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A review on decline of *Pinus halepensis* Mill., (1768) in urban and semi-urban areas of Quetta: Preconditions and signs

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SUMMARY

Pinus halepensis Mill., (Aleppo or Jerusalem pine) is a drought-tolerant tree native to the Mediterranean region and widely introduced in arid and semi-arid habitats, including Quetta, Pakistan. This study investigates the ecological adaptability, morpho-physiological responses, and current decline in the urban and peri-urban landscapes of Quetta. The species shows strong resilience through various characteristics such as deep rooting, serotinous cones, and physiological plasticity, while key factors responsible for its decline include irregular rainfall, extreme heat, prolonged drought conditions, urban heat island effects, soil compaction, pest infestations, secondary pathogen invasion, and limited forest management. Visible morpho-physiological signs, such as chlorosis, premature needle fall, dieback, discoloration of needles, and reduced growth, are observed in urban Aleppo pine trees of Quetta, and the lack of research on the species further intensifies the problem. A structured narrative review was conducted using systematic search and screening procedures, following PRISMA-inspired guidelines to ensure transparency, reproducibility, and thematic synthesis of 130 selected studies. This review recommends monitoring and management practices based on scientific procedures such as chlorophyll content and fluorescence, biochemical assays of proline, dendrometric investigation, deep watering irrigation, the use of biofertilizers, and integrated pest management, and also emphasizes the need for multi-stakeholder collaboration in ensuring and implementing effective urban forestry planning. The introduction of targeted conservation scientific strategies and sustainable urban forestry policies can significantly enhance the resilience and long-term health of Aleppo pine during the ongoing climate crisis and global warming.

Keywords: Aleppo pine, morpho-physiological, pinaceae, stressors, water use efficiency

INTRODUCTION

The Aleppo or Jerusalem pine (*Pinus halepensis*), a member of the Pinaceae family, is native and indigenous to Mediterranean, named officially by renowned English botanist Philip Miller in 1768 in his book, The Gardener's Dictionary (Aisner and Terkel, 1992). The size of Aleppo ranges from 50 to 80 feet in height, 50 to 60 inches in diameter and bark is thick and orange-red in color. The leaves 2 to 5 inches long with yellowish-green in color, and they are produced in pairs sometimes in exceptional case they come in threes (Fig-1). The cones are 2 to 4 inches long and 1 to 2 inches broad on average at base when closed. The cones are opened within five years but the process is stimulated when exposed to heat. The size of opened cone ranges from 2 to 4 inches wide, which allows the 0.1875 to 0.25 inches long with 08125 winged seeds (Fig-2) to disperse (Ayari and Khouja, 2014; Moya et al., 2013; Nathan et al., 1999).

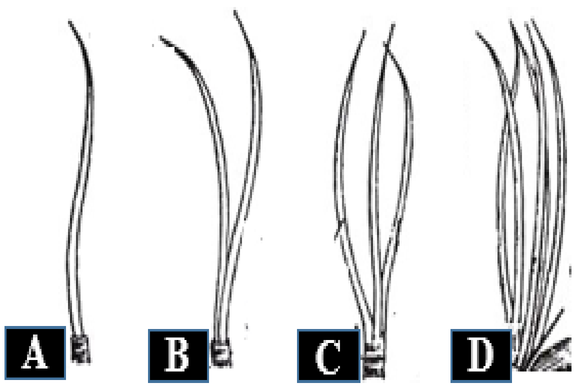

Figure-1: A; *Pinus monophylla* (Nut pine or Pinyon), B; *Pinus sylvestris* (Scots pine) *and Pinus halepensis* (Aleppo pine) C; *Pinus gerardiana* (Chilgoza or Neoza pine) *Pinus roxburghii* (Chir pine), D; *Pinus wallichiana* (Himalayan blue pine)

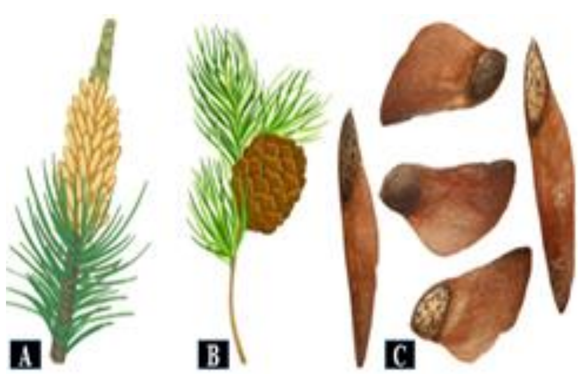

Figure-2: A; Male cone, B; Female cone, C; Seeds

Pinus halepensis Mill., ecologically thrives in arid and semi-arid zones like some part of southern Europe, Middle East and North Africa (Richardson and Rundel, 2000; Will, 2004). This species is drought tolerant having fast growth and adapted to poor soils. It is considered as a choice species for afforestation and reforestation (Sánchez-Salguero et al., 2012). Aleppo pine is not indigenous to Pakistan but introduced and planted on a large scale in upland and dry areas like Quetta, Kalat, Ziarat, Zhob, Pishin, Barkhan, Musakhel (Gill et al., 2021; Rahman et al., 2014) for urban greenery and ornamental purposes. It is ecologically important, aesthetically and ornamentally valued plant species. It has adapted to the subtropical sub-continental arid highland climatic conditions, adding climatic relief to barren landscape of Quetta.

