timing and efficiency of agricultural production (Shang *et al.,* 2024; Prajapati *et al.,* 2024).

46   Food safety is the key goal to sustainable development, as it supports human health, societal stability, and economic

47   prosperity. Climate-related catastrophes like droughts, floods, and storms can worsen food insecurity by destroying crops,

48   animals, and infrastructure, disrupting supply networks. Crop diversification entails growing multiple crops with various

49   features and growth requirements to reduce risk and increase resistance to climatic unpredictability. Planting varied crops

50   can help farmers offset the effects of harsh weather and pests.

51   diseases, resulting in a more consistent and secure food supply. Breeding resilient crop varieties through traditional and

52   biotechnology can improve tolerance to climate-related stresses, leading to improved yields and food safety in the aspect of

53   global heating. Sustainable land management strengthens agricultural systems' resilience to climate change while also

54   promoting soil health, biodiversity, and ecosystem services. Climate-smart crop breeding in India has resulted in resilient

55   crop types that can withstand heat, drought, pests, and diseases. Researchers have utilized participatory plant breeding and

56   genomic selection to develop high-yielding, stress-tolerant crop varieties, such as drought-resistant rice, heat-tolerant wheat,

57   and pest-resistant maize. These improved varieties have significantly enhanced farm productivity and food security for

58   smallholder farmers in vulnerable regions (Toromade *et al.,*2024).

59   **1.2 The Concept of Stay-Green Traits**

60   Plant leaves serve as a distinctive and easily accessible genetic system for studying aging, senescence, and death-related

61   processes. Additionally, leaf senescence offers a valuable opportunity to explore the process of orderly degradation, in

62   contrast to the many biological studies that focus on biogenesis and assembly processes (Woo *et al.,*2013). This final stage

63   of development involves the breakdown of cellular components and macromolecules, ensuring the reallocation of nutrients

64   to other growing parts of the plant (Sakuraba *et al.,*2020). In the context of modern agriculture, where maximizing productivity

65   and sustainability is paramount, understanding and manipulating leaf senescence is crucial. Premature senescence can

66   lead to early crop decline, reducing the harvest period and overall yield. Conversely, delayed senescence, or "stay-green"

67   traits, though beneficial in extending photosynthetic activity, can sometimes interfere with nutrient remobilization needed for

68   seed development. Balancing these factors to optimize both yield and quality under various environmental stresses remains

69   a critical and ongoing challenge for crop scientists and geneticists.

70   The stay green trait, characterized by delayed leaf senescence in plants, has emerged as a promising frontier in agricultural

71   research, offering transformative potential for crop enhancement strategies. This phenomenon, which allows plants to

72   maintain green and photosynthetically active leaves for extended periods compared to conventional genotypes, holds

73   significant implications for enhancing crop resilience and productivity in difficult environmental conditions such as drought,

74   heat stress, and nutritional deprivation. This trait is valuable because it enables vital plant functions such as photosynthesis

75   and nutrient absorption, ultimately resulting in increased grain output and overall plant growth (Verma *et al.,* 2020). Despite

76   its prevalence across various plant species, the molecular mechanisms and genetic underpinnings of stay green remain

77   subjects of intense investigation. In this comprehensive review paper, we delve into the physiological significance of stay

78   green traits, explore the genetic diversity and molecular pathways governing this trait across diverse crop species, and

79 discuss its prospective applications in breeding efforts focused at generating durable and high-yielding agricultural types
80 capable of flourishing in changeable environmental landscapes. By synthesizing current research findings and highlighting
81 recent advancements in the field, This assessment will provide useful perceptions into the promise of stay green as a catalyst
82 for sustainable agriculture. and offer a roadmap for future research directions in crop improvement strategies (Christopher
83 *et al.,* 2008).

84 **1.2.1. Classification of stay green**

85 Stay-green traits in plants manifest through alterations in genetic processes governing senescence initiation and
86 progression, leading to prolonged photosynthetic activity and potentially higher yields. Functional stay green types sustain
87 photosynthesis longer than usual, enhancing productivity. Conversely, non-functional stay green mutants retain chlorophyll
88 due to impaired catabolism but lack photosynthetic competence.

89

90 **Fig. 1. Classification of Stay-Green Phenotypes in Plants (Das *et al.*, 2015)**
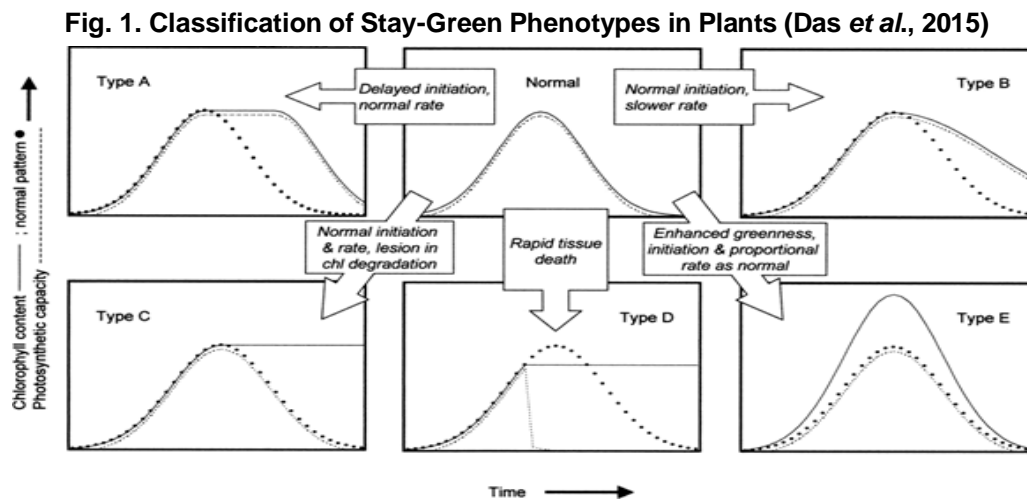
91 Classifying stay green into five categories based on senescence timing and duration provides insights into their mechanisms:
92 Type A delays senescence initiation but proceeds normally afterward; Type B initiates senescence timely but progresses
93 slowly; Type C results from chlorophyll degradation defects; Type D maintains green colour until leaf death; Type E maintains
94 chlorophyll content despite reduced enzyme activity. This classification aids in understanding stay green's diverse effects
95 on plant physiology and productivity.

