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Review Article

Adaptation and Agricultural Significance of *Syzygium cumini* L. in Saline Environments: A Global Perspective on Jamun Cultivation and Salt Stress Resilience

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Abstract

Syzygium cumini L., known commonly as jamun, is a fruit tree with significant adaptability to diverse environmental conditions, particularly saline soils. This review comprehensively explores the adaptation mechanisms of jamun to saline environments and its agricultural significance on a global scale. Given the increasing soil salinization worldwide, understanding the resilience of crops like jamun is crucial for sustainable agricultural practices in salt-affected regions. Jamun is native to the Indian subcontinent but has been cultivated in tropical and subtropical regions worldwide. Its ability to withstand various abiotic stresses, especially soil salinity, makes it an ideal candidate for cultivation in areas prone to such conditions. This review highlights the physiological and biochemical responses of jamun to high salinity, including ion regulation, osmotic adjustment, and antioxidant activity. These mechanisms help the plant maintain growth and productivity in environments where many other crops fail. Additionally, the review discusses the importance of jamun in traditional medicine and its nutritional benefits, emphasizing its potential for enhancing food security in saline-affected areas. The fruit's rich composition of vitamins, antioxidants, and minerals underscores its nutritional value, making it a beneficial addition to the diet in regions with limited crop diversity due to salinity. Furthermore, the paper addresses the agricultural practices conducive to maximizing jamun's yield in saline environments, including suitable propagation techniques and water management strategies. It also explores the genetic diversity within Syzygium cumini species, which could be leveraged to breed varieties with enhanced salt tolerance and better fruit quality. In conclusion, the global cultivation of jamun not only contributes to biodiversity but also offers a viable solution for agricultural productivity in salt-impacted soils. Continued research and development efforts are essential to optimize cultivation practices and expand the use of jamun in saline agriculture.

Keywords: Syzygium cumini, jamun, saline soil, salt stress, agricultural sustainability, plant adaptation, tropical fruit, genetic diversity, traditional medicine, nutritional benefits.

INTRODUCTION

Jamun (*Syzygium cumini* L.), also known as Indian blackberry, Java plum, black plum and jamblang (Kishore, 2019). It is a fruit native to Indian subcontinents. It is also grown in many tropical nations and locations, including as the West Indies, East and West Africa and certain subtropical places like Israel and Algeria. An estimated 13.5 million tonnes of jamun fruit are produced worldwide each year (Hameed *et al.*, 2020). Since ancient times, jamun fruit has been cultivated in India, particularly in the Indo-Gangetic Plain. It is predominantly grown in the Kumaon hills of northern Tamil Nadu in South India and in the lower Himalayan Mountain ranges. Revered as the "Fruit of the Gods" by many Hindus, especially in Gujarat, due to its abundance and significance in India. The tree is also esteemed by Buddhists in Southern Asia and appreciated by followers of Krishna, who consider it a significant deity in Hinduism (Oliveira *et al*., 2016). Jamun (*Syzygium cumini* L.) demonstrates adaptability to a broad spectrum of climatic conditions. It exhibits resilience to prolonged flooding as well as drought conditions. Typically, it thrives in proximity to rivers, yet it can also flourish in areas with shallow and rocky soils (Sarvade *et al.,* 2016).

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Vegetatively propagated trees typically commence fruiting within 5 to 6 years, while those grown from seeds typically bear fruit after a decade. A productive jamun tree yields an average of 80 to 100 kg of fruit annually. Categorized by shape, jamun fruits can be either oblong or ovoid. Oblong fruits typically feature a necked base and a pointed apex, while ovoid types exhibit a flat base and apex. Generally, oblong varieties possess lower seed weights, a higher proportion of fruit flesh, and elevated average pectin content compared to ovoid varieties. However, cross-pollination induces significant variation in fruit quality and maturity. Researchers and growers have identified region-specific selections chosen for factors such as fruit size, shape, taste, fruiting season, and maturity. Nevertheless, there are no standardized production practices for Syzygium cumini. For instance, in Indian states like Goa, Uttar Pradesh, Jharkhand, Gujarat, Karnataka and Maharashtra, a plethora of seedling strains are cultivated, each showcasing a diverse array of fruit shapes, sizes, pulp colors, acidities and maturities (Singh, 2017). Jamun (*Syzygium cumini* L.) is a member of the Myrtaceae family. The genus Syzygium, within the Myrtaceae family, comprises approximately 1200 species (Parnell *et al*., 2007). It holds the 16th position among the top 57 largest flowering plant genera globally (Frodin, 2004). Syzygium exhibits a wide distribution, primarily across southern and southeastern Asia, southern China, Australia, Malaysia, and New Caledonia. Some species are also present in Taiwan, southern Japan, the southwestern Pacific Islands, East Africa, Madagascar and the Mascarenes (Govaerts *et al*., 2008). While Malaysia serves as the center of diversity, the Melanesian-Australian region harbors the majority of its evolutionary diversity. In its native habitats, Syzygium stands as one of the most prevalent tree genera in forest environments. It predominantly thrives in tropical or subtropical regions, encompassing lowland to montane rainforests, wetlands, ultramafic forests, savannahs, and limestone forests. Syzygium plays a significant role as a food source for birds, insects, and small as well as large mammals (Parnell *et al*., 2007). Just a small portion of Syzygium species is economically grown or used for their fruit, timber, medicinal qualities, or as spices, despite the plant has wide species diversity. One species that is widely grown in the tropics for its essential oils is *Syzygium aromaticum* L., a relative of *Syzygium cumini* L. Even though Syzygium isn't thought of as a major source of timber, still several species are used locally in building. Moreover, various forest-dwelling Syzygium species find local applications in traditional medicine, fabric dye production, and culinary practices. *Syzygium cumini*, a widely distributed species, has been selectively cultivated across the tropics and subtropics worldwide (Soh and Parnell, 2015). It is characterized as a medium-sized trees with a straight trunk, a crown with many branches, light green twigs, and leaves with a thin, translucent edge (Ayyanar and Subash-Babu, 2012). Its vegetative shoots appear as terminal growths on branchlets from the previous season, and their growth is distinguished by several flushes throughout the course of the year. Jamun trees often undergo four to five vegetative flushes every year in areas with eastern tropical climates (Kishore, 2019).

Seed propagation is widely utilized for plant propagation across various growing regions worldwide. While it leads to significant genetic variability, it also allows for clonal selection, serving as an immediate basis for crop improvement (Devi *et al*., 2002). The jamun tree is successfully propagated through several grafting methods. Rootstock production on open nursery beds, especially in sandy soils, poses challenges. Therefore, seedling rootstocks are nurtured in containerized nurseries for 10 to 12 months with regular cultural care to attain the appropriate size. Veneer grafting is conducted monthly throughout the year on rootstocks aged 8 to 10 months. Micropropagation, using seedling explants, is another method for obtaining abundant, true-to-type planting material (Jain and Babbar, 2003). The large fruit (2.5-3.5 cm in length and 1.5-2.0 cm in diameter) and oblong shape of the 'Raja' jamun are its distinguishing features which is popular in northern India. the fruit becomes a deep purple or bluish-black hue, when fully ripe. This cultivar ripens in India in June and July and produces juicy fruits with tiny seeds (Singh *et al*., 2007). 'Goma Priyanka', another popular cultivar, has a spreading growth habit, is seedless, and is regarded as semi-dwarf. With its heavy foliage and hanging branches, it begins bearing fruit four years after planting. Within the hot, semi-arid ecology of western India, 'Goma Priyanka' is ideal for high-density planting and has yielded up to 44 kg per tree eight years after planting under rain-fed circumstances (Singh, 2017). It has an average weight of approximately 7 g and length of approximately 3 cm (Singh *et al*., 2009).

