The Science Behind Urban Plants and Human Health: Biological and Psychological Mechanisms of Nature-Based Healing

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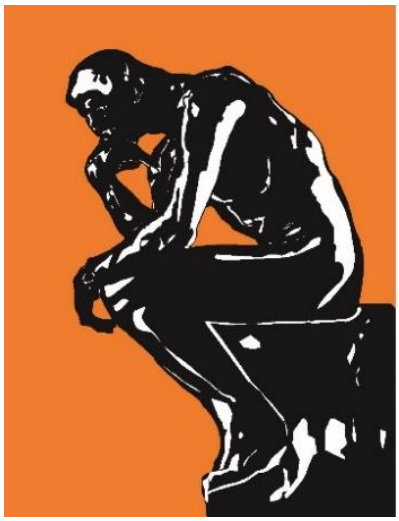

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> "A century-old myrtle tree stands tall and proud in an alley that appears almost deserted. At the end of the alley nestles a small lovely house, besides which tucks a mulberry tree.
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> The mulberry tree spreads its lust greenery wide across the vast courtyard. At noon, faint rays of sunlight would penetrate through the thick mulberry leaves, painting dots of sunny flowers on the yard, mesmerizing those passing by."
>
> — "Dream"; *Wild Wise Weird* (2024)

Abstract

As urbanization accelerates, diminishing green spaces pose growing public health challenges, exacerbating pollution exposure, stress, and chronic illnesses. This narrative review synthesizes research on the biological and psychological pathways through which urban plants promote human health. Biologically, urban greenery enhances air quality by filtering pollutants, strengthens immune function by increasing microbial diversity, and regulates stress physiology via endocrine mechanisms. Psychologically, nature exposure restores cognitive function, reduces stress, and fosters emotional resilience, as evidenced by neuroimaging and epidemiological studies. The findings suggest that integrating green infrastructure into urban environments yields measurable public health benefits, including lower mortality rates, reduced cardiovascular and respiratory disease prevalence, and improved mental well-being. However, critical research gaps remain regarding the optimal "doses" of nature for health, cultural differences in nature perception, and the potential role of incorporating insights from quantum and informational theories to study cognitive-environment interactions (e.g., Granular Interaction Thinking Theory). Addressing these gaps through interdisciplinary collaboration, artificial intelligence integration, and data-driven urban planning can help cities evolve into healthier, more sustainable ecosystems.

Keywords: urban greenery; human health; air quality; cognitive restoration; public health

Introduction

Modern urbanization presents a paradox: as cities expand, green spaces often shrink. More than half of the world's population now resides in urban areas, facing increased exposure to stressors such as noise, crowding, and pollution (Park & Evans, 2016). The loss of parks, trees, and gardens removes natural buffers against these stressors (Bikomeye et al., 2021), contributing to higher rates of chronic stress, mental health disorders, allergies, and respiratory illnesses among urban dwellers (Roe & McCay, 2021). Compared to rural populations, city residents face an elevated risk of anxiety, depression, and other health issues, a disparity partly linked to reduced daily exposure to nature (Selhub & Logan, 2012). This underscores the urgent need to explore how urban greenery can mitigate the health challenges of city life.

Developing a scientific framework for urban nature–health interactions is, therefore, essential. This framework must span multiple scales and systems—from air chemistry (e.g., how trees filter pollutants) to human biology (e.g., how nature contact regulates stress physiology) to psychology (e.g., how green views restore attention and promote mental well-being). Traditionally, fields such as environmental psychology and urban ecology have operated in isolation, but a holistic approach is needed to fully understand the intertwined biological and cognitive benefits of urban greenery (Liu et al., 2024). By integrating insights from medicine, neuroscience, immunology, and psychology, the current narrative review aims to address key questions:

- What are the key biological mechanisms through which urban nature enhances human health and well-being?
- What are the key psychological mechanisms underlying the health benefits of urban nature?
- How can insights from these biological and psychological mechanisms be applied in practice?

Answering these questions can inform urban design and public health policies, ensuring that cities are built to support human health and well-being.

The review has three main objectives. First, we survey the evidence linking urban green environments to improved health outcomes, examining both physiological markers (e.g., lung function, cortisol levels) and psychological indicators (e.g., attention restoration, mood enhancement). Second, we present the existing knowledge regarding the underlying mechanisms—differentiating biological pathways (e.g., air purification, microbiome modulation, neuroendocrine effects) from psychological theories (e.g., cognitive restoration, stress reduction). Third, we identify notable practical applications, provide policy implications, and highlight areas where knowledge remains limited—such as quantifying the optimal "dose" of nature for health benefits—and explore how future interdisciplinary research and urban planning, potentially aided by artificial intelligence, can optimize nature-based interventions.