The greenery in peri-urban and urban areas plays crucial ecological role in any city across the world especially in semi-arid and arid regions. It reduces air dust, mitigate the clime change and global warming as well as shape the fragile ecosystems for recovery (Rahman et al., 2014). Rise of problems like urbanization, extraction of groundwater in excess, emissions from vehicles and other sources, and long dry spells due to climate crisis, these urban forests are under significant ecological stress (Vicente et al., 2018). The Aleppo or Jerusalem pine contribute to major portion of urban plantation in most of the regions and this species shows physiological stress signs such as shedding of premature needle chlorosis, dieback, needle blights, pitch canker, needle rust, pine wilt nematode disease (Fig-3) and increased susceptibility to pests (Botella et al., 2010; La Porta et al., 2008; Morcillo et al., 2019; Zamora-Ballesteros et al., 2019). These conditions increase the mortality and ultimate decline of the species cover (Yang et al., 2020).

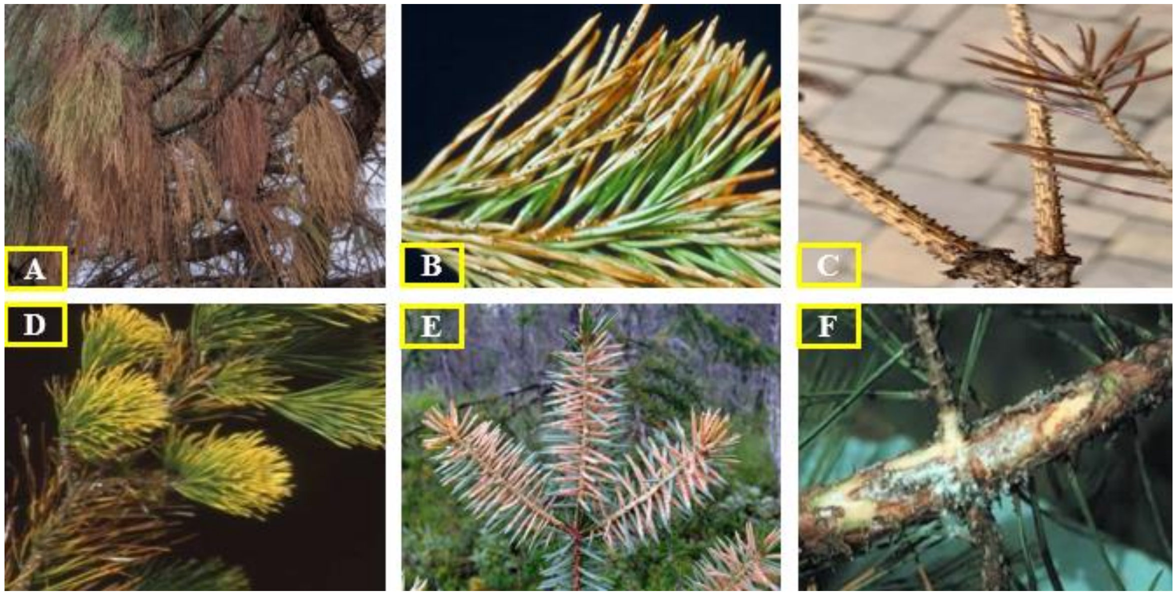

Figure-3: A; Dieback, B; Needle blight, C; Premature shedding, D; Chlorosis, E; Needle rust, F; Pitch Banker

MATERIAL AND METHODS

This review was conducted to synthesize current knowledge on *Pinus halepensis* (Aleppo pine) with a focus on its ecological adaptability, morpho-physiological responses, and decline in urban and peri-urban landscapes of Quetta, Pakistan.

Review Type

We conducted a narrative review using structured search and selection criteria to ensure transparency and scientific rigor. The review was guided by principles similar to PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to track literature identification, screening, and inclusion (Grant and Booth, 2009; Moher et al., 2009; Snyder, 2019).

Literature Search Strategy

We searched peer-reviewed journals, books, and reports from 1990 to 2025 using databases including Web of Science, Scopus, PubMed, Google Scholar, and FAO/UN publications. The search keywords included:

"*Pinus halepensis*", "Aleppo pine", "Jerusalem pine", "urban forestry", "drought tolerance", "morpho-physiological traits", "water use efficiency", "Quetta", "Pakistan", "Mediterranean", "climate stress". Boolean operators (AND, OR, NOT) were applied to refine the results (Moher et al., 2009).

Inclusion and Exclusion Criteria

We included studies that:

- Focused on *Pinus halepensis* ecology, physiology, morphology, urban forestry, or stress responses.
- Were published in English in peer-reviewed journals, books, or recognized reports.
- Covered Mediterranean, semi-arid, arid, or sub-humid regions with comparable climatic conditions.

We excluded:

- Studies not relevant to *P. halepensis*.
- Grey literature without scientific validation or peer review.
- Articles not available in full text.

Screening and Selection

From an initial pool of 351 articles, we screened titles and abstracts for relevance. After removing duplicates and irrelevant studies, 130 studies were selected for full-text review. Data were extracted and synthesized according to the following themes: ecological adaptability, drought tolerance mechanisms, morpho-physiological responses, urban and peri-urban stressors, decline symptoms, and management strategies.

