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Bougainvillea as a shield against urban air pollution: mechanism, tolerance assessment and phytoremediation

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Abstract

Metropolitan cities across the globe are grappling with deteriorating outdoor air quality driven by rapid urbanization, industrial expansion, and intensifying vehicular traffic. Nature-based solutions, particularly phytoremediation through strategically deployed ornamental plants, offer a sustainable, economically-viable, and visually enriching pathway to counteract this challenge. The present review systematically examines the physiological and morphological mechanisms that enable ornamental plants to intercept particulate matter and metabolize gaseous pollutants such as nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and ground-level ozone (O_3). The Air Pollution Tolerance Index (APTI) is critically evaluated as a screening tool for selecting robust species suitable for urban green belts. Special focus is placed on Bougainvillea, a widely cultivated tropical ornamental plant, whose distinctive leaf surface morphology, high tolerance to drought, and documented capacity for lead (Pb), cadmium (Cd), NO_2, and particulate matter accumulation render it an exceptional candidate for urban phytoremediation. Evidence from metropolitan case studies spanning Delhi, Mumbai, Metro Manila, and Beijing is synthesized to highlight practical successes and context-specific constraints. Considerations regarding green infrastructure design, species selection, and future research priorities are also discussed. Collectively, this review reinforces the case for embedding ornamental phytoremediation into mainstream urban planning policies.

Key words: Air Pollution Tolerance Index, Bougainvillea, Particulate matter, Phytoremediation, Ornamental Plants, Urban greening

Unprecedented pace of urban expansion witnessed during the past five decades has fundamentally altered the atmospheric chemistry of cities across the world. Emissions from millions of motor vehicles, energy-intensive industries, construction sites, and domestic combustion collectively generate a complex burden of primary and secondary pollutants that now exceed safe threshold limits in most megacities (WHO, 2022). Among these, fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and ground-level ozone (O_3) stand out for their documented toxicity to human respiratory and cardiovascular systems (Manisalidis *et al.,* 2020). Engineering-based interventions such as catalytic converters, industrial scrubbers, and electrostatic precipitators have contributed meaningfully to reducing point-source emissions; however, they remain prohibitively expensive, energy-intensive, and largely ineffective against diffuse, traffic-related pollution at the street level. This has prompted a global scientific interest in nature-based solutions, of which phytoremediation — the deliberate deployment of living plants to intercept, accumulate, or biochemically transform environmental contaminants — has emerged as a particularly promising and multi-functional strategy (Rocha *et al.,* 2022; Piacentini and Di Baccio, 2024).

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Ornamental plants occupy a special niche in this discourse because they simultaneously deliver ecosystem services and aesthetic enrichment without entering the agricultural food chain, thereby eliminating the risk of toxin transfer to human or animal consumers (Francini *et al.,* 2022). Decades of applied research at ICAR-Indian Agricultural Research Institute (IARI), New Delhi, have highlighted the multifunctional potential of ornamental species not only for beautification but also for ecological services in urban and peri-urban settings (Singh *et al.,* 2019; Jain *et al.,* 2020). Studies on indoor air purification through potted plants have further demonstrated the relevance of ornamental flora in managing sick-building syndrome and confined-space pollution (Tiwari *et al.,* 2019a). Earlier work on floriculture development in India has comprehensively documented the diversity of available ornamental species and their adaptability to varied agro-climatic conditions, providing a valuable foundation for urban greening programmes (Jain *et al.,* 2022a).

Among ornamental taxa evaluated for pollution tolerance, Bougainvillea has consistently attracted attention owing to its vigorous growth, xeric adaptability, striking bract display, and documented tolerance to atmospheric contaminants. A practical guide to quality seedling production of Bougainvillea published by scientists of this laboratory (Jain *et al.,* 2019) further underscores its horticultural and environmental relevance for urban programmes. The present review synthesizes contemporary evidence on ornamental plant-based air pollution mitigation, with concentrated emphasis on Bougainvillea, and offers a critical appraisal of mechanisms, metrics, case studies, and pathways for mainstreaming this approach in metropolitan planning.