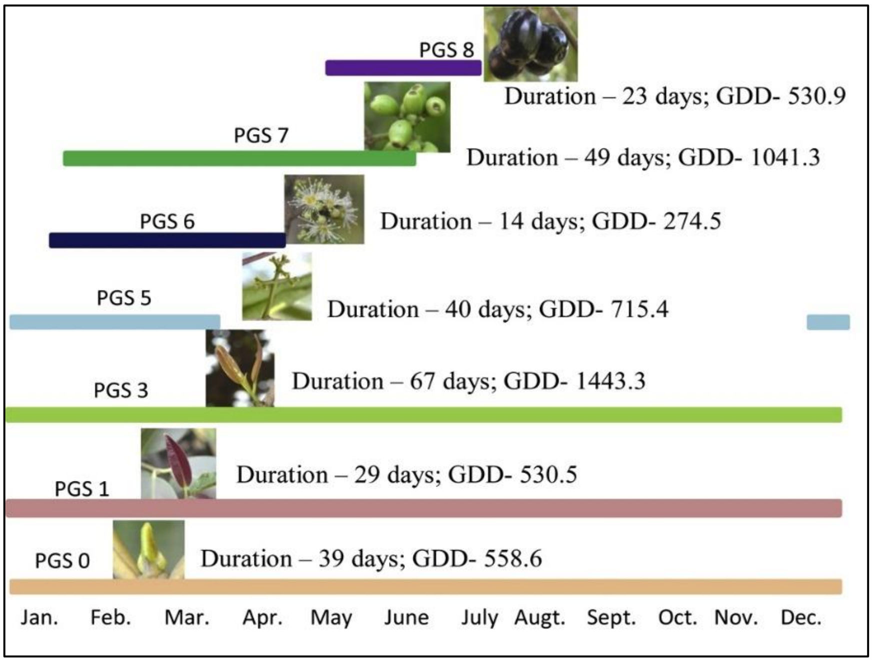

Figure 1: Phenological growth stages and heat unit requirement of *Syzygium cumini* L. (Kishore, 2019)

Climate change has notably heightened the incidence of abiotic stresses in fruit crops, such as salinity, water scarcity, and high temperatures, leading to a significant reduction in the harvest index of major crops (Carmen *et al*., 2011). The demand for sustainable nutrient consumption coupled with a high requirement for fertilizers contributes to increased production costs and yields for farmers worldwide (Shrivastava *et al*., 2015). Conversely, abiotic stresses remain a significant constraint on agricultural production globally, exerting considerable pressure on the environment (Meena *et al*., 2017).

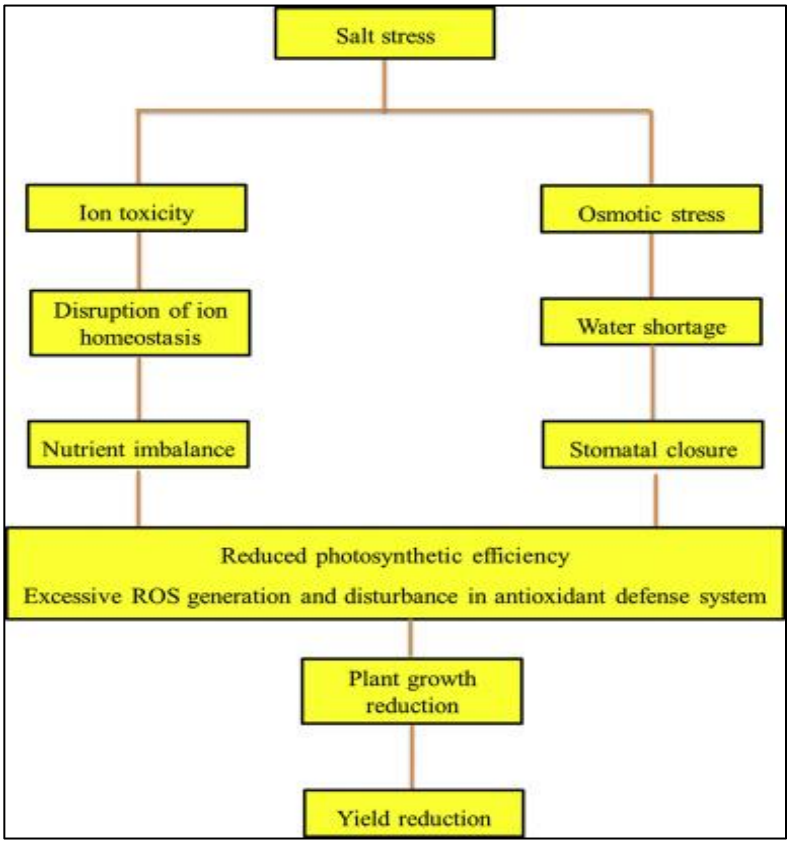

Figure 2: Physiological and molecular basis of salinity tolerance in fruit crops (Ahmad *et al*., 2020)

Among these stresses, salt accumulation poses a particularly significant threat to crop yields. Soil salinization, a long-standing environmental concern, is increasingly becoming a global issue of soil degradation in arid and semi-arid regions (Safdar *et al*., 2019). Saline soils harbor excessive amounts of soluble salts, including sodium, calcium, sulfate, potassium, and carbonate, in the root zone. The accumulation of these salts renders the soil unsuitable for crop production and nutrient supply. According to the Food and Agriculture Organization, the global extent of salt-affected soils encompasses 424 million hectares of topsoil (0-30 cm) and 833 million hectares of subsoil (30-100 cm), representing 73% of the mapped land (FAO, 2021).

It is widely acknowledged that salinity stands as one of the primary abiotic factors constraining agricultural productivity globally (Hussain *et al*., 2019). Soil salinity affects almost 7% of the world's land area (Fahmi *et al*., 2011), with approximately 900 million hectares affected by sodic and saline conditions globally (Munns and Tester, 2008). Salinity-affected regions encompass 40% of farmland and 50% of irrigated land (Roy and Chakraborty, 2014). Pakistan, with a total geographical area of 79.6 million hectares (World Bank, 2012), comprising arid and semi-arid zones, suffers annual losses of approximately US $2 billion in the agriculture sector due to salinity, a figure expected to rise in the future. Currently, around 14% of irrigated land is affected by salinity, increasing by 40,000 hectares annually (Iqbal *et al.*, 2009; Batool *et al*., 2014), resulting in an estimated loss of irrigated land in Punjab amounting to 20 billion rupees (350.88 million dollars) (FAO, 2008).

Salt-affected soils are categorized into three types based on salt presence: sodic (exchangeable salts), saline (soluble salts), and saline-sodic soil. These soil conditions, characterized by elevated salt levels-whether soluble, exchangeable, or both-deteriorate soil chemical properties and severely impact plant growth. Salinity poses a significant challenge in regions with limited water availability, as there isn't sufficient water input to adequately remove salts from the plant root zones, hindering crop productivity. Salinity disrupts various aspects of plant physiology and biochemistry, leading to a substantial decline in crop productivity, especially in horticultural crops (Amir *et al.*, 2019).