96 **1.3 Objectives of the Review**

97 This review aims to shed light on the importance of this trait in sustainable agriculture and offer insights into future directions
98 for crop improvement strategies. Therefore, expected to give a higher production and productivity of grain as well biomass
99 under biotic and abiotic stress condition. Genetic variation exists in the timing and rate of leaf aging, both between species
100 cum genotypes. Furthermore, mutants also occur whose leave remain green for longer than those of the parental genotype.
101 The presence of this trait leads to an extended period of foliar (leaf) greenness, which is directly linked to delayed
102 senescence, the natural aging and deterioration of leaves. (Xu *et al.,* 2000). Chlorophyll breakdown occurs alongside the
103 aging or ripening of green plant organs. Even so, there exists a genetic variation that slacks up or halts this disintegration
104 process, leading to plants retaining their green color even as they reach the end of their growth cycle. These stay-green
105 mutations predominantly emanate due to alterations in the stay-green protein gene (SGR) (Abdelrahman *et al.,* 2017). The
106 ability of this trait, is considered one of the most thoroughly understood attributes that contribute to drought tolerance in
107 numerous crops.

2. Morphological and Physiological Basis of Stay-Green Traits

2.1. Morphological basis

2.1.1 Delayed leaf senescence

Senescence is an active phase of plant development that includes degradation and remobilization activities. Under optimal conditions, the beginning and duration of senescence are predictable and strongly tied to the crop's phenological development. Leaf senescence is a tightly regulated process in which nutrients are transported from the senescent leaf to other sections of the plant, resulting in leaf death. During senescence, the leaf yellows as chlorophyll degrades and photosynthesis decreases (Chibane *et al.*, 2021). Senescence of plant tissues or organs is a developmental process in plants that occurs between the vegetative and reproductive stages. Crop yields may be reduced due to premature senescence induction caused by poor environmental circumstances. Several studies have found a positive relationship between leaf area elongation and yield, although many green cultivars have little influence on productivity due to senescence (Naz *et al.*, 2023). Drought, salinity, hot or low temperatures, darkness, nutritional inadequacy, and pathogen infection are all common stressors that can cause it. Premature leaf senescence is a degenerative physiological process that lowers photosynthetic efficiency and nutrient buildup, lowering crop production. Abiotic stress induces leaf senescence, which has a considerable impact on agricultural productivity and quality. Delaying leaf senescence can improve drought tolerance and photosynthesis, which is the foundation of high yields. Exploring techniques to delay leaf senescence is thus necessary for sustaining and improving agricultural production under abiotic stress conditions. The differential expression of senescence marker genes, as well as the NAC and WRKY transcription factors, reflects leaf senescence (Yang *et al.*, 2023).

2.1.2. Senescence and Stay-green

Senescence is a physiological mechanism in which nutrient stores are mobilised into fruits and seeds. Stay-green is a key trait that helps plants to keep their leaves in an active photosynthetic state even when they are stressed. Senescence influences crop plant assimilation and grain filling at an early stage. Increased green leaf area at maturity, leaf nitrogen status, and transpiration efficiency were all linked to higher grain yield in stay-green genotypes compared to senescent genotypes. The emergence and progression of senescence are phenological indicators of climate change vulnerability, implying that a better understanding of stay-green will aid in the development of potential crop forms. As a result, any defense mechanisms that delay the onset of senescence and hold leaves green are expected to increase crop yield (Hiremath *et al.*, 2017). Stay-green is also one of the important parameters to assess the yield under drought condition with good root system (Hilli *et al.*, 2021).

2.1.3. Enhanced root system

Roots play an important function in anchoring and resource acquisition. The availability of nutrients can alter the way the root grows in radial or longitudinal directions, impacting the three-dimensional root structure. They generally exhibit plasticity, allowing them to function well by adjusting to their surroundings (Kalra *et al.*, 2024). Root architecture is the spatial layout of root systems that determines plant anchoring, water and nutrient absorption, inter- and intra-plant communication, and competition. It is argued that changing the root system design could be a viable alternative way to increasing crop productivity, resulting in a second green revolution. Plants' root systems provide them with morphological, structural, and physiological adaptability in response to environmental changes. As a result, combining root architectural and physiological traits will aid in the development of drought-tolerant genotypes. Breeding for superior root qualities in

crops involves not only efficient and improved screening procedures, but also in-depth knowledge of specific functions of roots, such as water extraction and nutrient absorption from the soil (Sofi *et al*., 2021). The most consensus attribute contributing to drought avoidance in highland circumstances is a deep root system, which allows a plant to hunt mineral resources, absorb water from deeper layers, and respond to evaporative demand, assuming water is accessible in places investigated by roots. The development of crops with more effective roots may be dependent on RSA, which includes structural phenes such as root length or elongation, spread, branching, growth angle, and the amount and length of lateral roots, which have been shown to influence root system architecture. An increased quantity of fine roots and root hairs is connected to better water and nutrient intake, as well as increased resilience to stress (Shafi *et al*., 2023).

2.2. Physiological basis

2.2.1 Hormonal regulation

Richmond and Lang were the first to show that cytokinins exhibit antisenescent effects on excised leaves of tobacco and cocklebur plants. (Honig *et al* ., 2018). Cytokinin negatively regulates it and enhances long suffering to some of the abiotic stresses. Pathogens and herbivores frequently employ CK's senescence-delaying feature to create "green islands."(Walters *et al*.2008). The plant hormone ethylene triggers leaf senescence. Salicylic acid (SA), another plant hormone, also plays a crucial role in initiating and progressing leaf senescence, as demonstrated in Arabidopsis research. Moreover, the plant hormone abscisic acid (ABA) facilitates leaf senescence. Rate of leaf senescence is influenced by environmental factors such as light intensity, quality, and the ratio of red to far-red light (Guo *et al.,* 2021).Leaf senescence is a complex, genetically controlled process involving a series of coordinated events, including the breakdown of chlorophyll and other cellular components. This intricate process is finely regulated at multiple levels within the plant including chromatin remodelling, transcription, and post-translational modifications. The existence of auxin-responsive genes that encode ARFs or IAA proteins suggests that it has a part in controlling foliar senescence (Schippers *et al*.2015). Mutants insensitive to ethylene (ETR1-1, EIN2) show delayed aging. Introducing an ARF2 mutation in these plants causes an additional delay in senescence, indicating that ARF2 functions separately from the ethylene pathway (Grbić,bleeker *et al*.,1995).