Urban Air Pollution: Sources and Health Implications

Urban air is a dynamic mixture of gases and aerosols generated by both anthropogenic and natural processes. The principal pollutants of concern in metropolitan contexts are particulate matter (PM), nitrogen oxides (NO_x), sulphur dioxide (SO_2), carbon monoxide (CO), and volatile organic compounds (VOCs) (Seinfeld and Pandis, 2016). Vehicular traffic constitutes the dominant anthropogenic source of NO_x and PM in most cities, with power generation, industrial combustion, construction activities, and resuspended road dust contributing additional loads (EEA, 2023).Particulate matter is conventionally partitioned by aerodynamic diameter into coarse particles (PM_{10}, ≤10 µm) and fine particles ($PM_{2.5}$, ≤2.5 µm). Fine particles are of greater toxicological concern because they penetrate deep into the alveolar region of the lungs and may translocate to the bloodstream, inducing systemic inflammation (Pope and Dockery, 2006). Long-term exposure to $PM_{2.5}$ is strongly associated with chronic obstructive pulmonary disease (COPD), ischaemic heart disease, stroke, and lung cancer (Schraufnagel *et al.,* 2019). Children, pregnant women, the elderly, and individuals with pre-existing cardiorespiratory conditions bear a disproportionate burden of these health outcomes (Manisalidis *et al.,* 2020).

Heavy metals constituting a trace fraction of urban PM represent an additional hazard. Lead (Pb), cadmium (Cd), arsenic (As), and zinc (Zn) originate largely from vehicular exhaust, tyre and brake abrasion, and smelting operations. Research conducted on warm-season turf grasses irrigated with wastewater in an urban Indian setting revealed significant accumulation of heavy metals in plant tissues, reaffirming the pathway through which plants intercept and bio-concentrate atmospheric and soil-borne metal pollutants (Balaji *et al.,* 2025). Complementary investigations on marigold and calendula subjected to heavy-metal-spiked wastewater irrigation documented species-specific translocation factors and tolerance thresholds, providing a quantitative basis for ornamental plant use in contaminated urban soils (Verma *et al.,* 2023; Vignesh *et al.,* 2023).

Phytoremediation: concept and mechanisms

Phytoremediation is a solar-energy-driven remediation technology that exploits the inherent biological and biochemical capabilities of plants to remove, immobilize, or transform environmental contaminants present in soil, water, or air. When applied to the atmospheric compartment, it capitalises on two broad categories of processes: physical deposition of particles onto foliar surfaces, and biochemical assimilation of gaseous pollutants through the stomatal pathway (Nowak *et al.,* 2014; Piacentini and Di Baccio, 2024).

Particulate matter interception

The interception and retention of airborne particles by plant canopies is governed by an interplay of aerodynamic, gravitational, and surface-adhesion forces. Turbulent deposition, impaction, and sedimentation collectively deliver particles from the ambient air stream onto leaf surfaces (Beckett *et al.,* 2000). The efficiency of this process is profoundly influenced by leaf micromorphology. Leaves bearing dense trichomes (leaf hairs), pronounced epidermal ridges, and waxy cuticular layers exhibit markedly superior particle retention relative to smooth, glabrous surfaces (Weerakkody *et al.,* 2018; Sgrigna *et al.,* 2015). Rainfall events periodically wash deposited particles from leaves to the soil surface, effectively transferring the pollutant load from the atmospheric compartment to the pedosphere where further microbial and chemical transformations can occur (Chen *et al.,* 2017).

Stomatal uptake and metabolism of gaseous pollutants

Gaseous air pollutants enter leaf mesophyll tissue principally through stomatal apertures during daylight hours when gas exchange is most active. Once inside the sub-stomatal cavity, NO_2 is dissolved into the apoplastic water film and enzymatically reduced to nitrite, then further assimilated into amino acids via the glutamine synthetase/glutamate synthase (GS/GOGAT) pathway (Takahashi and Morikawa, 2014). Sulphur dioxide is oxidised to sulphate, which is subsequently incorporated into cysteine and other sulphur-containing organic compounds. Ozone, a potent oxidant, reacts with mesophyll cell membranes, generating reactive oxygen species (ROS); tolerant species counteract this through up-regulation of ascorbate peroxidase, superoxide dismutase, and catalase activities. The leaf phyllosphere microbiome also contributes to the degradation of certain organic gaseous pollutants, adding a microbial dimension to plant-mediated air purification (Papen and Gessler, 2019). Studies on ornamental chrysanthemum at IARI have shown that leaf biochemistry — particularly chlorophyll stability and osmolyte accumulation under stress — directly reflects the capacity of plants to withstand oxidative insults analogous to those imposed by air pollution (Vanlalruati *et al.,* 2023; Vanlalruati *et al.,* 2021).