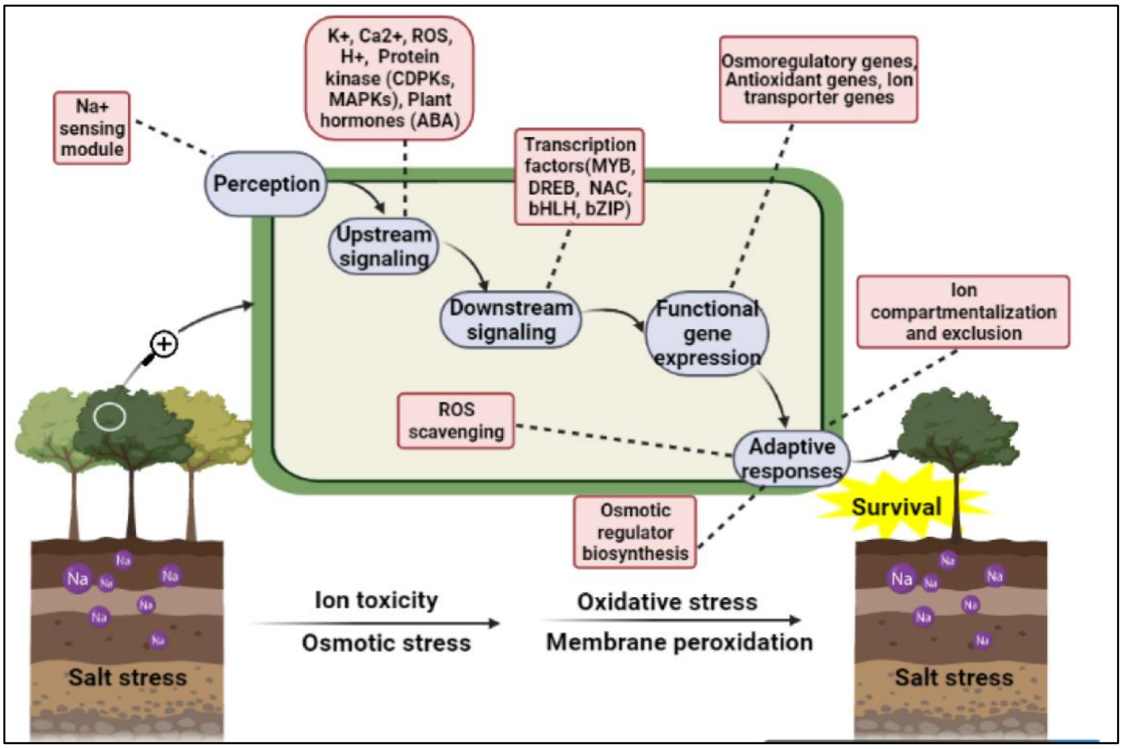

Figure 3: The process of plant salt tolerance development (Hao *et al*., 2021)

Plants experience a scarcity of water due to the greater solute levels in the saline soil, which then causes particular ionic toxicity (Munns and Tester, 2008). Whether present in irrigation water or the soil, these salts inhibit plant growth by altering permeability of membranes, producing nutrient imbalances, affecting biomass, relative growth rates, photosynthesis, transpiration rate, stomatal conductance, osmotic stress, generating reactive oxygen species (ROS), ion toxicity, and changing the properties of plant gas exchange (Nawaz *et al*., 2010). Salt levels, ranging from mild to severe, primarily impede carbon dioxide diffusion in leaves by reducing stomatal and mesophyll conductance. This phenomenon arises due to the accumulation of extreme levels of sodium and chloride ions, coupled with reduced uptake of other essential mineral nutrients such as calcium (Ca^{2+}), potassium (K^{+}), and manganese (Mn^{2+}) (Huang *et al.*, 2009). Consequently, osmotic and turgor potential are affected, leading to leaf wilting, epinasty, curling, abscission, decreased photosynthetic activity, loss of cellular integrity, fluctuations in respiration, tissue necrosis, and ultimately plant demise. However, salt tolerance varies among plant species and cultivars of the same crop species (Ismail *et al.*, 2017). Fruit trees, in general, exhibit high sensitivity to soil salinity (Singh *et al.*, 2019). The jamun (*Syzygium cumini* L.) plant holds significant value for its delectable tropical fruit, rich in vitamin C, minerals, and natural antioxidants (Araujo *et al*., 2015; Flores *et al*., 2015). Notably, the jamun tree stands out as one of the hardiest tropical fruit trees, exhibiting remarkable adaptation to diverse environmental conditions and superior productivity compared to most other fruit crops (Sharma *et al*., 2010). To enhance sustainable horticultural production, the development of salt-resistant varieties is deemed one of the most effective strategies to address this challenge. However, there is a lack of reported work on jamun plants regarding salinity tolerance. The demand for jamun utilization is steadily increasing, particularly for commercial purposes. This necessitates a broad genetic base for selection and breeding of the most suitable varieties for different environments and purposes. Thus, comprehensive information regarding existing genotypes, their precise distribution within agro-climatic zones, their level of genetic diversity, nutritional value of fruits, and genotype tolerance is crucial for accessing the genetic resources of this species (Bhattarai *et al*., 2020).

Salinity A thread to Agriculture

Syzygium cumini L. is a fast-growing evergreen tropical tree of medium to large size, renowned for its multifarious uses in medicine, woodcraft, fuel, food, fruit, pharmaceuticals, and ornamental purposes. Virtually every part of the plant holds significant importance. The ripe fruits are not only edible but also utilized in the preparation of health drinks, squashes, preserves, jellies, and wine, among other products. The seeds are highly valued for their medicinal properties, effectively treating various ailments. Extracts from *Syzygium cumini* L. exhibit a plethora of pharmacological properties, including antibacterial, antiulcerogenic, antiallergic, antiviral, antidiarrheal, antifungal, hepatoprotective, and cardioprotective effects. Additionally, the timber is utilized in construction, as well as for crafting agricultural tools, utensils, and furniture. Given its widespread occurrence worldwide, both in the wild and under cultivation, *Syzygium cumini* L. has been bestowed with numerous vernacular names across different languages (Binggeli, 2006).

Syzygium cumini L. demonstrates significant variability, particularly in its growth habit, foliage, and fruits, owing to its adaptation to various soils and climatic conditions. The tree typically reaches its full size in approximately 40 years, with mature trees varying in height from 15 to 40 meters and trunk diameters ranging from 0.5 to 2.5 meters. The main trunk often bifurcates into multiple branches shortly above the ground, eventually branching profusely upward. The tree is typically adorned with dense foliage and flowers. The bark on the lower stem appears rough, cracked, flaking, and discolored, transitioning to a light gray to grayish-brown smooth texture towards the upper portions. While the blaze color is usually light pinkish-white, some specimens exhibit a dark red blaze. The wood is characterized by its whitish hue, hardness, and durability. The shape and size of leaves vary greatly among individuals; they can be lanceolate, ovate-elliptic, oblong-ovate, or narrowly elliptic, with an acute, acuminate, or occasionally obtuse apex. There are also variations in the leaf base, which might be difficult to subtruncate. When leaves are young, they usually have reddish or pinkish colors before turning green (Bukya and Madane, 2018).