Data Synthesis

We applied a narrative synthesis approach, summarizing findings thematically and integrating evidence from Mediterranean and Pakistani urban settings. Figures and tables were adapted from original studies to illustrate key physiological traits, stress responses, and urban forestry challenges (Baier, 2017; Grant and Booth, 2009; Morcillo et al., 2019).

RESULTS AND DISCUSSION

Adaptive characteristics and Ecology of Plants

The Aleppo pine is a potentially drought tolerant evergreen conifer, booming in arid, semi-arid to sub-humid climates and poor calcareous soils having pH usually higher than 7.0. The species is generally found at an elevation above the sea level up to 3000-3500 feet and forms sparse canopy open forests or mixed stands with other vegetation i.e. sclerophyll including banksias, callistemons, melaleucas, grevilleas and eucalyptus etc. The adaptive trait and attributes of the plant species include deep root system, developing thick bark for fire resistance, early reproductive maturity of male and female cones and serotinous cones that open in answer to high temperatures. This facilitates and helps post-fire regeneration of species. The species is also observed and noted in different regions to exhibit significant phenotypic plasticity and high active resistance to water stress which make it well-suited to degraded or marginal environmental conditions (Moya et al., 2013; Yang et al., 2020). However, despite being resilient to ongoing climate change crisis and consequences, anthropogenic activities pose threats to its health, survival and distribution in urban and peri-urban areas of Quetta.

Physiological plasticity and tolerance to water deficiency

The plant has outstanding and remarkable physiological plasticity (table-1), which helps the species to survive in unfavorable conditions such as prolong drought. This flexibility and plasticity is obvious in its capacity to adjust stomatal conductance, reduce the transpiration to minimum level and sustain the photosynthesis under limited water. Osmotic adjustment, accumulation of proline as compatible solute, changes in root to shoot ratio etc. enhance water uptake ability.

Table-1: Pinus showing Physiological mechanisms during drought

Physiological trait	**Response**	**Useful significance**	**Ref**
Regulation of stomatal conductance	Decline in stomatal opening under dry condition	Reduce water loss through minimizing transpiration	Baquedano and Castillo, 2006
Photosynthesis	Maintains growth during moderate drought	Support carbon assimilation and maintains plant growth	George et al., 1997; Klein et al., 2011
Water Use Efficiency (WUE)	Maximum WUE during drought	Improvement of drought resistance and productivity	Baquedano and Castillo, 2006; Flexas et al., 2004
Accumulation of	The proline amount increases during	Works as osmo-protectant, which	Sánchez-Salguero et

Proline	osmotic stress	stabilizes proteins and membranes	al., 2012; Klein et al., 2011
Ratio of root-to-shoot	Roots are strengthened compared to shoot growth	Increases water uptake under dry condition	Moya et al., 2013; Raventós et al., 2001
Osmotic adjustment	Accumulation of compatible solutes such as sugars, amino acids etc.	Sustains cell turgor and biochemical enzymatic function under drought	Baquedano and Castillo, 2006; George et al., 1997
Post stress rapid physiological recovery	Boosting growth and photosynthesis after rehydration	Survival and supports competitiveness in different habitat	Anderegg et al., 2013; Klein et al., 2011
Serotinous cones and cone pre-maturity	Cones are opened after exposure to temperature such fire or extreme dry condition	Helps in natural regeneration in post stress environments	Nathan et al., 1999; Moya et al., 2013

These abilities of the plant (table 1) improve drought resilience properties and support its survival in degraded lands. Studies on different species of genus *Pinus* have shown that the plant maintains a relatively high Water Use Efficiency (WUE) as shown in fig-4 and retrieves physiological functions of plant promptly after drought stress, which makes it a model species for afforestation and reforestation in arid and semi-arid areas (Baquedano and Castillo, 2006; George et al., 1997).

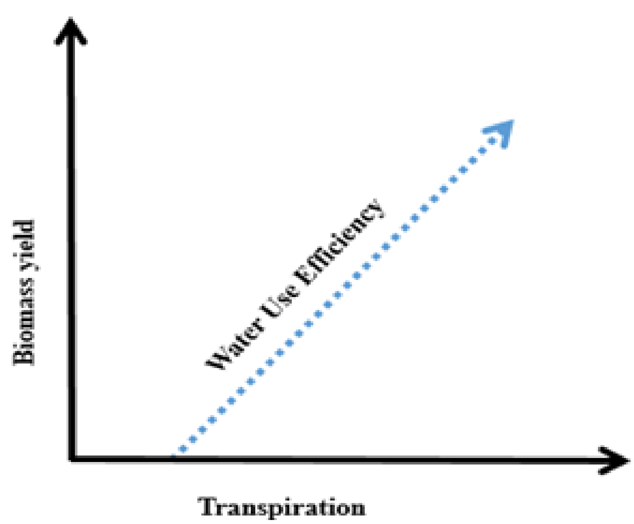

Figure-4: The amount of biomass produced per unit of water used by the plant (WUE).

Plant growth patterns under drought condition

Under drought condition and stress, *Pinus halepensis* shows growth limitations such as reduction in needle length, minimize photosynthesis, shoot elongation, restricted antioxidant defense system, slowness of apical dominance, decrease in rubisco efficiency and decline stem radial growth (Klein et al., 2011; Sala and Tenhunen, 1996). These morphological, biochemical and physiological changes of plant are thought and considered adaptive strategic plan to minimize the loss of water and allocate biotic resources efficiently under unfavorable conditions (Fig-5 and Fig-6). The resilience of plant to unfavorable conditions is influenced by the climatic conditions of subsequent years. In severe arid environmental conditions, the impact of dryness can result in prolonged or irreversible recovery, whereas in less arid environment, *Pinus halepensis* may get quicker compensatory growth in all respects, once favorable conditions return (Anderegg et al., 2013; Raventós et al., 2001). These growth patterns highlight the importance of climatic effects in shaping the growth dynamics of Aleppo pine.