2.2.2. Reactive Oxygen Species (ROS) Scavenging

ROS are extremely reactive and poisonous chemicals. ROS are usually produced as a byproduct in some of the cell organelles. Superabundance of this species during the external environmental stress response causes oxidative stress.. During stress, their production increases significantly, causing cellular toxicity and damage (Khanna *et al.,* 2013). Many cellular processes are governed by ROS, which operate as essential signaling intermediaries in growth and development and also conformant to varied stress tolerance in plants. (Haider *et al.,* 2021). Stress conditions such as salinity, drought, extreme temperatures, heavy metal exposure, pollution, high light intensity, and pathogen infections can disturb the fragile balance between the production and scavenging of reactive oxygen species (ROS). To counteract this, plants have evolved a robust antioxidant system comprising two key components: (i) enzymatic elements, including SOD, CAT, APX, GPX, GR, MDHAR, and DHAR, and (ii) chemical antioxidants like ABA, reduced GSH, and α. These components collaborate to mitigate ROS levels effectively. (Das *et al.,* 2014). Plants under mild photorespiration release $1O_2$, $O \bullet 2^-$, and H_2O_2 at the same time, making it difficult to determine their individual roles. Research has revealed that singlet oxygen ($^1O_2$) is the primary source of senescence-related oxidative stress in sage chloroplasts. This conclusion was drawn from the significant degradation of β-carotene and α-tocopherol observed in drought-stressed plants, indicating increased production of singlet

184   oxygen. Hydrogen peroxide (H_2O_2) plays a crucial role in the aging process of plants. It acts as a signaling molecule,

185   accelerating aging in various plant species. Research shows peroxide interacts with other signaling molecules involved in

186   plant development and aging, such as stress hormones and ripening hormones. This complex interplay influences the overall

187   aging process in plants. External application of hydrogen peroxide (H_2O_2) increases the production of mRNAs for enzymes

188   involved in creating oligosaccharides (complex sugars). These sugars help plants survive drought. Furthermore, H_2O_2 can

189   be used by Class III peroxidases in the plant cell wall, which are crucial for defending against plant pathogens (Jajic *et al.,*

190   2015).

191

192   **2.2.3. Nutrient Remobilization**

193   **2.2.3.1. The Green Essence: Chlorophyll in Plant Life**
194

195   The green pigment in plants, plays a critical part in photosynthesis—the process by which plants convert sunlight into energy.

196   As leaves age, green pigment degrades, leading to a yellowing of the foliage. However, delaying this degradation, particularly

197   during the reproductive stage, prolongs photosynthetic activity, ultimately boosting yield and biomass production. This

198   continuous photosynthesis is closely related to functional stay-green features, which indicate the transformation from C

199   capture to N mobilization in leaf growth. (Thomas and Oughum, 2014). Thus, preserving chlorophyll content not only

200   maintains leaf greenness but also enhances plant productivity and crop yield. Prolonged leaf longevity in this genotype may

201   improve agricultural yields by revive nutrients from resource allocation under diverse stressors and low nutrient situations.

202   CN cycles as energy sources begin to reactivate by piling up sugars in the leaves to meet the sink's nitrogen demands. On

203   the other side, a scarcity of nitrogen causes leaf senescence and encourages N recycling and remobilization. Ideal nitrogen

204   concentrations increase leaf greenness and growth, remobilizing N that would otherwise be destroyed by chloroplast protein

205   and making molecules of nitrogen available. These physiological changes impact its metabolism by weakening translocation

206   pathways, leading to an unequal distribution between source and sink. (Munaiz *et al.,* 2020).

207   **2.2.3.2. Relation of N_2 With stay green traits**
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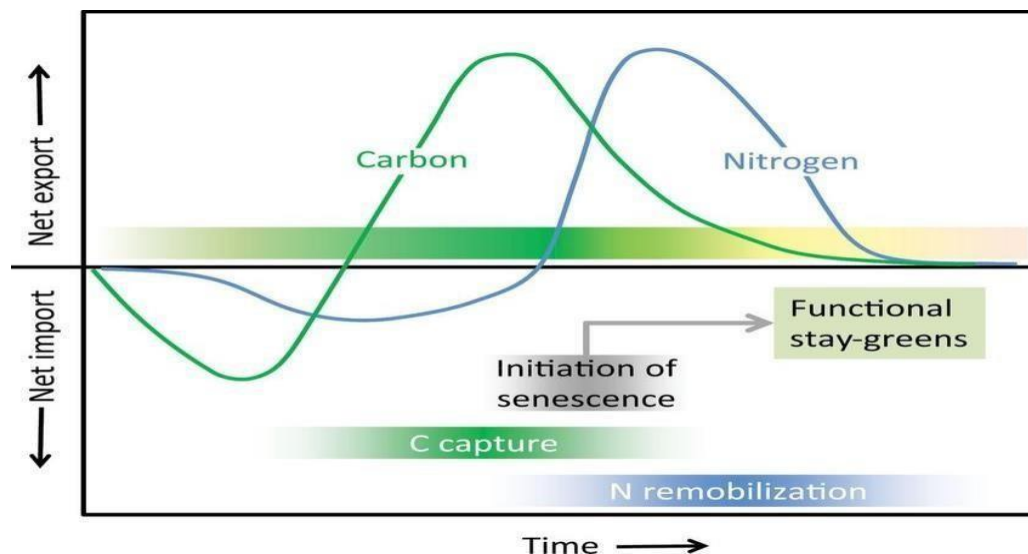
211 **Fig. 2. Carbon sequestration and nitrogen recycling in stay-green plants. (Thomas, H., & Ougham, H. 2014)**

212 Leaves undergo a dynamic transition, shifting from nutrient-demanding consumers to net contributors of photosynthates

213 to the entire plant. This transition signals the functional start of senescence, with the leaf's C-capture phase followed by

214 net organic N remobilization. This mechanism is essential for plant health and productivity.. While laboratory studies

215 provide insights, scaling issues must be considered when extrapolating findings to field conditions. Stay-green genotypes

216 exhibit delayed C-N transition points or slow subsequent yellowing and N remobilization, highlighting their importance in

217 sustaining leaf function and overall plant performance (Lim *et al.,* 2007). Plants remobilize nitrogen and carbon from dying

218 leaves into new tissues and storage organs, allowing them to adapt to changing conditions. Efficient nitrogen

219 remobilization minimizes the need for nitrogen fertilizer and significantly impacts grain yield and quality during seed

220 development. Small grains, like wheat and rice, efficiently recycle up to ninety precent of their nitrogen from vegetative

221 parts, whereas maize recycles only 35-55%.

222 **2.3. Photosynthetic Efficiency and Water-Use**

223 **2.3.1. Prolonged Photosynthetic Activity**

224 The environmental importance of the extended grain filling time associated with the SG trait is diverse and crucial for

225 agricultural productivity and resilience. By staying green longer, these plants extend the time for grain filling, leading to

226 improved yield, quality, and ecosystem function (Mahalaskshmi *et al.,* 2002). Firstly, the extended grain filling period allows

227 for prolonged photosynthetic activity, enabling the continued assimilation of carbon dioxide and production of assimilates

228 essential for grain development. This sustained carbon supply enhances the accumulation of dry matter and facilitates

229 optimal grain filling, contributing to increased yield potential. Moreover, the prolonged grain filling duration offers greater

230 flexibility in resource allocation, allowing plants to allocate resources towards grain development over an extended period

231 (Silva *et al*., 2004). This resource partitioning ensures efficient nutrient remobilization from source tissues to developing

232 grains, thereby enhancing nutrient use efficiency and grain quality. Furthermore, the prolonged grain filling period conferred

233 by the stay-green trait enhances the resilience of crops to environmental stresses, particularly drought and heat stress. By

234 maintaining functional green leaves for an extended period, stay-green plants exhibit improved water and nutrient uptake