Ultimately, this interdisciplinary synthesis reinforces the idea that urban greenery is not merely an aesthetic amenity but a critical component of a healthy city—warranting intentional integration into urban design and policy.

Biological Mechanisms: How Urban Plants Affect the Human Body

Air Quality and Respiratory Health

Urban plants play a crucial role in improving air quality, one of the most immediate ways they enhance physical health. Trees, shrubs, and green walls act as natural air filters, removing airborne pollutants and reducing human exposure to harmful substances. Foliage traps particulate matter (PM) on leaf surfaces and absorbs gaseous pollutants through leaf stomata (Prigioniero et al., 2023). This process significantly lowers concentrations of fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), ozone (O_3), and volatile organic compounds (VOCs). For instance, a field study in Rio de Janeiro found that a dense botanical garden had 33% lower $PM_{2.5}$ levels than a nearby urban area with sparse greenery (Junior, Bueno, & da Silva, 2022). Similarly, modeling studies estimate that urban trees in U.S. cities collectively remove approximately 711,000 metric tons of air pollutants annually, contributing to large-scale air quality improvements (Nowak, Crane, & Stevens, 2006).

The public health benefits of urban greenery are substantial. Long-term $PM_{2.5}$ exposure is linked to cardiovascular and respiratory diseases, as well as premature mortality (Junior, Bueno, & da Silva, 2022). By reducing ambient PM levels, urban tree canopies and parks

can help lower the incidence of asthma exacerbations, lung cancer, and heart attacks (Mandal et al., 2023). Beyond particulate pollution, urban vegetation also mitigates gaseous pollutants that contribute to oxidative stress and airway inflammation. Trees absorb NO_2, sulfur dioxide, and ozone, improving respiratory health (Nowak, Crane, & Stevens, 2006). Additionally, exposure to volatile organic compounds (VOCs) naturally emitted by trees has been associated with enhanced immune function (e.g., increased natural killer cell activity), reduced inflammatory responses, and reduced psychological stress, further supporting human well-being (Mei et al., 2021).

Research shows that roadside hedges and green barriers can significantly improve air quality by creating cleaner air on their lee side. For example, a study in Bangkok's parks found that $PM_{2.5}$ concentrations were 34% lower behind a vegetative barrier (inside the park) compared to the roadway just outside, thanks to the buffering effect of trees and shrubs (Heshani & Winijkul, 2022). Similarly, "green walls"—vertical gardens on buildings—can capture traffic pollutants at street level. Pugh et al. (2012) found that enhancing pollutant deposition through vegetation in street canyons can lower street-level concentrations by up to 40% for NO_2 and 60% for PM. Green walls have also been found to absorb O_3, SO_2, and CO, further improving urban air quality (Tang, 2023). These air quality improvements have tangible health benefits, including fewer emergency room visits for asthma and chronic obstructive pulmonary disease (COPD) (Hansel et al., 2022; Gent et al., 2023).

However, the net impact of urban trees on air quality can vary depending on local conditions. In some cases, dense tree canopies in street canyons can trap pollutants, and certain tree species release biogenic VOCs that contribute to ozone formation, exacerbating pollution (Sawers, 2018). Due to these complexities, researchers have yet to reach a unanimous consensus on whether urban trees always reduce asthma rates via air quality improvements (Eisenman et al., 2019). Nonetheless, the preponderance of evidence suggests that well-planned urban greening—choosing low-VOC-emitting species and avoiding barrier effects in narrow, high-traffic streets—results in cleaner air and healthier lungs (Eisenman et al., 2019; Diener & Mudu, 2021).

In essence, urban plants function as a natural pollution control system, directly enhancing respiratory health by filtering air pollutants. Their effectiveness depends on leaf characteristics: trichomes, ridges, or grooves trap super-micrometer particles; stomatal properties absorb sub-micrometer particles and gases; and small, complex leaves maximize pollutant removal efficiency (Barwise & Kumar, 2020).

Microbiome Diversity and Immune System Modulation

Beyond air purification, urban plants influence human health through microscopic biological exchanges. The biodiversity hypothesis suggests that exposure to diverse natural environments—and the myriad benign microbes they harbor—is essential for developing a

well-regulated immune system (Flies et al., 2020). In contrast, urban lifestyles with limited green contact may lead to reduced microbial exposure, potentially contributing to immune dysregulation and the rise of allergies, asthma, and inflammatory diseases (Logan, Jacka, & Prescott, 2016).