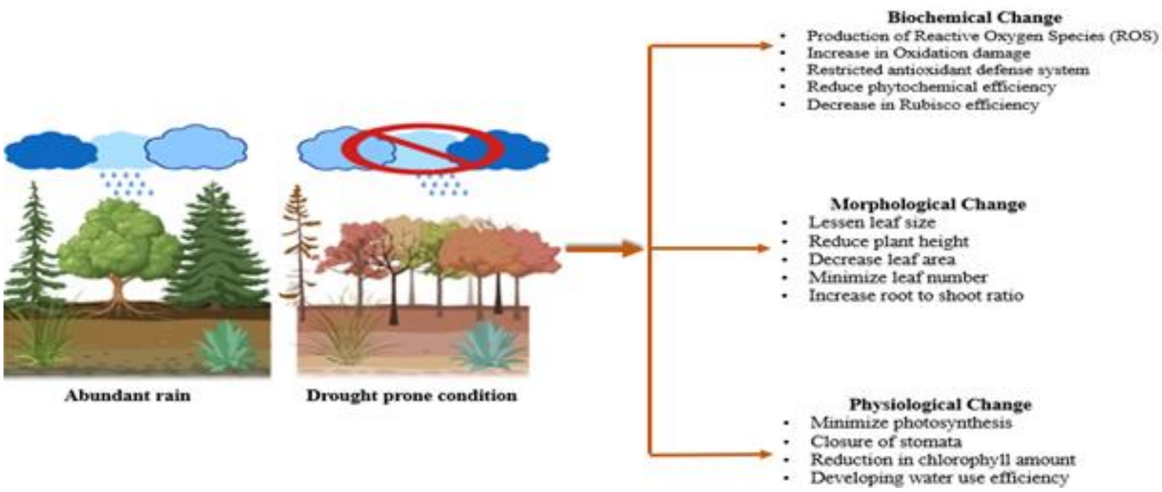

Figure-5: Different changes are adapted by *Pinus halepensis* during arid conditions

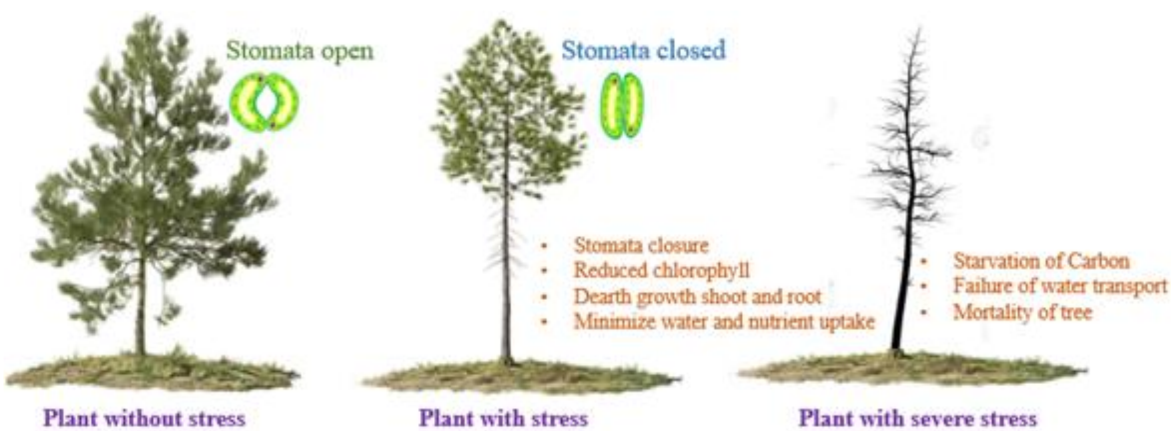

Figure-6: Effect of drought stress on the physiology and morphology of plant

Preconditions leading to decline of *Pinus halepensis*

The decline of *Pinus halepensis* in the urban and peri-urban zones is primarily attributed to combination of abiotic stressors such as extreme temperature, drought, salinity, nutrient deficiency, heavy metals and anthropogenic pressures (Fig-7). These changes the scenarios of ecosystem, habitat and biodiversity. The prolonged drought and minimum precipitation is major abiotic factor, reduces soil moisture which leads to hydraulic failure and carbon starvation (Flexas et al., 2004; Sala et al., 2010). The urban heat island (UHI) effect increases evapotranspiration, further pressurizes the trees (Calama et al., 2020) in Quetta. Moreover, land use change and development of cities fragment the pine stands, changing the genetic diversity and prone the species to pest and pathogen attack (Allen et al., 2010). Other abiotic and anthropogenic factors such as pollution, soil quality and construction activities, cause compaction and adds to minimize root respiration and nutrients uptake (McDowell et al., 2008). Additionally, insufficient regeneration planning, poor forest management, least priority to natural resources, lack of awareness also exacerbate the situation in Quetta.