The fruit, a berry, has notable variations in pulp color and flavor in addition to shape, size, and thickness. The berries are green at first, then turn light violet-red or purplish-red, and then, when fully ripe, they turn dark purple to black. Fruits are typically divided into two categories in India according to their size, flavor, and color. One variety has big, oblong fruits with tiny seeds, pink or violet sweet content, and skin that ranges from dark purple to black. The other variety, known as the wild type, consists of small, spherical fruits that range in color from green to pale violet-red or black and have a thin, white flesh that is somewhat sour. A variation with white fruits has been reported from Indonesia occasionally, seedless fruits have been observed (Sagrawat *et al.*, 2006). *Syzygium cumini* L., or "jambavam" in Sanskrit, the official language of ancient India, has substantial therapeutic value in that country. Known as "jamboo," the tree was said to be extensively scattered throughout the area in antiquity and represented a tree that produced fruits and blossoms year-round. According to historical reports, this species of tree was initially discovered south of Mahameru, where its indigenous taxonomical features were noted. Syzygium cumini is considered as one of the divine trees (mahavrikshas) on Earth in Puranic literature, along with other renowned trees like makanda (Mangifera indica), peral (Ficus benghalensis), and kadamba (Neolamarckia cadamba) (Singh *et al*., 2018).

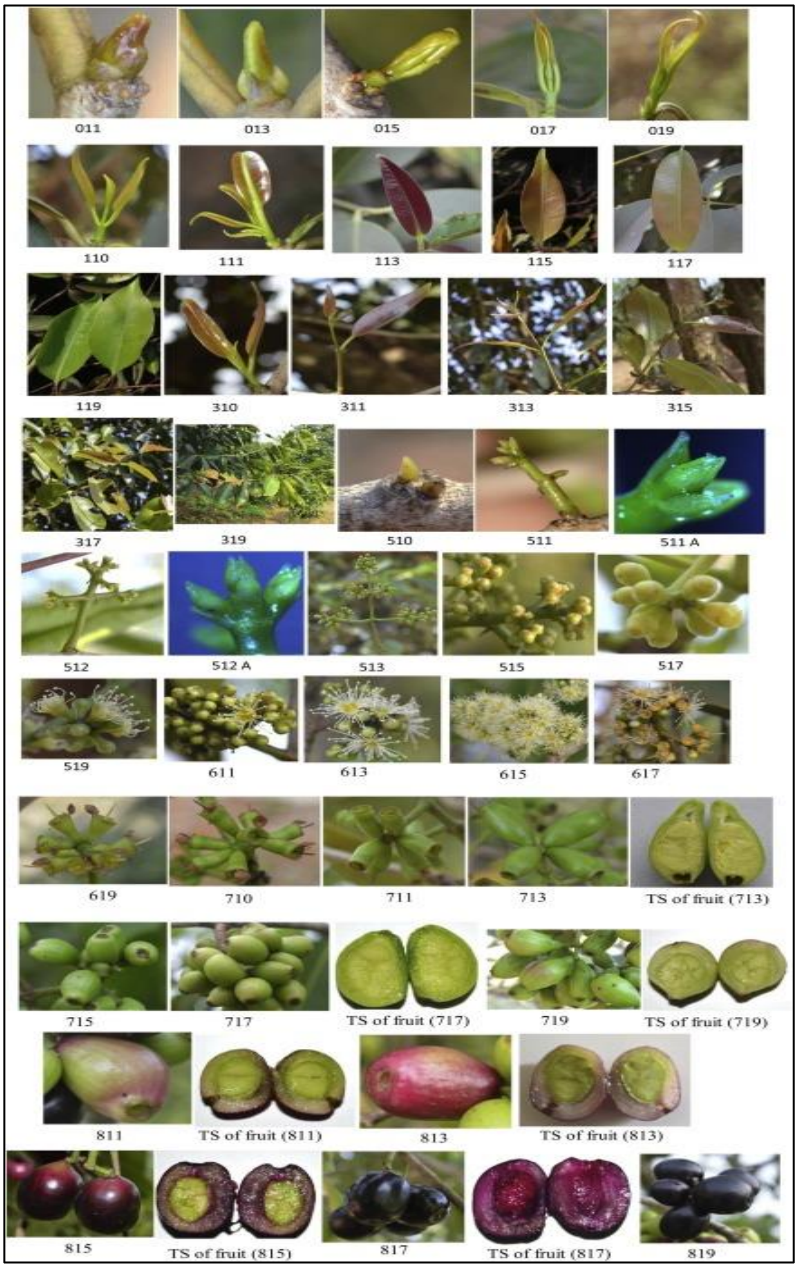

Figure 4: Phenological growth stages of *Syzygium cumini* according to the extended BBCH scale (Kishore, 2019)

Plant Propagation

Jamun seeds do not produce offspring true to their parent type. However, the nature of polyembryony (20-50%) allows for the utilization of nucellar seedlings to produce uniform rootstocks for grafting and budding. Germination of seeds typically begins about two weeks after sowing, with seedlings becoming suitable for grafting during the spring season. Due to late fruit bearing resulting from seed propagation, vegetative propagation methods are preferred for improved or selected varieties. Fresh seeds, which exhibit no dormancy, can be sown about 4-5 cm deep at a distance of 25x15 cm, and seedlings are ready for transplanting into the main field during either spring (February to March) or the next monsoon season (August to September). Budding is a more successful method of propagation for jamun, particularly during the July-August period in regions with low rainfall. Patch or shield methods of budding, if performed in March, yield success rates exceeding 75% (Singh *et al*., 2011). The robust tap roots of jamun may be disturbed during graft transplantation, which could have a negative impact on the grafts' ability to grow and establish in the field. An attempt has been made to solve this problem using in situ patch budding; plants produced through this method in March and April showed success rates of 80.25% and 77.50%, respectively (Singh *et al*., 2009). The mature branches, which are 2-3 months old and measure 15-20 cm in length, are usually defoliated 12-15 days before the grafting procedure. Next, these shoots are cut off from the parent plant using a sharp grafting knife or secateurs. An alternate technique for propagation is micropropagation, which allows for the quick regeneration of disease-free, true-to-type plants from tiny plant fragments in an artificial growing medium while maintaining aseptic conditions. For this, a variety of tissue culture techniques can be used, including cell culture, meristem culture, embryo culture, callus culture, protoplast culture, and embryo culture (Singh *et al*., 2019).

Cultivation, Pests and Diseases

The land preparation involves ploughing, harrowing, and leveling to create an appropriate terrain. It's essential to ensure a moderate slope to facilitate adequate irrigation and efficient drainage, particularly during the rainy season, to mitigate water-related issues. Jamun cultivation offers versatility, being adaptable to various cropping systems, such as orchard cropping in dedicated land or integration into agroforestry schemes within mixed cropping systems. Following site marking, pits measuring 90×90×90 cm are typically excavated during the summer months. Next, a mixture of topsoil and 20-30 kg farmyard manure is added to these pits. The soil in the pits is ready for planting during the rainy season, and should be irrigated after planting. Usually, jamun trees are placed 10×10 m apart. High-density planting at 5×5 m spacing has worked well in some regions, including Godhra, to maximize jamun productivity (Singh *et al*., 2018b). In western dry lands of india, closer spacing of plantings combined with appropriate canopy management led to higher yields and better fruit quality (Singh *et al*., 2017c). These investigations examined the effects of shoot pruning on the yield and quality of the Goma Priyanka variety of jamun.