235 capabilities, reducing the negative impact of water deficiency on grain filling and yield. Additionally, the extended grain

236 filling phase promotes canopy maintenance and ground cover, which reduces soil moisture loss through evaporation,

237 suppresses weed growth, and enhances soil moisture conservation. This contributes to improved soil health, water use

238 efficiency, and ecosystem stability. Overall, the prolonged grain filling period associated with the stay-green trait not only

239 enhances crop yield and resilience to environmental stresses but also has broader ecological implications for sustainable

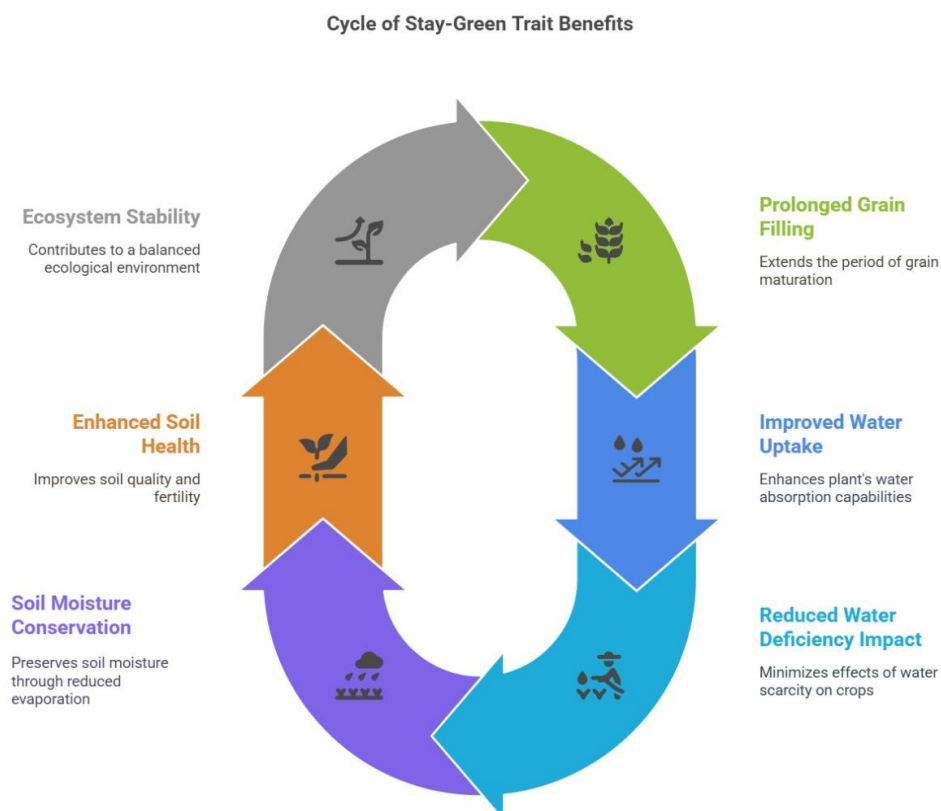240 agricultural practices and ecosystem functioning.

241

242

243

Cycle of Stay-Green Trait Benefits

Ecosystem Stability
Contributes to a balanced ecological environment

Prolonged Grain Filling
Extends the period of grain maturation

Enhanced Soil Health
Improves soil quality and fertility

Improved Water Uptake
Enhances plant's water absorption capabilities

Soil Moisture Conservation
Preserves soil moisture through reduced evaporation

Reduced Water Deficiency Impact
Minimizes effects of water scarcity on crops

244

245 **Fig.3. Cycle of stay green benefits**

246 **2.3.2. Water-Use Efficiency**

247 Initially, water use efficiency (WUE) was defined as the ratio of crop output (biomass or grain) to water input. This concept
248 evolved to represent crop yield per unit of water lost to the atmosphere (evapotranspiration). Breeding for drought-tolerant
249 crops with improved WUE has been a major focus to combat water scarcity and ensure food security (Mbava *et al.,* 2020).
250 While further WUE improvements are expected, enhancing the efficiency of light reactions in photosynthesis has a profound
251 impact on yield under stress. This efficiency significantly influences a plant's ability to Optimize water and nutrient uptake,
252 Effectively transition from vegetative to reproductive growth and Balance resource allocation between photosynthetic tissues
253 (sources) and growing parts (sinks) throughout its lifecycle (Snowdon *et al.,* 2021). Drought, a critical worry in today's climate,
254 is one of the most severe abiotic stresses affecting regions all over the world. Moisture stress arises when plants cannot
255 adequately meet their water needs through evapotranspiration. Drought significantly impacts plant growth and metabolism,
256 posing a major threat to global agricultural production. It primarily caused by irregular rainfall or insufficient irrigation,
257 significantly impacts crop yields. Factors like soil salinity, poor soil quality, and extreme temperatures can exacerbate drought
258 stress. Throughout the growing season, inadequate water availability, including both rainfall and the soil's ability to retain
259 moisture, limits the crop's potential to reach its maximum yield (Begna *et al.,* 2021). Modifying irrigation and fertilization
260 practices can increase yield by up to 30% under comparable conditions. Understanding the mechanisms that allow crops to
261 grow under limited to severe stress, and applying these insights to build crop resilience methods, could assist improved
262 yield and WUE. Sophisticated technologies allow for the intelligent management of water in agricultural fields. This is
263 achieved by accurately tracking how much water crops need and how they react to water shortages. These technologies

264 can also help plants recover from minor water stress, prevent excessive growth, and regulate the balance between water
265 loss and carbon uptake through signals that travel from the roots to the leaves. (kang *et al*., 2021).

266 **3. Genetic Determinants of Stay-Green Traits**

267 **3.1. Identification of Stay-Green Genes**

268 The inheritance pattern of the stay-green trait in plants exhibits a complex interplay of genetic factors across various
269 species. In wheat, (Silva *et al.,* 2001) identified four recessive genes governing stay-green, which segregate
270 independently and interact additively. Similarly, in rice, the recessive variant gene sgr(t) on chr 9 regulates the stay-green
271 phenotype (Cha *et al.,* 2002) and (Jiang *et al.,* 2007). In Arabidopsis, the stay-green trait is controlled by the subordinate
272 gene fiw located on chr 4 (Nakamura *et al.,* 2000). These findings underscore the multi-factorial nature of stay-green
273 inheritance, with different genetic loci contributing to its expression in distinct plant species. To effectively breed crops
274 that can withstand drought and other stresses, it's essential to understand the genetic factors that contribute to the 'stay-
275 green' trait. This knowledge is crucial for developing resilient crop varieties (Munaiz *et al*., 2020).