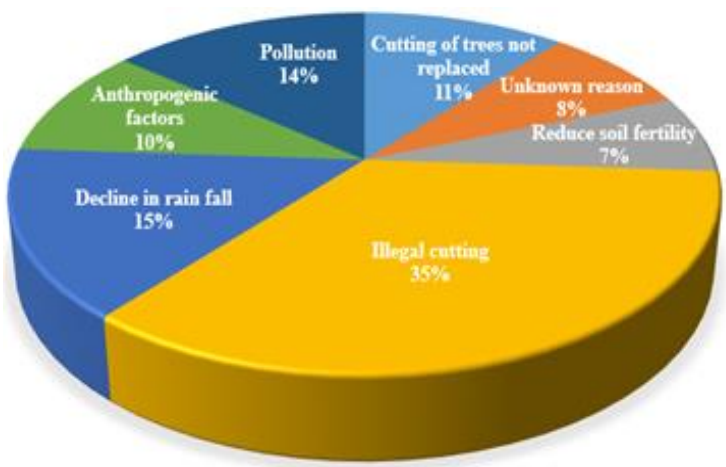

Figure-7: Underlying causes of *Pinus halepensis* decline

Irregular precipitation patterns and dry spells

The climatic conditions show a continuous rise in aridity and erratic rainfall patterns across the most climate change affected regions especially different areas of Pakistan. The Sixth Assessment Report of Intergovernmental Panel on Climate Change 2021 and according to global climate risk index, Pakistan has been ranked as 5th most affected and vulnerable country due to extreme weather conditions. The IPCC-2021 Sixth Assessment Report also outlined that of most affected regions will experience rise in temperature from 2.2 to 5.1 °C by the end of 21st century along with reduction in rainfall from 20% to 30%. These shifts and tendencies raise the patterns of drought and reduce the resilience of local species such as *Pinus halepensis* (Intergovernmental Panel on Climate Change (IPCC), 2023; Jaffar et al., 2019).

The sensitivity of vegetation increases under extreme climatic conditions (Camarero et al., 2021). According to recent studies increased inter-annual change of rainfall and frequent continuous dry spells disrupt the phenology and natural regeneration capacity of Aleppo pine (Lionello et al., 2006). Furthermore, water scarcity and unusual precipitation not only decrease the vitality of vegetation but also increase vulnerability to fires, pest attacks and other mortality events (Moore and Olden, 2017).

Table-2: Physiological mechanisms of Pinus during drought.

Stress/Pressure	Factor	Impact on vegetation	Ref
Abiotic	Temperature and drought	Hydraulic failure and carbon starvation	Flexas et al., 2004; Sala et al., 2010
	salinity and nutrient deficiency	Growth minimized, physiological stress, and stunted development	McDowell et al., 2008
	Heavy metals toxicity	Root systems and metabolic functions damage	McDowell et al., 2008
	Urban Heat Island (UHI)	Elevation of evapotranspiration and thermal stress	Calama et al., 2020
	Soil compaction	Decreased root respiration and nutrient uptake	McDowell et al., 2008
Anthropogenic	Urban development	Fragmentation of habitat, reduction in genetic diversity, vulnerable to pests	Allen et al., 2010
	Pollution (air, soil, water)	Photosynthesis alteration, weakened immunity	McDowell et al., 2008
	Invasive species	Competition for required resources, ecological imbalance	Allen et al., 2010
	Climate change	Drought, Temperature rise, shifts in suitable community	Sala et al., 2010
	Overexploitation	Decrease of supportive environmental factors	Flexas et al., 2004
	Lack of regeneration and forest management planning	No sprouting of young trees, aging population, decline in stand growth and health	Allen et al., 2010; Local field knowledge
	Insufficient public awareness	weak conservation efforts, unmanaged degradation of natural stands of vegetation	Local observation

Soil moisture limitation and shallow rooting in urban soils

The urban and peri-urban soils are usually compacted and distinguished by less permeability and reduced organic matter, which increases surface moisture evaporation, transpiration and restrain percolation. These changes and altered conditions decrease water holding capacity and restrict root penetration, forcing the vegetation to depend on inconsistent surface moisture (Gregg et al., 2003; Lorenz and Lal, 2009; Zhan et al., 2023). Aleppo pine, in natural or semi natural habitats retrieve deep soil horizon moisture via deep root system (Padilla and Pugnaire, 2007), in urban settings the plant is forced to adapt and adjust its water uptake. This leads to rise in vulnerability to short term dryness. Availability of surface moisture is limited and highly sensitive to irregular precipitation (Reviews, 1993). Scientific studies highlighted that under soil compaction, development of roots in Jerusalem pine is undersized, which leads to reduce physiological resilience during prolong dry spells (Review, 2023).

Temperature stress and urban heat islands (UHI)

In urban and peri-urban environments, the urban heat island (UHI) phenomenon effects air and surface soil temperature significantly. The higher temperatures increase evapotranspiration rates and intensify the water stress on vegetation in urban regions (Kong et al., 2021). This type of stress impacts on sensitive species such as *Pinus halepensis*, which is vulnerable already to dry conditions. A scientific study was conducted on this species in a Mediterranean urban area showed that the temperature of soil surface under conditions in urban heat island were higher from 3–7°C than nearby rural areas. It also showed reduce seedling germination and suppressing success by more than 30% due to physiological stress and decreased soil moisture induced by higher temperatures (Frosini et al., 2024; Veuillen et al., 2023). Moreover, these conditions lead to a series of morpho-physiological and biochemical limitations such as reduced chlorophyll fluorescence, reduced root elongations, higher mortality in seedling stages, production of ROS, closure of stomata, reduce rubisco efficiency, limitation in phytochemical ability.