Air Pollution Tolerance Index (APTI): Principle and Application

A scientifically grounded approach to urban species selection requires quantitative tools that rank plants by their resilience to pollution stress. The Air Pollution Tolerance Index (APTI), originally conceived by Singh and Rao (1983), integrates four key leaf biochemical parameters into a composite score that reliably distinguishes sensitive from tolerant species. The index is calculated as:

$$APTI = [A\,(T + P) + R] / 10$$

where A = ascorbic acid content (mg g^{-1} fresh weight); T = total chlorophyll content (mg g^{-1} fresh weight); P = pH of leaf extract; and R = relative water content (%). Each parameter captures a distinct dimension of pollution resilience. Ascorbic acid serves as a front-line antioxidant quenching ROS generated by oxidising pollutants (Agbaire and Esiefarienrhe, 2009). Chlorophyll integrity reflects the photosynthetic machinery's capacity to continue functioning under pollutant load — a relationship well documented in ornamental crops including chrysanthemum (Joshi and Swami, 2009; Vanlalruati *et al.,* 2021). Leaf pH modulates enzyme activity in detoxification pathways, while relative water content indicates stomatal regulation competence (Rai and Panda, 2014).

Based on their APTI scores, plant species are categorised as: sensitive (APTI < 10), intermediate (APTI 10–16), or tolerant (APTI > 16). Species occupying the tolerant category are recommended for planting in high-exposure sites such as highway medians, industrial buffer zones, and roadside green belts. Sensitive species, conversely, serve as early-warning bioindicators, with visible foliar injury providing a non-instrumental signal of elevated pollution episodes. Tolerant ornamental species identified through APTI screening thus form the backbone of effective urban phytoremediation programmes (Singh and Rao, 1983; Rai and Panda, 2014).

Ornamental Plants in Urban Phytoremediation: An Overview

Ornamental horticulture has traditionally been evaluated through the prism of aesthetics, productivity, and postharvest quality; however, an expanding body of literature now recognises its ecological service dimension. The fact that ornamental species are not harvested for human or animal consumption eliminates the toxin-transfer risk that constrains the use of food or forage crops in contaminated urban environments (Asgari Lajayer *et al.,* 2019). This inherent biosafety advantage, combined with the psychological and societal benefits of living greenery, positions ornamental phytoremediation as an eminently practical urban health intervention (Francini *et al.,* 2022).

India's floriculture sector, characterised by remarkable species diversity and expanding urban demand, offers a substantial reservoir of candidate phytoremediators. A comprehensive status and prospects report on Indian floriculture (Jain *et al.,* 2022a) catalogued the wide spectrum of ornamental crops commercially cultivated in the country, many of which demonstrate morphological and physiological attributes favourable for pollution interception. Assessments of foliage potted plants for urban and peri-urban environments conducted at ICAR-IARI confirmed that several commonly available indoor and outdoor species perform well under the abiotic stress conditions typical of Indian cities (Jain *et al.,* 2020). Urban landscaping strategies, when designed with species selection underpinned by pollution tolerance data, can meaningfully contribute to ambient air quality improvements while simultaneously fulfilling civic beautification objectives (Singh *et al.,* 2019).

Table 1: Air Pollution Tolerance Index (APTI) of selected ornamental plant species

Plant species	Family	APTI value	Tolerance category	Recommended use
Bougainvillea spectabilis	Nyctaginaceae	14.2	Intermediate	Roadside hedges, green belts
Hibiscus rosa-sinensis	Malvaceae	16.8	Tolerant	Urban parks, buffer zones
Ixora coccinea	Rubiaceae	12.5	Intermediate	Ornamental gardens
Nerium oleander	Apocynaceae	15.3	Intermediate	Highway medians, industrial areas
Rosa sp.	Rosaceae	11.8	Intermediate	Residential gardens
Chrysanthemum sp.	Asteraceae	13.6	Intermediate	Indoor/outdoor landscaping
Mixed Ferns	Various	10.2	Intermediate	Shaded areas, ground cover

Plants with high leaf area index (LAI), dense branching architecture, and persistent foliage extend the duration and spatial extent of particle deposition. Rapid growth and high biomass turnover further amplify the quantity of pollutants sequestered per unit time, while regular pruning facilitates the physical removal of accumulated toxin-laden biomass from the urban system. The integration of ornamental planting with engineered green infrastructure — road green belts, vegetated walls, and green roofs — multiplies these benefits by creating continuous phytoremediation corridors within the urban matrix (Abhijith *et al.,* 2017).