276 The transcription factors from WRKY background plays an important lead in plant habituation to soil-moisture stress.
277 Recent studies have identified a novel SbWRKY gene, named SbWRKY30, which is predominantly expressed in the
278 taproot and leaves of jowar under water deficit conditions. This suggests that SbWRKY30 functions as an effective regulator
279 of drought response and holds significant potential for improving drought tolerance in various crops. Additionally, other
280 genes—such as SbWRKY45, 79, 83, and 16—also showed high expression in sorghum during water shortage, further
281 highlighting the essential part of SbWRKYs in promoting drought tolerance (Prasad *et al*., 2021).

282
283 **Table 1. Key Genes Associated with Stay-Green Phenotypes.**
284

Protein	Genetic factor	Variant Phenotype	Progress
Stay-green	SGR,NYE-1SID	sgr = stay-green	**Binding light harvesting complex II and catabolic enzymes, stabilising its complex**
Chlorophyll b reductase	NYC NOL HCAR	nyc (rice and Arabidopsis) = stay-green	**NADPH dependent two-step conversion of chlorophyll b to a**
Phaeophytinase	PPH CRN1 NCY3	pph = stay-green	**Dephytylation ofphaeophytin**

Phaeophorbide a oxygenase	PAO ACD1 LLS1	acd1 = cell death, cosmetic stay-green	**Ferredoxin (Fd)dependent oxidativeopening macrocycle to form RCC**
RCC reductase	RCCR ACD2	acd2 = cell death, cosmetic stay-gree	**Fd dependent reduction of RCC to pFCC**

285

286 Senescence onset triggers chloroplast breakdown and stromal enzyme degradation, leading to reduced photosynthesis

287 (Ahlawat *et al.*, 2008). Chlorophyll degradation, catalyzed by six chlorophyll catabolic enzymes (CCEs) within

288 chloroplasts, is an ensign of aging.

289 ## 3.2. Molecular Breeding and Genetic Engineering

290 ### 3.2.1 MAS

291 It revolutionizes plant breeding by integrating genetic knowledge into practical applications. It is a cornerstone of modern

292 crop improvement, enabling the development of high-yielding, stress-resilient, and nutritionally enhanced crop varieties,

293 which is crucial for insuring lacking of food insecurity and adapting to environmental fluctuations . MAS is particularly

294 helpful for attributes that are difficult to analyze through conventional breeding methods, such as those controlled by

295 multiple genes (quantitative traits) or expressed only under specific environmental conditions. Furthermore, integrating

296 nanomaterials with genetic engineering facilitates precise gene modification, boosting stress tolerance and sustaining the

297 stay-green phenotype. Although there is limited research on nanotechnology in agriculture, its potential is significant.

298 Nanoscience, with its unique properties, has the potential to revolutionize agriculture and promote sustainability (Chippa

299 *et al.,* 2019).

300

301 **Marker-Assisted Selection for Drought Tolerance**

302 By 2025, over 65% of the world wide population is expected to face water scarcity. In agricultural systems, drought occurs

303 when plants cannot access sufficient water for transpiration. Drought is a noteworthy stress factor that hampers plant

304 progresss and reproduction, posing a major challenge for scientists. The main goal of plant breeding is to create crops that

305 can withstand or adapt to drought conditions. In the 21st century, developing high-yielding and stable crop varieties that are

306 also drought-resistant is crucial for ensuring a consistent food supply. One of the most effective approaches to achieve this

307 is through MAS. STAY GREEN-related genes in arabidopsis signifies in modulating foliage final developmental period and

308 chlorophyll disintegration under various stress conditions (Sakuraba *et al.,* 2014).

309 Globally, climate-resilient crops like sorghum are capable of thriving in regions with limited rainfall. However, climate change

310 has exacerbated conditions by increasing temperatures and reducing the frequency of rainfall, thereby impacting crop yields.

311 MAS leverages genetic markers to identify QTLs combined with drought tolerance traits, such as stay-green characteristics.

312 In sorghum, QTLs such as Stg1,2, 3, 4, 3A, and 3B have been linked to high yield and stay-green traits. These QTLs are

313   introgressed into senescent sorghum varieties through marker-assisted backcrossing (MABC), enhancing their drought

314   resilience and productivity (Kumari *et al.,* 2024).

315   **3.2.2. Quantitative Trait Loci (QTL) Mapping**

316   **Table 2. Stay-green QTL have been identified**

317

Crop	No. of QTLs	Identified QTL	Chromosome number	State of Observation	Reference
Wheat	3	QSg.bhu-1A QSg.bhu-3B QSg.bhu-7D	1A 3B 7D	Improving yield	**Kumar *et al.,* 2010**
Rice	4	TCS4,Csf16,CSF19/TCs9, Csf12 Yld6,Y1d9-Csf16,TCs9	4,6,9,12 6,9	Improvement of yield	**FU *et al.,* 2011**
Maize	14	sg1.1.1, sg1.6.1, sg2.1.1, sg2.1.2, sg2.2.1, sg2.3.1, sg2.5.1, sg2.8.1, sg3.1.1 ,sg3.2.1,sg3.5.1,sg3.9.1, sg4.1.1, sg4.2.1 2	1,6,1,1,2,3,5,8 ,1,2,5,9,1,2	Post flowering	**Zheng *et al.,* 2009**
Sorghum	4(9)	StgB, Stg1, Stg3 and Stg4	------------------	Drougt tolerance-improving yield	**Kassahun *et al.,* 2010**
	61	-----------------------------	----------------	Post rainy	**Rama Reddy *et al.,*2014**
Barley	10	----------------------------	3H,4H,5H,6H and 7H	6- terminal heat-stress , 4- terminal water stress	**Gous *et al.,* 2016**

318
319   The understanding of stay-green traits in plants is fundamental for unraveling the mechanisms that enable prolonged

320   photosynthetic activity, thus contributing to enhanced crop productivity and stress tolerance (Hortensteiner *et al.,* 2011).

321   In (Table 1), several key genes associated with stay-green phenotypes are outlined, each playing a crucial role in

322   chlorophyll degradation and related processes. For instance, SGR (Stay-Green) controls the binding of light-harvesting

323   chlorophyll a/b-binding proteins (LHCII) and catabolic enzymes., thereby stabilizing the catabolic complex essential for

324   chlorophyll breakdown. Similarly, genes like NYC (Non-yellow coloring) and PPH *(Phaeophytinase)* are involved in the

325   stepwise transformation of *chl b* to *chl a* and the dephytylation of phaeophytin, respectively. These molecular components

326   collectively contribute to the maintenance of chlorophyll levels and leaf greenness during plant senescence.In addition to

327   understanding the genetic basis of stay-green traits, the identification of QTLs affliated with these attributes further

328   elucidates their importance in crop improvement. (Table 2) highlights QTLs related to stay-green characteristics identified

329   in various cereal and other crops (Xu *et al.,* 2000). These QTLs, such as *QSg.bhu-1A* in wheat and TCS4 in rice (Park *et*

330   *al.,* 2003), have been linked to improvements in yield potential, particularly under stress conditions like drought. Identifying
331   genomic regions associated with stay-green traits allows researchers to use MAS to incorporate beneficial alleles into
332   elite germplasm, accelerating the development of improved crop varieties.