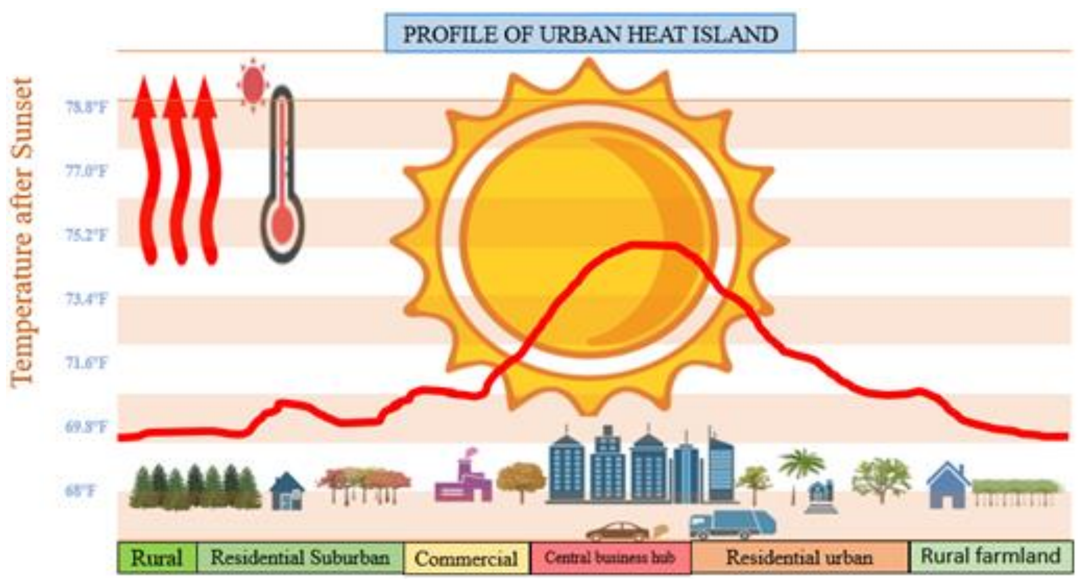

Figure-8: Urban heat islands show temperature fluctuations influenced by the presence or absence of vegetation

Other stressors

Other stressors such as pollution, soil salinity, and pest pressure significantly add to the vulnerability and exposure of *Pinus halepensis* in urban and semi-arid habitats. Impair seedling germination which is caused by excess NaCl ($\geq$100Mm) reduce water uptake and turn into ionic toxicity (Zouidi et al., 2019). Further it has been studied that compare $CaCl_2$ and $MgCl_2$, NaCl has more pronounced inhibitory effect. The salinity tolerance is not same and uniform across the different species of populations as seeds of different species and different ecological habitats display differing levels of resilience under saline conditions (Nedjimi and Guit, 2021; Sbay and Zas, 2018). This helps and highlights the basic selection of salt tolerant provenances species for afforestation and reforestation in degraded urban and peri-urban soils.

The scientific data about pressure of pest on *Pinus halepensis* in Quetta is limited, however, Mediterranean basins give a convenient and helpful model due to similarities in ecological habitats. Pine processionary moth (Thaumetopoea pityocampa) is one of the most injurious destructive pests affecting *Pinus halepensis* in these areas. This insect reduces the photosynthetic capacity of tree by defoliating, damaging needles and thus weakening the species. Beside harmful to plant species, urticating hairs of insects (Fig-9) also poses human and animal health hazards (Cayuela et al., 2014). Scientific experiments in Morocco have gathered significant documentations on variability in infestation severity, suggesting genetic differences in pest resistance among the populations of *Pinus halepensis* (Sbay and Zas, 2018). The defoliation, weak photosynthesis, damaged needles may further worsen the situation by making the plant more susceptible to attack of secondary pathogens such as urban anthropogenic pollution stressors. Accordingly, the effects of both biotic and abiotic stressors underscore the need for integrated management and choice of selection in urban and other forestry programs.

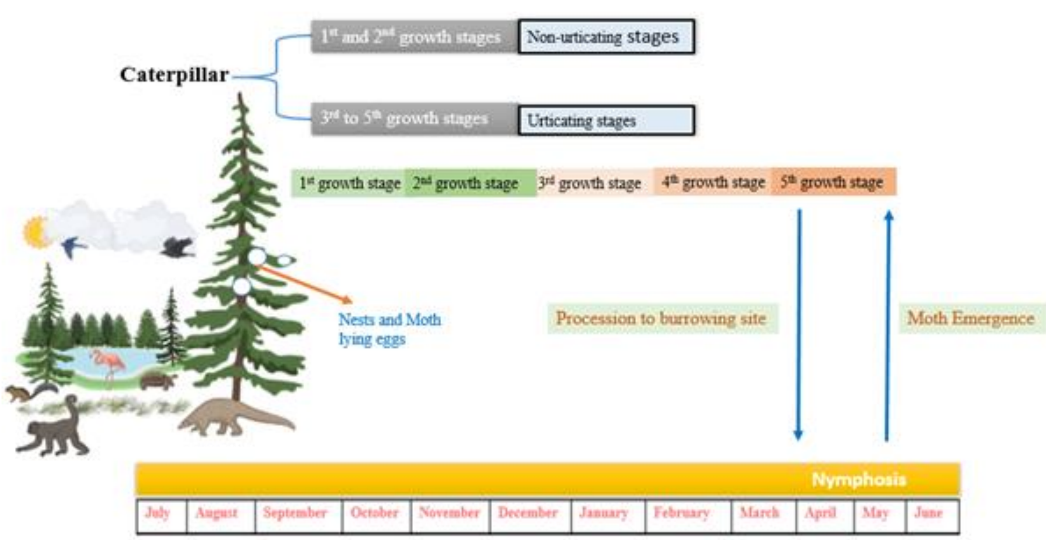

Figure-9: Life cycle of Pine processionary (*Thaumetopoea pityocampa*) in urban forest