Bougainvillea: an outstanding ornamental phytoremediator

Bougainvillea (Bougainvillea Comm. ex Juss.) family Nyctaginaceae, native to the coastal and tropical forests of South America, has been naturalized across tropical and subtropical urban landscapes worldwide. Its prolific growth, tolerance to periodic drought, and minimal maintenance requirements made it a mainstay of Indian urban horticulture decades before its phytoremediation potential was systematically investigated. Research emanating from ICAR-IARI, New Delhi has addressed the horticultural management of this species, including the standardization of quality seedling production protocols that ensure uniform, vigorous planting stock for urban programmes (Jain *et al.,* 2019), providing a crucial practical link between laboratory science and field deployment.

Foliar morphology and particulate matter retention

The leaf surface of Bougainvillea spectabilis is characterised by a moderately rough adaxial epidermis, the presence of uni- and multicellular trichomes, and a wax-coated cuticle — features collectively identified as determinants of superior particle adhesion (Weerakkody *et al.,* 2018). Seasonal measurements of foliar dustfall on Bougainvillea leaves in polluted urban settings have confirmed significant accumulation of total suspended particles and PM_{10} fractions, validating its status as an effective phytomonitor and passive phytoremediator for particulate pollution (Prajapati and Tripathi, 2008). Annual $PM_{2.5}$ removal efficiency of approximately 8.5 g m^{-2} leaf area and PM_{10} removal of 15.2 g m^{-2} have been reported, placing Bougainvillea among the better-performing ornamental species in this regard (Das and Prasad, 2012; Table 2).

Nitrogen Dioxide tolerance and assimilation

Traffic-generated NO_2 represents one of the most pervasive gaseous pollutants in Indian metropolitan corridors. Experimental fumigation studies have shown that Bougainvillea can absorb and metabolise significantly elevated ambient NO_2 concentrations (45–120 μg m^{-3}) over continuous exposure periods without exhibiting severe visible phytotoxicity symptoms (Singh and Agrawal, 2007; Das and Prasad, 2012). The absorbed NO_2 is enzymatically processed through nitrate reductase pathways and assimilated into organic nitrogen compounds, effectively removing the pollutant from the atmospheric pool. This biochemical flexibility, combined with high leaf area per plant, translates into substantial NO_2 removal rates per unit of planted area in road green belts.

Heavy Metal Accumulation and Bioindicator Potential

The potential of Bougainvillea spectabilis to accumulate atmospheric heavy metals was persuasively demonstrated by Dela Cruz *et al.* (2013) in Metro Manila, where leaves harvested from plants growing in the heavily trafficked Ermita district showed lead concentrations more than three-fold higher than those from the comparatively cleaner Las Piñas suburb over a nine-month period. Foliar Pb concentrations ranged from 0.006 to 0.387 ppm, with accumulation increasing progressively through the monitoring period in the polluted zone — a trajectory consistent with combined foliar absorption and root-to-shoot translocation. Cadmium accumulation (0.15–0.42 ppm) along urban roadsides has been similarly documented (Zou *et al.,* 2025). These findings mirror the heavy metal bio-concentration patterns observed in related ornamental species at ICAR-IARI, where wastewater-irrigated turf grasses and marigold accumulated Pb, Cd, and Zn proportional to external exposure levels, indicating consistent mechanisms of uptake across ornamental taxa (Balaji *et al.,* 2025; Vignesh *et al.,* 2023).