3.2.3. CRISPR and Gene Editing Technologies

334   To improve agriculture for future generations, genetic modification technology needs to accelerate domestication. Due to
335   rising food demand, only 15 out of 30,000 edible plants meet 70% of human calorie requirements, highlighting the need for
336   genetic diversity. For this purpose, CRISPR Cas technology provides fast crop variety enhancement. Bacterial type II Cas
337   nine systems have been widely utilized in agricultural research to address several stress, increase production, resist
338   herbicides and diseases, and improve nutrition (Matinvafa *et al.,* 2023). This technology has revolutionized plant genome
339   editing by enabling precise, efficient, and targeted modifications of specific genes. This technology holds immense potential
340   for editing stay-green genes, which are crucial for improving crop resilience to environmental stresses. By altering these
341   genes, CRISPR can help to the development of stress-resistant, high-yielding crops. Recently, researchers successfully
342   utilized this system to modify the lettuce genome by targeting two genes involved in chlorophyll metabolism. The SGR gene
343   encipher a Magnesium -dechelatase enzyme which catalyzes the degradation of chlorophyll a (Chl a). Meanwhile, *BCM*
344   functions as a scaffold protein, playing a pivotal role in maintaining chlorophyll levels by regulating both its synthesis and
345   degradation. Our lssgr lettuce mutant displayed a stay-green phenotype, which has the potential to minimize postharvest
346   food waste (Ito et al. 2024). As in tomato also, The SlSGR1 gene enrolling in the color change during tomato fruit ripening.
347   Using this genome editing to knock out SlSGR1 expression resulted in fruits with a distinct wild fruits have a murky brown
348   color and substantially higher quantities of green pigment and carotenoids. (Ma *et al.,* 2022). A chimeric Cas9-VirD2 protein
349   was designed to enhance HDR performance in plants.VirD2, a bacterial protein, cuts the Ti plasmid at specific sites (Wang
350   *et al.,* 2021b).This method was used to precisely edit the OsALS gene in rice, conferring herbicide resistance (Zafar *et
351   al.,*2023). Moreover, introducing a donor DNA template and a geminivirus-based system enhanced glyphosate resistance
352   in rapeseed (Wu *et al.,* 2020).

4. Applications in Crop Improvement

4.1. Breeding Stay-Green Varieties

4.1.1. Case Studies

356   Stay Green (SG) is a crucial trait where plants maintain photosynthesis after flowering, even under stress. Stay-green plants
357   exhibit extended grain-filling periods, leading to higher yields. The SG trait has been identified as a valuable characteristic
358   for commercial breeding of cereals, helping to address current yield stagnation while enhancing yield flexibility and stability.
359   Breeding for functional SG has contributed to improved agricultural productivity, especially when paired with other
360   advantageous traits. (Kamal *et al.,* 2019).

Rice

362   (Reynolds *et al* ., 2010) investigated drought tolerance in rice by examining three "stay-green" (SG) mutants derived from
363   the wild-type rice, Nagina 22 (N22). The stay-green characteristic of the mutants was confirmed through dark-induced
364   senescence experiments. Researchers evaluated the mutants' performance under both normal and drought conditions by
365   measuring agronomic traits, the activity of enzymes related to oxidative stress, and the expression levels of 15 genes

associated with chlorophyll breakdown and senescence. Whole-genome sequencing provided the genetic information for these candidate genes. Two mutants, SGM-1 and SGM-2, showed a complete absence of senescence, while SGM-3 exhibited delayed senescence. Gene expression in the mutants remained relatively stable over time, unlike the wild type. However, SGM-3 showed a significant increase in ATG6a gene expression over time. While all rice varieties performed better under drought, only SGM-3 produced a higher grain yield. Under drought conditions, all 15 genes were over expressed, with N22 and SGR-30 showing the highest levels of up-regulation.

Sorghum

According to (Crasta *et al.,* 1995), sorghum is the 5th significant cereal crop, after remaining prime cereal crops . Most US sorghum is grown without irrigation, making water availability the main yield limiter. Drought stress impacts sorghum differently depending on the growth stage. Post-flowering drought often causes leaves to prematurely age, especially during grain development. Genetic studies show that the stay-green trait, which delays leaf aging, is primarily controlled by a single dominant gene. (Mwamahonje *et al.,* 2021) certain sorghum varieties exhibit the stay-green trait, where green, productive leaves are maintained under drought stress during grain filling, making the crop essential for ensuring food and nutritional security. Conventional methods rely on phenotyping the SG trait, being complex due to its polygenic nature, environmental interactions. MAS, involves QTL mapping and introgression of stay-green traits into senescent varieties through MABS, guided by field phenotypic data.

Wheat

(Christopher *et al.,* 2018) had been Stay-green wheat maintains green leaves longer after flowering, boosting biomass and yield. Developing stay-green wheat varieties can increase yields under drought stress while maintaining productivity in other conditions. This trait might arise from early changes in plant structure (canopy and roots). The objective of this study was to identify genetic regions (QTLs) associated with SG traits in a doubled haploid wheat population, including leaf greenness, senescence onset and duration, and senescence rate, across eight subtropical environments. The relationship between these stay-green traits and yield varied depending on drought conditions.

Maize

(Trachsel *et al.,* 2016) focuses on identifying genetic regions that influence phenotypic variation of the trait associated with vitality and SG traits that contribute to drought tolerance in tropical maize. By analyzing two connected advanced backcross populations, the researchers aimed to uncover genetic factors that enhance early growth and delay senescence under drought conditions. The identification of these QTLs provides valuable insights for breeding programs targeting improved water defecit endurance in tropical one. The findings highlight the potential of marker-assisted selection in developing maize varieties with enhanced early vigor and stay-green traits, contributing to increased resilience against drought stress. It advances our knowledge on heritable basis of drought tolerance in maize and offers practical applications for crop improvement in water-limited environments.

Cucumber

(Dong *et al.*, 2023) studied the genetic basis of low-temperature (LT) tolerance in cucumbers. Using genome-wide association, a specific genetic variation (SNP) within the *STAYGREEN* (*CsSGR*) gene, located at the *gLTT5.1* locus, was

401   identified as being linked to LT tolerance. CRISPR-Cas9 gene editing was used to create *CsSGR* knockout mutants, which

402   displayed improved LT tolerance, specifically by maintaining higher chlorophyll levels and accumulating less harmful reactive

403   oxygen species (ROS) under cold stress. The *CsSGR* gene was found to be activated by the *CsCBF1* transcription factor.

404   Further investigation revealed that the LT-sensitive version of *CsSGR* (*CsSGRHapA*), unlike the LT-tolerant version

405   (*CsSGRHapG*), interacts with *CsNYC1* to promote chlorophyll breakdown.