Decline symptoms of *Pinus halepensis*

The plant species has clear noticeable signs and indications, when it is under prolonged drought and urban metropolitan stress. The reduced chlorophyll content and stomatal conductance is considered as compromised photosynthetic function. The visual signs include shortened needles, minimize shoot elongation, less radial growth, premature defoliation, pale discolored needle leaves and stale appearance due to crown thinning (Quézel and Médail, 2003).

Physiological markers

The Aleppo pine exhibits several physiological alterations under dry condition. Reduced photosynthetic efficiency is due to less chlorophyll content caused by closure of stomata and restricted gas exchange (Alonso et al., 2001). The osmotic adjustment occurs through the accumulation of soluble sugars and amino acid i.e. proline, while the antioxidant responses are marked by shifts in glutathione γ-glutamyl-cysteinyl-glycine (GSH) and methionine (Met) levels, especially in seedlings (Klein et al., 2011).

Growth inhibition

Stunting and growth inhibition in *Pinus halepensis* under dry condition has been widely documented, with several morpho-physiological characters showing highly marked declines. Field observations and scientific experiments showed highly reduced shoot elongation, polycyclic branching, needle color, length of needles, radial growth, alteration of crown architecture, reduction in photosynthesis due to limited surface area, limited cambium activity, reduced increment in height under dry conditions (Baffoin et al., 2021; Borghetti et al., 1998; Camarero et al., 2015; Spelsberg et al., 2025; Zheng et al., 2025). These growth limitations are connected to dry conditions, which cause closure of stomata, reduce cell turgor and imbalance of hormonal activity which affects the meristematic efficiency. Above all extreme and rhythmic drought periods further complicate the situation notably in young saplings or in urban environment where microclimate stressors limit root volumes and exacerbate water availability (Barbeta et al., 2013; Sánchez-Salguero et al., 2010). The duration and frequency of drought is intensified by climate change. Reduced growth help in identification of early warnings of population decline in semi natural habitats and urban microclimates.

Visual and physical signs in urban areas

In response to extended drought and environmental stress, the Aleppo pine shows distinct visual and structural decline signs such as crown thinning, discoloration of needles, loss of needles at early age, dieback of branches, attack of pests and reduced growth (Camarero et al., 2015; Veuillen, 2023). These signs and symptoms are carried by variable tree mortality within road side, urban green belts, parks, greenways, countryside, especially where trees are planted in shallow soils having compacted compressed substrates, which further restrict rooting, poor water permeability and percolation.

Under the prolonged drought conditions in urban and peri-urban, a critical adaptive response notably observed is the shift in rooting depth. In such cases, the trees depend on unreliable surface moisture rather than on reserves in deep soil, primarily due to reduced infiltration and space of root in paved disturbed urban areas (Barbeta et al., 2015; Kurz-Besson et al., 2016). This change accommodates drought resilience, which leads to canopy shrinkage and limit the transpiration magnitude. In a scientific study conducted across regions where *Pinus halepensis* is abundant—such as Barcelona, Valencia, Rome, Istanbul, Marseille, Alexandria, as well as urban zones of southern France and eastern Spain—a noticeable decline has been observed even among drought-adapted Pinus species. This decline is particularly evident during prolonged drought periods, suggesting that these species may be approaching a critical threshold beyond which their physiological tolerance begins to fail. (Gazol et al., 2017; Sánchez-Salguero et al., 2012). Remarkably the snag and declining species usually show dry desiccated crowns, delicate stems, high vulnerability to secondary pests including fungal attack, colonization of beetles, all such conditions increase the mortality risk of tree.

These visual signs and indicators present the critical analytic early warning intimations for urban forestry and wildlife custodians and highlight points for taking prompt necessity of preemptive measures such as deep watering, planning, mulching, and constraint of anthropogenic activities.

Quetta: context and relevance

The district Quetta, a capital of Baluchistan, located in northern Baluchistan, lies within an arid and semi-arid climatic zone with average annual rainfall of approximately 250 to 350 mm, condensed in early winter and spring (Sarfaraz et al., 2014). Afforestation and greenway schemes in Quetta have usually labored to plant *Pinus halepensis* and the choice of species id due to its tolerance to dry conditions, rapid early growth, and adaptation to degraded soils (Höhl et al., 2020). Increasing settlements, global warming, lack of awareness, climate change, and expanding urban footprint however, accelerated the pressure of anthropogenic activities on green belts. These activities include soil compaction, alteration of microclimate, road side grazing, contamination of water through heavy metals and restricted rooting zones (Ahmad et al., 2012; Chen et al., 2023; Kumar et al., 2023)

Long term scientific studies on its radial growth dynamics, morpho-physiological stress responses, mortality trends and decline patterns are lacking in Quetta, despite of plantation of *Pinus halepensis* in many peri-urban and urban areas such as on roadside, parks, hospitals, educational institutions, government buildings, cantonment and recreational zones. All these comprise a major research gap, specifically in recent climatic shift scenarios. Quetta has experienced irregular rainfall and snow patterns, extreme temperature, drought condition, pollution and anthropogenic activities, though the species has been considered drought resilient (Camarero et al., 2021; Rubio-Cuadrado et al., 2021; UN FAO, 2009).