Practical Advantages in urban deployment

From a horticultural management standpoint, Bougainvillea offers several attributes that facilitate large-scale urban deployment: (i) drought tolerance and capacity to thrive on minimal supplemental irrigation once established; (ii) adaptability to a wide pH range (5.5–7.5) and varied soil textures; (iii) rapid extension growth enabling establishment of dense canopies within two to three seasons; (iv) versatility as a climber, hedge, standards, or espalier, permitting its integration into diverse street furniture and architectural contexts; and (v) prolific flowering that sustains ornamental value year-round in warm climates (Gilman, 1999; Jain *et al.,* 2019). These traits collectively lower the cost per unit phytoremediation benefit, making Bougainvillea an economically attractive component of municipal greening budgets.

Metropolitan Case Studies

Delhi, India

Delhi epitomises the intersection of rapid metropolitan growth and severe air quality degradation. The capital city consistently records $PM_{2.5}$ levels several multiples above the national ambient air quality standards, particularly during post-monsoon and winter months when thermal inversions trap vehicular and crop-burning emissions (Chowdhury *et al.,* 2018). Urban greening initiatives in Delhi have explored the establishment of dense multi-layered road green belts along arterial roads as a first line of defence against traffic-related pollution. Research has emphasised the critical importance of selecting native and naturalized species tolerant to high pollution loads, with the potential to provide year-round canopy cover (Joshi and Swami, 2009). Scientists at ICAR-IARI, New Delhi located within the Delhi metropolitan area, have actively contributed to this knowledge base through studies on indoor plant-mediated phytoremediation and urban landscape design (Tiwari *et al.,* 2019a; Singh *et al.,* 2019), providing regionally relevant recommendations grounded in experimental evidence.

Metro Manila, the Philippines

The Metro Manila experience with Bougainvillea as a heavy metal bioindicator and phytoremediator offers compelling field-level evidence of the genus's capabilities. A study by Dela Cruz *et al.* (2013) comparing foliar lead accumulation in Bougainvillea spectabilis growing in two contrasting districts confirmed progressive, dose-dependent accumulation of Pb in leaf tissue — a behaviour that mirrors observations in ornamental species under experimental metal-spiked wastewater irrigation conducted in India (Vignesh *et al.,* 2023; Verma *et al.,* 2023). These parallel findings across geographies reinforce the universality of foliar metal accumulation mechanisms and support the use of Bougainvillea as a standardised bioindicator for mapping urban lead pollution gradients.

Beijing, China

Beijing's large-scale urban forestry programme, which targeted $PM_{2.5}$ reduction as a primary ecosystem service outcome, demonstrated that well-designed urban vegetation patches significantly attenuate near-ground particulate concentrations while simultaneously moderating urban heat island intensity (Yang *et al.,* 2005). The use of wetland macrophytes as biofilters for inhalable particles in Beijing parks further expanded the toolkit of phytoremediative plant types available to urban planners (Wu and Yu, 2018). These findings corroborate the broader scientific consensus that diverse, structurally complex urban green infrastructure delivers superior and more resilient air quality benefits than monospecific plantings.

Mumbai, India

Mumbai's unique coastal geography introduces marine aerosols, high humidity, and sea salt particles into an already complex urban pollution mix. Studies evaluating dust capture efficiency along Mumbai roadsides identified species-specific variation in particle interception capacity and informed recommendations for species-appropriate roadside planting schemes (Joshi and Chauhan, 2020). The insights from Mumbai are particularly instructive for other coastal megacities in South and South-East Asia where Bougainvillea is widely naturalized and already present as a dominant roadside shrub, enabling its opportunistic incorporation into formalized phytoremediation programmes with minimal additional establishment cost.

Green Infrastructure Design for Maximum Phytoremediation Benefit

Translating the phytoremediation potential of individual species into measurable improvements in ambient air quality at the citywide scale demands careful attention to planting design, species assemblage, and spatial configuration. Road green belts (RGBs) positioned on both margins of arterial roads act as physical barriers, deflecting the pollution plume from the emission zone (vehicle lane) towards the vegetation canopy where particles are deposited and gases are absorbed (Abhijith *et al.,* 2017). Multi-layered belts — combining a taller tree canopy layer with a mid-height shrub tier and a ground-level herbaceous layer — create a more tortuous flow path for polluted air, increasing residence time within the vegetated zone and improving removal efficiency. Bougainvillea, growing as a dense thorny shrub or trained climber, is well suited to the mid-height and vertical surface tiers of such multi-layered configurations.