Irrigation

Water is a precious and limited natural resource, particularly in semi-arid and arid regions. Hence, it is crucial to use water judiciously. Overwatering jamun plants can lead to the development of a superficial root system. Ideally, irrigation should be conducted in the evening to minimize water loss through evaporation. The pH of irrigation water should ideally fall within the range of 6.5-7.5, and it must be free from harmful salts to avoid adverse effects on plant health (Singh *et al*., 2011). Soil water deficiency, especially during fruit development, can significantly affect metabolic activity and fruit yield (Singh *et al*., 2010). Both excess and insufficient water can result in significant losses in both the quantity and quality of jamun fruits. Therefore, it's crucial to use the best water management strategies while taking application methods and water requirements into account. An efficient high-tech solution in water-scarce places is drip irrigation. This technology uses a network of pipes to directly supply the crop's root zone with a sufficient supply of water at low pressure. Irrigation efficiency with drip irrigation can approach 90%, while conventional irrigation technologies only achieve 30%-40% irrigation efficiency (Singh *et al*., 2018a).

Mulching

The efficacy of mulches in conserving moisture is typically more pronounced during drought conditions and in the early stages of plant growth when canopy cover is minimal. Given that soil moisture is a critical factor for successful jamun cultivation, the use of mulch proves highly advantageous (Singh *et al*., 2017). Mulching eliminates competition between weeds and fruit trees by reducing soil moisture loss, increasing the rate at which irrigation or rainfall penetrates the soil, and suppressing weed growth. Various organic materials or black polythene can be used as mulching materials. Mulching with grasses, rice husk, or paddy straw generally lowers weed populations and retains soil moisture. Additionally, the utilization of different mulches enhances the population of earthworms and microbes in the basin soil. Dry jamun leaves spread under the canopy effectively retain soil moisture, particularly during the summer months (Singh *et al*., 2010b; Singh *et al*., 2007e).

Nutrient Management

Jamun trees are hardy and can survive with little cultural maintenance. However, an adequate supply of nutrients and water is essential for ensuring maximum production. For instance, it's common practice to apply approximately 20 to 80 kg of farmyard manure per tree annually during both the pre-bearing and bearing periods. The ideal timing for organic manure application is typically a month before flowering. For fully mature trees, nitrogen fertilizer at a rate of 500 g and potassium fertilizer ranging from 300-600 g per tree per year are commonly administered. These fertilizers should be evenly distributed beneath the plant's canopy and incorporated into the soil. In nutrient-rich soils, trees tend to exhibit increased vegetative growth, flowering, and fruiting. In such cases, regular manuring may not be necessary. While frequent manuring is essential during the initial growth stages, once the trees are established, the frequency of manure application can be reduced (Reang and Das, 2010; Hiwale, 2015).

Flowering, Fruit Set and Fruit Drop

Usually, fruit set and flowering take place in March and April. Only 15-30% of the fruits mature, and fruit drop begins soon after fruit setting. There are three main stages in which flower and fruit drops are noticed. About 52% of the blooms drop off within four weeks of flowering, therefore the first drop, known as the pre-harvest drop, happens during or soon after bloom. About 35-40 days following full bloom, the second drop begins; growing and aborting fruits are not easily distinguished from one another. According to Singh *et al.* (2011), the third decline happens 42-50 days after full bloom and lasts till July 15. It has been demonstrated that the amount of flower and fruit drop in jamun can be decreased by applying two sprays of 60 ppm GA_3, firstly while in full bloom and another around fifteen days after the first fruit setting. Furthermore, Apis dorsata bees in North India rely heavily on the blooms as a source of honey (Singh *et al.*, 2010).

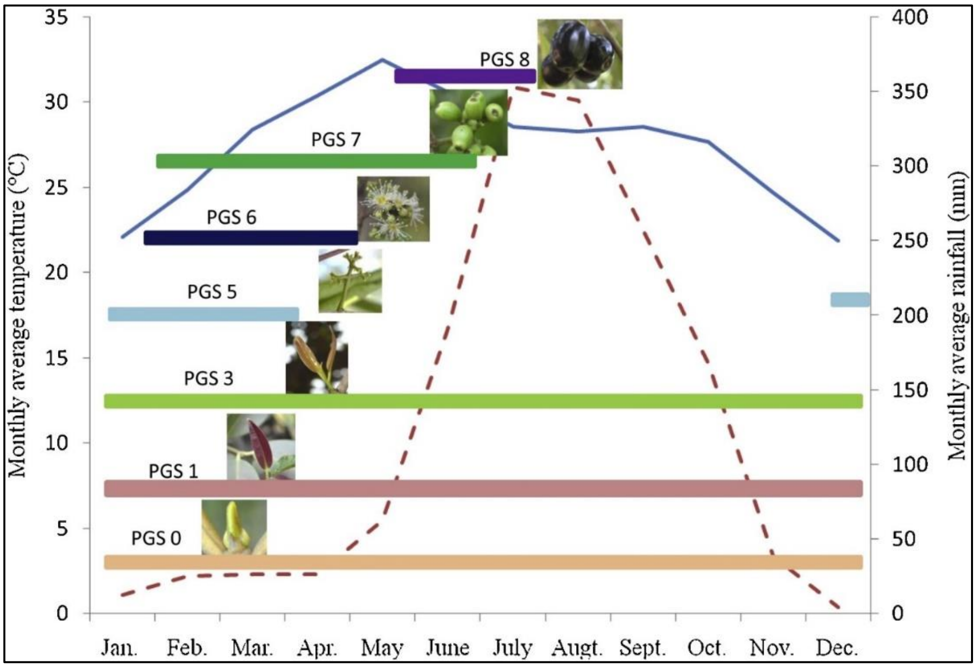

Figure 5: Sequential progression of principal growth stages of *Syzygium cumini* (Kishore, 2019)

Harvesting Practices

Harvesting and value addition of Syzygium cumini plants typically begin 8-10 years after planting for seedlings, while grafted one's bear fruit in 4-5 years. The fruits ripen during June-July, displaying a deep purple or black color when fully ripe. It's essential to harvest the fruits immediately after ripening to minimize wastage. Grading based on size, ripeness stages, uniformity, and cleanliness is necessary to maximize returns. Pre-packaging the fruits in leaf cups covered with perforated polythene reduces weight loss and shriveling, enhancing appearance compared to conventional methods (Singh *et al.*, 2019c). Given the high temperatures (35-42°C) during harvesting, jamun fruits rapidly deteriorate, necessitating measures to prolong their shelf life during storage. A pre-harvest spray of calcium chloride (1-1.5%) significantly enhances fruit quality and increases shelf life at room temperature. By preventing ethylene from building up in fruit tissue, GA_3 controls the production of proteins and nucleic acids and slows down the ripening process. By reducing transpiration and respiration at room temperature, fruits treated with GA_3 and kept in perforated polyethylene bags have a extensive shelf life (Singh *et al.*, 2019b).