In Pakistan, especially Quetta the urban forestry is further constrained by illicit cutting without planning and limited water resources for irrigation (Fernandes, 2022). The future scientific research must study and assess the indicators such as chlorosis of needles, osmotic regulation, stomatal closure and behavior, annual ring width decline, and other all biochemical and morpho-physiological early signs of stress under local climatic extreme events (Deligoz and Gur, 2015; Ghazghazi et al., 2022; Gill et al., 2021; Qi et al., 2018; Schwanz and Polle, 2001)

Monitoring and management recommendations

The aim and objective of monitoring and management recommendations is the early detection of stress signs and long-term health of Aleppo pine plantations across the regions. These planning's and strategies help in timely interventions by combining physiological assessments, growth volume tracking and improvements in habitat.

Tree physiological monitoring

- Systematic analysis and assessment on regular basis of chlorophyll content and fluorescence using soil plant analysis development meter (SPAD).

- Study and monitoring of osmoprotectants such as proline contents and soluble sugars in needles as stress indicators under extreme dry and heat conditions.

- Conduct experiments on antioxidant enzyme assays such as catalase, peroxidase and glutathione on foliage of young saplings and mature trees to detect oxidative stress due to aridity and environmental pollutants.

These guidelines and parameters will help to identify early signs and symptoms of physiological decline before visual symptoms appear (Klein et al., 2011).

Assessment of growth trends

- For continuous monitoring of radial increment in living trees use dendrometers and correlate growth patterns with temperature shift and seasonal precipitation.

- Determine growth rings and long term increment suppression trends, apply increment core sampling and comparative analysis with botanical studies of pine in Mediterranean regions can guide and contextualize local decline (Giorgi and Lionello, 2008).

In context of Quetta it is crucial where winter rainfall is decreasing and summer temperatures are increasing.

Soil improvement approaches

- Employing organic mulching around the tree at base can reduce soil surface evaporation, reduce soil temperature and restrict weeds.
- Start deep slow irrigation or deep root watering cycles during the extreme temperature or at summer peak by using water where possible.
- Relieve and attenuate the compaction of soils in parks, roadside greenbelts and greenways especially in populated areas such as picnic points, recreational parks, educational sectors, government offices and hospitals. Using mechanical aeration or bio-infiltration trenches to improve water infiltration.
- Using mycorrhizal bio-fertilizers or compost for enhancing soil fertility may improve the strength of pines for drought resilience.

Propagation of adapted species

- Select mature and physically healthy pines which are local and naturally adapted for seed collection and nursery propagation.
- Stop planting of monoculture and promote diversity for enhancing resilience of species against the unexpected future climatic conditions.
- Assess the seedling performance under local controlled conditions in experimental plots especially in botanical garden of University of Baluchistan before mass plantation.

Disease monitoring and integrated Pest management

- Initiate monitoring on regular basis for surveillance of pests especially examination of pine processionary moth (Thaumetopea pityocampa).
- Employ the biochemical pheromone traps and local reporting systems in urban recreational parks, roadside plantations and other greenbelts of Aleppo pine for early detections and sightings.
- Collaborate with microbiologist to take precautionary measures for secondary infections such as bacterial, fungal pathogens and bark beetles.
- Use environmental friendly measures to control pest i.e. biological control and mechanical removal rather than employment of chemical pesticide especially in sensitive urban areas.

Future directions and urban forestry policy

- It is recommended that the Forest and Wildlife department may engage, Quetta Metropolitan Corporation, non-governmental organizations, local universities, student led surveys and other stakeholders, to adopt these measures for long term tree health monitoring.

CONCLUSION

The survival of *Pinus halepensis* in urban and peri-urban regions such as Quetta reflects the complicated interaction between harsh climatic conditions and anthropogenic pressures. The species shows notable tolerance to dry and extreme conditions such as adaptation to degraded soil and physiological plasticity, however, its survival is challenging due to increasingly threatened by prolonged dry spells, irregular rainfall, urban heat island phenomenon, compaction of soils, over exploitation, increasing human population, city expansion and pest outbreaks. The early symptoms of fall in population are morpho-physiological, structural and visual which are noticeable and needs concern on urgent basis. The survival of Aleppo pine in congested and arid continental highlands such as Quetta demands science based multifaceted approaches like physiological monitoring, habitat improvement, integrated pest management, selection of adaptive species, soil reclamation, disease identification and management, and biochemical tests for monitoring pathways within the cells. Research backed urban forestry policies are need of hour for current climate change and anthropogenic trends. Combined synergetic collaborative engagement between government departments, academia and nature based civil society organizations is quite essential for ensuring the sustainable management of species and conservation of stands. The implementation of recommended monitoring and management measures can significantly enhance the resilience of urban green belts, preserve ecological functions, and secure the future of *Pinus halepensis* as a key species in urban landscapes of Quetta.

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