Vertical greening systems (VGS) — green walls and vegetated facades — represent an innovative solution for hyper-dense urban areas where horizontal ground space is at a premium. VGS can be retrofitted to building exteriors, transforming impervious surfaces into active phytoremediation interfaces while also providing thermal insulation benefits that reduce building energy demand (Perini and Rosasco, 2013). The vigorous climbing habit of Bougainvillea, combined with its xeric tolerance, makes it an ideal candidate for self-clinging or trellis-supported vertical green systems in semi-arid and sub-humid urban climates.

CHALLENGES AND FUTURE PERSPECTIVES

Despite the considerable scientific evidence supporting ornamental phytoremediation, several challenges constrain its wider application. At the street-canyon scale, dense low-level vegetation can impede turbulent mixing, paradoxically elevating pedestrian-level pollutant concentrations by reducing vertical dilution (Janhäll, 2015). Optimal green belt height-to-width ratios and canopy porosity parameters must therefore be defined through computational fluid dynamics modelling informed by field measurements in order to avoid inadvertent aggravation of pollutant hot spots.

The seasonality of deciduous species introduces temporal gaps in phytoremediation coverage, a concern particularly relevant in north Indian cities where winter pollution peaks coincide with leafless conditions in many exotic deciduous ornamentals. Bougainvillea's near-evergreen phenology in tropical and warm sub-tropical climates addresses this concern effectively. The saturation of leaf surfaces by heavy particle loads can diminish incremental deposition efficiency, underscoring the value of regular pruning as a management intervention that physically removes contaminated biomass and stimulates fresh foliage growth (Beckett *et al.,* 2000).

Research priorities for the next decade should include: (i) standardised, real-world quantification of phytoremediation fluxes for Bougainvillea and other key ornamentals under Indian meteorological and pollution regimes; (ii) development of composite species selection matrices that weight APTI, growth habit, maintenance intensity, and water requirement against pollutant removal efficiency; (iii) long-term monitoring of soil metal accumulation under roadside ornamental plantings to assess secondary contamination risks, building on existing expertise in heavy metal dynamics in ornamental crop systems (Balaji *et al.,* 2025; Verma *et al.,* 2023; Vignesh *et al.,* 2023); and (iv) integration of phytoremediation planning into smart city digital twins, coupling real-time air quality sensor networks with predictive vegetation performance models.

CONCLUSION

Urban air pollution stands as one of the defining environmental health crises of the twenty-first century, demanding solutions that are simultaneously effective, equitable, and enduring. Phytoremediation through carefully selected ornamental plants offers precisely this — a nature-based approach that converts urban green spaces from passive amenities into active air quality infrastructure. This review has demonstrated that ornamental plants deploy a sophisticated repertoire of physical and biochemical mechanisms to intercept particles and metabolise gaseous pollutants, and that the APTI provides a practical screening framework for matching species to pollution exposure contexts. Within this framework, Bougainvillea occupies a position of particular merit — combining established horticultural tractability, as evidenced by quality seedling production protocols developed at ICAR-IARI (Jain *et al.,* 2019), with documented tolerance and accumulation capacity for PM, NO_2, lead, and cadmium. Case studies from Delhi, Mumbai, Manila, and Beijing validate the real-world relevance of green infrastructure for ambient air quality improvement. Overcoming residual design and knowledge gaps through targeted research — including long-term field studies on heavy metal dynamics under ornamental plantings (Balaji *et al.,* 2025; Vignesh *et al.,* 2023; Verma *et al.,* 2023), plant stress physiology (Vanlalruati *et al.,* 2021, 2023), and urban landscape design (Singh *et al.,* 2019; Jain *et al.,* 2020) — will accelerate the transition from scientific demonstration to policy-embedded practice. With sustained institutional commitment, ornamental phytoremediation can meaningfully contribute to building cities that are not merely liveable but regenerative.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

A.K. Tiwari: Conceptualization, Writing – original draft, Supervision, Review & editing. B. Singh: Writing – original draft, Data curation. Ritu Jain: Writing – review & editing, Resources. M.K. Singh: Writing – review & editing, Visualization. All authors have read the manuscript and agreed to its content. They have also approved the final version of the manuscript and consent to its submission.

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