Tomato

407   (Yang *et al.*, 2023) Research has identified that mutations in the STAY-GREEN 1 (SGR1) gene inhibit chlorophyll

408   degradation during tomato fruit ripening. This inhibition leads to the retention of chlorophyll, and when combined with the

409   accumulation of lycopene, results in a brown or "green flesh" phenotype. A study titled "Recoloring Tomato Fruit by

410   CRISPR/Cas9-Mediated Multiplex Gene Editing" demonstrated that targeted mutations in the SGR1 gene, along with other

411   genes involved in pigment biosynthesis, can effectively alter fruit coloration.

4.1.2. Challenges and Opportunities

413   The intricate interactions between traits and environmental variability make precise trait predictions difficult. Smaller breeding

414   programs with constrained resources often face challenges in accessing advanced technologies. Overcoming these

415   obstacles requires coordinated efforts and collaboration among scientists, breeders, policymakers, and other stakeholders

416   (Chaudhary *et al.,*2024).The challenge in introgressing these QTLs lies in the low level of genetic polymorphism between

417   the both parents. The understanding of the stay-green trait and the genetic regulation of mechanisms underlying its

418   expression in sorghum remains incomplete. For example, recent findings showed that alleles from the B35 (BTx642) donor

419   parent at the stay-green QTL Stg1 enhanced water extraction in the moderately senescent caudatum variety S35 but did

420   not have the same effect in the highly senescent durra variety R16. This highlights the need to identify optimal germplasm

421   donors for each component which may vary depending on genetic forms as well as specific external conditions where

422   improved drought tolerance is sought. The lack of alternative SSRs and limited polymorphism posed a significant challenge.

423   Many of the stay-green QTLs targeted for introgression were associated with broad confidence intervals between flanking

424   markers, combined with a lack of flanking SSR polymorphisms between the donor and recurrent parents. (Vadez *et al.,*

425   2013).

426   Early maturation in wheat is advantageous for avoiding abiotic stresses such as drought and heat, thereby enhancing

427   resilience in unpredictable climates. However, accelerating the growth cycle can lead to reduced biomass accumulation,

428   potentially compromising grain yield and quality. This trade-off necessitates a careful balance between achieving early

429   maturity and maintaining optimal yield and quality. Discussion emphasizes the importance of understanding the genetic and

430   physiological mechanisms underlying early maturation to develop wheat varieties that can effectively balance these

431   competing factors. By identifying and manipulating specific genetic determinants, breeders can aim to produce early-

432   maturing wheat cultivars that do not sacrifice yield or quality, thereby meeting the demands of both farmers and consumers.

433   While early maturation offers significant benefits in adapting to changing environmental conditions, it presents challenges

434   that require a nuanced approach to wheat breeding, ensuring that the advantages of early maturity do not come at the

435   expense of other critical agronomic traits (Singh *et al.,*2024).

436   Breeding crops with the SG attributes , presents notable challenges due to trade-offs with other agronomic traits. For

437   instance, while stay-green can enhance drought tolerance by maintaining photosynthetic activity during stress, it may also

438 reduce nitrogen remobilization efficiency, potentially impacting grain filling and yield. Furthermore, the leaf longivety trait has

439 been linked to reduced tillering and altered stomatal behavior in sorghum, which could affect overall plant architecture and

440 water use efficiency. Future research opportunities include dissecting the various mechanisms underlying this trait to mitigate

441 these trade-offs. Advancements in molecular breeding and genomic selection could facilitate the development of stay-green

442 varieties that maintain yield and quality. Moreover, exploring the interaction between stay-green traits and environmental

443 factors may provide insights for optimizing crop performance under varying conditions (Lu *et al.,* 2024).

4.1.3. Significance of stay green

4.1.3.1. Stay-green attribute vital for crop resilience and productivity

446 The stay-green trait in plants is indispensable in diverse agricultural and ecological settings, particularly in environments

447 where plants encounter stressors or constraints that can impede their growth and productivity (Rosenow *et al.,* 1983) and

448 (Wahid *et al.,* 2007). Specifically, it is important in drought and heat stress conditions to maintain leaf greenness over an

449 extended period, especially throughout the grain loading stage, thereby enhancing grain yield (Spano *et al.,* 2003).

4.3.1.2. Significance of stay-green traits in agricultural and horticultural crops

451 Their performance extends across both agronomical and horticultural crops, offering multifaceted advantages crucial for

452 sustainable agriculture. In agronomical crops, delayed senescence, particularly in stay-green plants, emerges as a

453 cornerstone for enhancing yield and biomass production. This trait facilitates elevated nitrogen uptake during grain filling,

454 a pivotal stage for crop productivity, compared to senescent genotypes (Gregersen *et al.,* 2008). Moreover, stay-green

455 genotypes exhibit enhanced nutrient uptake and utilization by postponing leaf senescence, thus optimizing resource

456 allocation, especially in nutrient-deficient soils. As climate change increases the frequency and intensity of weather events,

457 agronomic crops' resilience becomes critical, with stay-green features playing a crucial role in enabling improved adaptation

458 to changing climatic conditions. (Borrell *et al.,* 2014). Additionally, the sustained activity of leaves in stay-green crops

459 mitigates the need for excessive fertilizer and irrigation, promoting more sustainable agricultural practices (Thomas and

460 Howarth, 2000). Furthermore, the trait contributes to lodging resistance and bolsters resilience against biotic and abiotic

461 stresses, ensuring crop stability and productivity in challenging environments.

462 In horticultural crops, the importance of stay-green traits transcends mere productivity and extends to enhancing market

463 value and produce quality. The preservation of greenness prolongs the harvest period and improves the marketability of

464 fruits, vegetables, and ornamental plants. Various approaches, including manipulation of hormone levels or responses in

465 transgenic plants, have been employed to mitigate postharvest yellowing, thereby extending post-harvest shelf life and

466 facilitating long-term transportation. By maintaining visual appeal and quality, stay-green traits boost market value and

467 reduce post-harvest losses, ensuring economic viability and endurability throughout the agricultural supply chain.

4.2. Phenotyping Technologies for Stay-Green Traits

4.2.1. High-Throughput Phenotyping

470 Plant breeding is a lengthy and expensive process, constrained by several factors. These include the breeder's confidence

471 in the selected phenotype and its relationship to the underlying genotype, as well as the capacity to anticipate phenotypic

472 performance across different conditions. By focusing on variables that capture dynamic fluctuations in leaf greenness and

473 canopy architecture, we may be able to link stay-green features to changes in leaf area and N remobilization during grain

474 loading. To assist with this, the CSIRO High Resolution Plant Phenomics Centre created a portable Phenomobile that

475 incorporates a Greenseeker® for precise NDVI measurement and LiDAR to analyze the vertical distribution of green leaf

476 biomass and leaf area throughout the canopy. With Global Positioning System –linked spatial coding, the device can rapidly

477 and non-destructively assess canopy architecture traits across one hectare of breeding lines (approximately 1,000 plots) in

478 under an hour. For instance, the evolution of NDVI during grain filling was evaluated for sixty four wheat genotypes with

479 contrasting canopy architectures (Rebetzke *et al.,* 2016).