Food Uses

Fruits boast a rich array of bioactive compounds including alkaloids, tannins, anthocyanins, flavonoids, phenolic acids, and procyanidins, which exhibit diverse functional properties. These properties include antioxidant, anti-inflammatory, anti-diabetic, and anti-carcinogenic effects, offering protection against various degenerative and chronic diseases. These compounds are recognized for their health-promoting and disease-preventive characteristics. Extracting these phytochemicals from plants involves employing various extraction techniques. *Syzygium cumini* L. (also known as Eugenia jambolana) or Jamun plant is renowned for harboring a diverse range of phytochemicals, many of which confer health benefits. Among these, seeds have been extensively studied. Polyphenols, naturally present in numerous fruits, serve as antioxidants, offering antioxidative properties with minimal toxicity. The antioxidant activity of fruit phenolics primarily stems from their redox properties, enabling them to function as reducing agents. The present study aims to screen the various phytochemicals present in Jamun seeds, extracted using different extraction methods, both qualitatively and quantitatively (Singh *et al.*, 2019b).

Salinity Effects

Salinity stress poses a significant challenge to agriculture worldwide, causing a decline in productivity across the globe. Therefore, it is crucial to address salinity issues to promote sustainable agricultural practices and meet the current and future global food demands (Zorb *et al.*, 2019). Salinity adversely affects both the morphological and biochemical functions of plants. It inhibits seed germination, plant growth, development, and yield in fruit plants (Zhang *et al.*, 2019). Salinity disrupts the photosynthetic machinery, transpiration, and gaseous exchange by reducing the levels of chlorophyll and carotenoids, distorting chloroplast ultrastructure and the PSII system, and decreasing stomatal conductance (Li *et al.*, 2020).

Moreover, soil salinity reduces soil water potential and leaf water potential, disrupting plant water relations and diminishing plant turgor, ultimately leading to osmotic stress (Navada *et al.,* 2020). Plants absorb salt from the soil through transporters, which can lead to ion toxicity, disrupting mineral uptake and ion homeostasis. Salinity results in the extensive accumulation of ions such as Na^+ and Cl^- while inhibiting the uptake of essential ions like K^+ and Ca^{2+}, causing an ionic imbalance. Additionally, salinity increases the content of reactive oxygen species (ROS) in plant cells, inducing oxidative stress. The detrimental effects of ROS include lipid peroxidation, membrane degradation, and damage to DNA and proteins (El Ghazali *et al.,* 2020).

Organic soil can be used to solve nutritional deficiencies caused by salt and metal stress. We exposed salt-sensitive strawberry and lettuce to four salinity (0-60 mM NaCl) and three contamination (0.3-5 mg Cd/kg) rates in peat (pH H_2O = 5.5). The results showed that salt stress had a significant impact on rhizosphere biogeochemistry and physiological processes even at 20 mM NaCl, resulting in leaf-edge burns, chlorosis/necrosis, and decreased vegetative development in crops. The combined Cd x NaCl stressors, in contrast to the control, increased the accumulation of leaf Cd (up to 42 times in lettuce and 23 times in strawberries), whereas the salinity of NaCl increased the amount of Zn (>1.5 times) and Cu (up to 1.2 times). As much as 12.6 mg/kg of hazardous Cd was deposited in lettuce leaves, indicating a robust root-to-shoot Cd transfer. The concentration of Cd in strawberry leaves and fruits, 2.28 and 1.86 mg/kg, respectively was similar (sub-toxic), indicating decreased root-to-shoot translocation and comparable xylem and phloem Cd mobility. Substantial organo- and chloro-complexation likely changed metal biogeochemistry towards organically rich rhizosphere, demonstrating the value of high-quality soils and water in preventing abiotic stressors and growing uncontaminated food (Ondrasek *et al*., 2021). Salt stress, mainly interferes with the diffusion of carbon dioxide in leaves by decreasing stomatal and mesophyll conductance; however, it does not affect the ability of plants to assimilate carbon dioxide biochemically (Zribi *et al*., 2009). Studies have shown that, large concentrations of sodium can lower the rate of CO_2 assimilation. The concentration of salt and chloride ions that result from salinization is inversely correlated with gas exchange characteristics such transpiration, stomatal conductance and photosynthetic rate (Abbas *et al*., 2010). Several agricultural crops have been the subject of numerous research, but there is little data available for horticultural crops. The current review work has discussed the possible role of Si in mitigating salt stress in horticultural crops as well as the likely mechanisms of Si-associated advantages in them. The present study also carefully considers the demand for future studies to evaluate the role of Si and gaps to saline stress in order to improve horticultural crops (Muneer *et al*., 2020).

Salinity poses a severe danger to global and Pakistani crop output. It severely reduces the production of horticultural crops. According to reports, proline helps different crops tolerate salt. As a result, a pot experiment was carried out to evaluate the contribution of proline treatment to improve salt tolerance in chili genotypes. Two genotypes of chilies, Plahi and A-120, were cultivated in a saline solution containing 50 mM NaCl. On seedlings that had been growing for a month, different proline concentrations (0.4, 0.6, 0.8, 1.0 and 1.2 mM) were sprayed over the leaves. Proline, however enhanced both genotypes' antioxidant enzyme activities and increased plant growth and antioxidant enzyme activities under salt stress conditions. Moreover, 0.8 mM of proline was found to be the optimal concentration in terms of growth, physiological, ionic and biochemical characteristics in both genotypes (Munns and Tester, 2008). Over 900 million hectares suffer from salt problems globally. various factors, including low precipitation, high surface evaporation, weathering of native rocks, use of saline irrigation water, and unsatisfactory farming methods, are contributing to the 10% yearly expansion of the salinized lands. By 2050, it is predicted that salinity will damage more than 50% of arable land, which makes this development concerning. Although only 0.2-0.4% of the total productive area is lost due to salinity and waterlogging, sodium chloride remains the major salt contributing to salinity, prompting the need for plants to evolve mechanisms to cope with its accumulation (Munns and Tester, 2008). Therefore, it is crucial to adopt income-generating agricultural practices in extremely salt-affected lands (Jamil *et al*., 2011).

It is difficult to pinpoint soil salinity precisely since salt damage varies based on the types of salts present, plant species, growth stage, and environmental conditions. On the other hand, 4.0 dSm-1 and greater electrical conductivity of the saturation extract (EC) is the threshold for soil salinity according to the USDA laboratory of salinity. Plant growth is impeded by soil water salinization, which is caused by both natural and human-induced processes that build up salts. Another type of salinity, sodicity, occurs when leaching flushes soluble salts into the subsoil, leaving Na^+ ions with a negative charge on clay particles due to an increase in their quantity (Rengasamy, 2006). Soil salinity and drought contribute to significant yield losses, ranging from 20 to 50% for all major crops, and these environmental conditions are expected to worsen in various regions due to climate change (Shrivastava *et al*., 2014; Arshad *et al*., 2024). The responses to saline stress result from complex interactions among morphological, physiological, and biochemical processes, including seed germination, water and nutrient uptake, plant growth, nutrient deficiency and oxidative stress. A significant factor contributing to low phosphorus levels in plant uptake is the precipitation of phosphate ions with calcium ions (Bano and Fatima, 2009). Saline stress has been shown to affect the growth of various vegetables by reducing photosynthesis, disrupting ionic homeostasis and antioxidant capacity, and causing membrane leakage due to oxidative stress (Ali *et al*., 2014; Farkhondeh *et al*., 2012; Abbaspour, 2012; Abbas et al., 2021). The toxicity of sodium and chloride ions disturbs hormonal and nutrient balance and disrupts leaf water relations (Eleiwa *et al*., 2011; Abbas *et al*., 2021a).

Salinity is an ancient environmental phenomenon and is recognized as a significant cause of land degradation, prevalent to varying degrees worldwide, earning its reputation as a quiet destroyer of natural resources. Watered areas constitute 17% of the world's productive land and contribute 30% of overall agricultural production. Salt leads to substantial losses in global agricultural production, estimated at about $12 billion annually, with projections indicating an increase in the coming years (Pitman *et al*., 2007; Arshad *et al*., 2024a). Overall, it is estimated that world food production needs to increase by 38% to 57% by 2050. food demand can be achieved by increasing yields and using the right crop genotypes to reclaim poor soils and make them productive (Iqbal and Ashraf, 2013). This is because irrigated areas have limited possibilities for expansion in some regions worldwide. Different physiological, biochemical, anatomical, and molecular adaptations affect a plant's ability to withstand salt. Ion exclusion, osmotic tolerance, and tissue tolerance are the three mechanisms that plants use to withstand salinity (Roy *et al*., 2014). The processes of osmotic tolerance pertain to the prompt and adaptive reactions of plants in response to elevated salinity stress within the rhizosphere (Flowers and Colmer, 2008; Rafeeq *et al.*, 2020). The movement of Na+ and Cl-ions throughout the root is a well-understood aspect of the ion exclusion process. By preventing the concentration of Na^+ and Cl^- ions in the leaves from rising to hazardous levels, this process helps the plants adapt to salt. This is accomplished by either the outflow of ions back into the soil, the retrieval of sodium from the xylem, or the compartmentalization of ions in the vacuoles of cortical cells (Zhang and Shi, 2013; Rehman *et al*., 2021; Abbas *et al*., 2021).

Plants employ the plant tissue tolerance mechanism to counteract the toxic levels of sodium and chloride in leaves. This mechanism generally involves compartmentalization of excessive ions at the intracellular and cellular levels. It requires synchronization with biochemical processes, including proton pumps, synthesis of compatible solutes, and ion transporters. Salinity tolerance mechanisms operate at the cellular, molecular, and whole-plant levels of organization (Roy *et al*., 2014). The percentage and rate of germination decrease and are delayed with increasing salinity, leading to decreased overall seedling growth characteristics. Genetic variation in salinity tolerance exists in most plants (Odjegba and Chukwunwike, 2012). During seed imbibition, salt stress causes an increased absorption of harmful ions and decreases water intake. Changes in evapotranspiration, drainage, water supply, and solute availability cause fluctuations in these salts. Important parameters for assessing a plant's ability to withstand salinity include germination and seedling characteristics (Akhter *et al*., 2017; Pervaiz *et al*., 2024). Salt stress raises osmotic pressure, which decreases water absorption and impacts physiological and metabolic functions. It delayed or prolonged germination (Zafar *et al*., 2015). Salinity tolerance indices reduce the fresh and dry weight of shoots. It includes the growth, shoot dry biomass and shoot/root length stress tolerance index (Sevengor *et al*., 2011).

High salinity reduces vegetative growth, significantly decreasing plant height, root length, stem diameter, total leaf area, expansion rate, plant fresh weight, and dry mass production (Parvaiz and Satyawati, 2008). Crop emergence is impacted by salt stress, which also speeds up maturity and reduces biomass growth and weight as well as leaf area. Particularly when the severity and duration of salinity increase, it decreases morphological factors and increases leaf abscission (Hussein *et al*., 2012). Additionally, root fresh/dry weights begin to decline at 60 mM and rise at low salt stress levels of 30 mM (Gao *et al*., 2015). Salt stress disrupts photosynthesis primarily by decreasing leaf area, chlorophyll content, and sub-stomatal conductance, thereby reducing the efficiency of photosystem II (Parvaiz and Satyawati, 2008). Different plant species exhibit variations in gas exchange attributes under salt stress. Salinity also significantly damages photosystem II, which is highly susceptible to the lethal effects of saline stress. Chlorophyll fluorescence traits, such as a reduction in Fv/Fm induced by salinity, serve as likely indicators of photosynthetic efficiency in plants (Gomathi and Rakkiyapan, 2011). Salinity causes various harmful effects, including reductions in chlorophyll content, photosynthetic rate, alterations in plasma membrane permeability, and other metabolic disruptions. It induces osmotic stress and restricts water absorption from the soil, leading to ionic stress due to high stages of actually toxic salt ions inside plant cells (Savvas *et al*., 2005). High salinity reduces photosynthetic indices, total chlorophyll content, and degrades chloroplast structure by minimizing grana (Arif *et al*., 2020). Many symptoms, including an increase in leaf succulence and thickness, abscission of leaves, necrosis of root and shoot and a decrease in leaf area and internode length, are frequently present in reaction to these changes. Salinity also slows down several physiological processes, including gene and protein synthesis, photosynthesis, transpiration, metabolic pathways and phytohormonal activities. Many research on silicon (Si), one of the useful elements in the Earth's crust, have been done in an effort to combat salinity (Isayenkov and Maathuis, 2019).