480 Advancements in high-throughput phenotyping (HTP) methods, particularly remote sensing and imaging technologies, have

481 significantly enhanced the assessment of stay-green traits in crop breeding programs. These technologies allow for quick,

482 precise, and non-harmful assessment of plant traits in large groups, facilitating the selection of desirable traits such as

483 delayed senescence. Remote sensing tools, including multispectral and image spectroscopy, provide deep insights on plant

484 health and physiology by measuring reflectance at various wavelengths. This allows for the monitoring of chlorophyll content

485 and photosynthetic activity, which are indicative of stay-green traits. Imaging technologies, such as RGB cameras and

486 thermal imaging, provide insights into canopy structure, leaf area, and temperature profiles, further informing assessments

487 of plant vigor and stress responses.The integration of these HTP methods into breeding programs accelerates the

488 identification and development of crop varieties with enhanced stay-green characteristics, contributing to improved yield

489 stability and resilience under stress conditions. For example, in sorghum, HTP of dynamic canopy characteristics associated

490 with SG has been successfully carried out utilizing these modern methods. (Liedtke *et al.,* 2020).

491   **4.2.2. Field-Based Phenotyping**

492 Observers have concentrated from base level enhancements in production potential to encourage this type of phenotyping.

493 Below-ground it is a significant bottleneck, and novel methods for measuring root-related traits are necessary (Roitsch *et*

494 *al.,* 2019).These platforms are widely acknowledged as the sole appliance capable of providing the necessary throughput

495 in plant, as well as an An errorless depiction of characteristic expression in the real world.Plants in controlled circumstances

496 often have substantially less soil volume than plants in the field, which has an impact on nutrition and water regimes, as well

497 as disrupting normal growth and development patterns. Enclosed controlled surroundings make it difficult to describe

498 reactions that might occur in the field. These include both ground and air-based techniques. Ground-based phenotyping

499 platforms include adapted vehicles and detection equipment, also known as 'phenomobiles'. Outdoors, accessible photos

500 provide information on canopy cover and hue.. Using a color threshold, an image processing method can predict canopy

501 cover. In the outdoors, a stereo camera system or images from several sites enable extensive reconstruction and

502 investigation of the canopy structure, providing crucial variables (Li *et al.,* 2014).

503 Field-based phenotyping is essential for understanding the expression of SG traits in crops under real-world conditions.

504 Evaluating this trait in natural field environments allows researchers and breeders to observe how it interacts with variable

505 factors such as soil type, climate, and management practices. By conducting phenotyping directly in the field, it is possible

506 to assess the performance and adaptability of stay-green traits across diverse environmental conditions. Advances in robotic

507 sensing platforms have aided HTP's success. The development of unmanned aircraft systems (UASs), often referred to as

508 drones, has significantly advanced High-Precision Phenotyping (HPP). Red, Green, Blue, multispectral, hyperspectral, and

509 infrared cameras are among the image sensors mounted on UAS. Advances in IoT sensors, such Field Server, have

510 benefited HTP, underlining the necessity to understand G×E (genotype-environment interaction) (Ninomiya *et al.,* 2022).

511 Machine learning advancements have allowed for fast phenotyping of crop stresses such as drought, pests, and diseases.

512 These projects range in scale from the leaf to the field level. The success of disease evaluation employing ground mobile

513 platforms, such as sugar beet cercospora leaf spot and wheat STB, has led to the widespread usage of such aircraft systems
514 for field-level disease assessment using RGB and multispectral images with CNN. (Guo *et al.,* 2021).

5. Conclusion

5.1. Summary of Key Findings

517 Stay-green characteristics play an important role in improving crop resilience and yield under stress circumstances like
518 drought, heat, and nutrient constraints. These traits, characterized by the delayed senescence of leaves, contribute to
519 prolonged photosynthetic activity, improved resource use efficiency, and sustained biomass production during critical growth
520 phases. Crops can maximize water and nutrient intake by keeping green foliage, while decreasing the deleterious
521 consequences of stress-induced premature leaf loss. Stay-green traits also enhance grain filling and overall yield stability,
522 making them invaluable in breeding programs aimed at improving food security. Furthermore, stay-green crops exhibit better
523 root development, which enables deeper soil exploration for moisture and nutrients, crucial for survival in arid or degraded
524 soils. Their ability to endure abiotic stresses without considerable loss in output is crucial in the context of climate change
525 and increasing environmental unpredictability. These tarits also indirectly contribute to carbon sequestration, soil health,and
526 ecosystem sustainability by extending vegetation cover. Modern molecular breeding and genetic engineering technologies
527 have enabled the identification and inclusion of stay green features into numerous crop species, hence expediting the
528 production of resistant cultivars.. The integration of these traits into crop improvement strategies aligns with global efforts to
529 ensure sustainable agricultural systems. Stay-green traits thus represent a cornerstone in the developing crops resilient to
530 harsh conditions, safeguarding food production for future generations

5.2. Implications for Sustainable Agriculture

532 The adoption of stay-green crops is a promising strategy to achieve sustainable agricultural systems that balance productivity
533 with environmental conservation. By enhancing resource use efficiency, improving stress resilience, and mitigating
534 environmental degradation, stay-green crops contribute to sustainable food production systems that can withstand the
535 challenges of climate change. Their widespread adoption could significantly contribute to global food security while
536 preserving ecological balance .Enhanced yield stability as improved grain filling and biomass production, ensuring stable
537 yields even under stress conditions, consistent productivity, critical for meeting the growing global food demand despite
538 erratic weather patterns. Stay-green (SG) traits are closely linked to improved tolerance to abiotic stresses such as drought,
539 heat, and salinity. These crops utilize available water and nutrients more efficiently, making them resilient in water-scarce
540 environments. Sustained chlorophyll content during heat stress ensures continued photosynthetic efficiency, mitigating yield
541 losses caused by climate-induced stress. Resource Use Efficiency: Reduced transpiration losses and prolonged canopy
542 greenness improve water use efficiency, Stay-green crops make better use of applied fertilizers by extending the
543 photosynthetic phase, reducing nutrient runoff and environmental pollution. Mitigation of Climate Change Impacts such as
544 Sequestering carbon, Prolonged green foliage increases the duration of carbon capture through photosynthesis and Efficient
545 use of inputs like water and fertilizers decreases emissions associated with intensive farming practices. Contribution to Food
546 Security in the form of resilience of stay-green crops ensures reliable food production in regions affected by climate variability
547 reffering to Adaptability and Improved storage and quality i.e., Extended leaf greenness can lead to higher-quality grains
548 and longer post-harvest shelf life, ensuring food availability. Promoting Sustainable Farming System in which crops support
549 long-term soil health by reducing soil erosion and improving organic matter content.

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