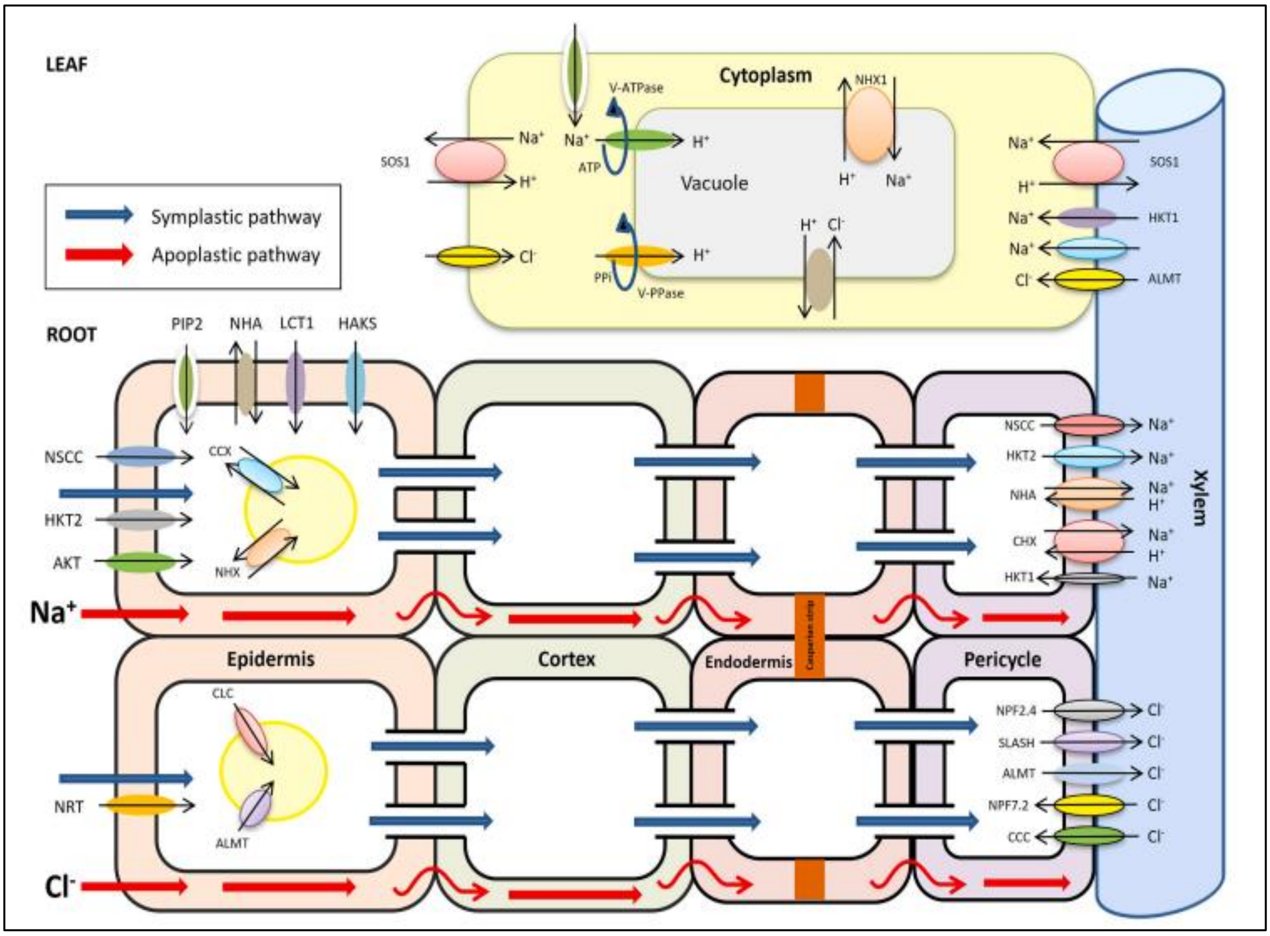

Figure 6: Sodium and Potassium exchanging mechanism in plant

These proteins, along with lower molecular mass scavengers such as glutathione, proline, and ascorbate, act as primary defenses against ROS production in various parts of plants. Catalase is located in glyoxysomes, peroxisomes, and mitochondria, but is absent in chloroplasts. Superoxide dismutase commonly converts photorespiratory or respiratory H_2O_2 into water and molecular oxygen. Similarly, peroxidases decompose H_2O_2 by oxidizing substrates such as antioxidants and phenolic compounds. Phenols are also oxidized to quinone by the enzyme polyphenol oxidase, which is synthesized alkaloids under both abiotic and biotic stress (Shamer and Venkateswarlu, 2011). A strong correlation between the non-enzymatic antioxidant parameters (DPPH sequestration activity, iron reducing antioxidant power, total flavonoid content and total phenol content) was observed. In summary, salicylic acid improved tolerance to guava salt by increasing the enzymatic (peroxidase and superoxide dismutase) and non-enzymatic activity (Shamili *et al*., 2021).

Different salt stress concentrations of NaCl (0, 5 and 10 dSm^{-1}) on guava plant. Plants growing in saline regions few reports have been made of the use of protective additives when growing under salt conditions. Therefore, current research focused on to moderate salt stress in guava. Therefore, guava plants were exposed to putrescine (0, 250 and 500 ppm) and NaCl (0, 5 and 10 dSm^{-1}). Results showed that sodium chloride resulted in increase of enzymatic profile viz. oxidase, catalase, while peroxidase and chlorophyll contents significantly reduced in current study (Galathi *et al.*, 2020).

Guava is a rich source of vitamin C with high yields. However, large tropical areas are exposed to salt water, growing this plant in these areas can affect yield and product quality. Therefore, this study examined leaf excision, dry matter, antioxidant enzyme activity and elemental content of guava plants, sodium chloride concentrations (1.7, 3 and 6 dSm^{-1}) and the use of gibberellic acid (0, 250 and 500 ppm). According to the results, the salt increased from 3 to 6 dSm^{-1}, chlorine, Na, K and Ca in leaves and roots increased and the number of leaves and dry matter decreased. The salt content decreased the activity of peroxidase and polyphenol oxidase, which increases the activity of catalase. Higher amounts of sodium and smaller amounts of potassium were found below 6 dSm^{-1} observed. Application of foliar gibberellic acid (500 ppm) in saline, reducing leaf excision and increasing levels of K, K / Na and Ca, which can be introduced as an effective method to reduce damage caused by the salt stress in guava plants (Pashangeh *et al*., 2020).

Guava (*Psidium guajava* L.) is a hardy fruit tree and present study examined the response of guava to salt stress during the growth phase. The plants were obtained from rooted cuttings from the Calvillo Siglo XXI and Merita varieties. The experiment was performed in a hydroponic system with liquid root in a 50% Steiner solution. Five salinity conditions were evaluated, the electrical conductivity with NaCl at 2.0, 2.5, 3.0 and 3.5 dSm^{-1} and the control at 1.2 dSm^{-1} were adjusted without NaCl. The Calvillo Siglo XXI variety exceeded its chlorophyll content value (36.35 versus 32.74 SPAD units); In contrast, Merita showed a higher concentration of P (0.1230 vs. 0.1010%) and Ca (1.0514 vs. 0.7463%) in the leaf. The salt content reduced the half-life of the leaves from 74 to 42 days. The leaves contain a higher K concentration on average than the roots (0.966%). In EC 3.5 dSm^{-1} the concentration of K in the leaves decreased by 31.8% and in the roots by 55.5% and the concentration of Na in the leaves increased by 68.6% compared to the witness. The ability of both varieties to maintain a high concentration of K in the leaves, as well as the transport of Na to the leaves, increased the resistance to salinity to the observed values. The salinity did not have a significant influence on the growth of the guava plants (Inda-Romero *et al*., 2020).

CONCLUSION

The comprehensive analysis of *Syzygium cumini* L. (jamun) within this review underscores its profound resilience and adaptability to saline environments, positioning it as a vital agricultural asset in salt-affected regions globally. Jamun's inherent tolerance to salinity, coupled with its array of physiological and biochemical mechanisms, enables it to sustain growth and productivity where many other crops might falter. These adaptive traits, such as efficient ion regulation, osmotic adjustment, and robust antioxidant activity, are critical for survival in harsh saline conditions and highlight the potential for developing other salt-tolerant crops. Moreover, the significance of jamun extends beyond its environmental resilience. It is a culturally valued fruit with substantial economic and medicinal benefits, offering a source of nutrition and health in diverse agro-climatic zones. The fruit’s rich content of vitamins, antioxidants, and minerals plays a crucial role in diet diversification, particularly in regions where agricultural variability is limited by soil salinity. This makes jamun not only a buffer against food insecurity but also a means to enhance dietary quality. The review also addresses the practical aspects of jamun cultivation, from propagation methods to genetic diversity, which are essential for optimizing yield and quality in saline-prone areas. The insights into agricultural practices and water management strategies provide a framework for sustainable cultivation, ensuring that jamun can be a reliable crop under varying environmental stresses.

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