Green spaces, such as parks and community gardens, host rich microbial communities in soil, plant surfaces, and air (Mills et al., 2020). When people spend time in these environments—through direct contact with soil, inhaling outdoor air, or even being downwind of vegetation—they incidentally encounter a greater variety of microbes. This increased microbial diversity can enhance the skin, respiratory tract, and gut microbiota, training the immune system to tolerate harmless substances and reducing the likelihood of overreactive immune responses, such as allergies (Hanski et al., 2012; Selway et al., 2020; Khavkin & Nesterenko, 2022). Supporting this idea, children raised on farms or near forests—environments rich in microbial diversity—have lower rates of asthma and atopy compared to urban-raised children, an effect attributed to differences in microbial exposure (Flies et al., 2020). Consistent with the biodiversity hypothesis, research shows that city residents tend to have less diverse environmental microbiomes and higher rates of immune-related disorders (Flies et al., 2020). Simply put, urban green spaces may help reintroduce some of the microbial "old friends" that humans co-evolved with, strengthening immunoregulation. Experimental studies confirm that contact with soil microbes can shift immune function toward a more balanced, anti-inflammatory state (Flies et al., 2020).

One notable line of research focuses on *Mycobacterium vaccae*, a soil bacterium commonly found in natural environments. *M. vaccae* has been described as a "microbial ally" for mental and immune health. When people inhale dust while gardening or walking in a park, they may incidentally be exposed to this bacterium, which interacts with the body in beneficial ways. Laboratory studies show that *M. vaccae* exposure stimulates immune pathways that trigger serotonin release in the brain, a neurotransmitter crucial for mood regulation—many antidepressants function by increasing serotonin levels. In an experiment where researchers injected heat-killed *M. vaccae* into mice, serotonin levels and metabolites increased in the brain, while stress-induced behaviors decreased. The exposed mice exhibited 50% lower rates of stress-induced colitis, suggesting a potent anti-inflammatory effect as well (Reber et al., 2016; Frank et al., 2018; Hassell et al., 2023). Although injections are not how people typically encounter microbes, this study highlights a broader principle: contact with nature's microbiome can positively influence human biochemistry, fostering an immune system that is less prone to chronic inflammation and a mental state more resilient to stress.

Urban green spaces function as natural training grounds for the immune system by increasing exposure to microbial diversity. Preliminary human trials have even explored the idea of "prescribing" microbial exposure—for example, by allowing children to play in soil-enriched playgrounds—resulting in improved immune markers and reduced eczema symptoms (Flies et al., 2020). Beyond microbial benefits, certain plants release bioactive

compounds known as phytoncides, which, when inhaled, can enhance immune function. Research on forest bathing (*Shinrin-yoku*) has shown that phytoncide exposure can boost natural killer cell activity and other immune defenses, underscoring the physiological benefits of nature immersion (Tsao et al., 2018; Putra et al., 2018). While further research is needed to fully map the interactions between plant-associated microbes and immune outcomes, it is increasingly clear that urban vegetation provides essential immunological benefits.

By integrating elements of wilderness into cityscapes, urban planners can help reintroduce microbial inputs that support healthy immune development (Flies et al., 2020). In essence, urban plants contribute to human health in two complementary ways: they remove harmful agents (pollutants) while supplying beneficial ones (microbes)—an elegant biological mechanism in which nature's biodiversity acts as a natural prophylactic for the immune system (Rook, 2021).

Endocrine Regulation and Stress Physiology

One of the most well-documented physiological effects of nature is its ability to reduce stress. Urban environments, with their relentless stimuli—honking horns, crowded streets, and limited restorative spaces—tend to keep the body in a heightened state of arousal. This is marked by elevated cortisol (the primary stress hormone), increased sympathetic nervous system activity ("fight-or-flight" mode), and reduced parasympathetic activity ("rest-and-digest" state). Green spaces can counteract this by engaging neuroendocrine mechanisms that shift the body toward a more relaxed state.

Research in environmental health consistently shows that even brief exposure to nature leads to measurable physiological changes: the heart rate slows, blood pressure drops and cortisol levels decrease (Park et al., 2009). For example, in field experiments across 24 forest sites in Japan, volunteers who spent just 15 minutes walking in a forest experienced a 13–16% reduction in cortisol levels, along with lower pulse rates and blood pressure, compared to time spent in urban environments (Park et al., 2009). These findings indicate a strong activation of the body's natural relaxation response when immersed in nature.

The endocrine effects of natural exposure extend beyond cortisol to include neurotransmitters that regulate mood and well-being. Dopamine and serotonin—chemicals linked to pleasure, motivation, and emotional stability—can be influenced by natural experiences. As mentioned earlier, soil microbes can stimulate serotonin release (Reber et al., 2016; Frank et al., 2018; Hassell et al., 2023). Additionally, scenic beauty, birdsong, and natural scents activate dopamine pathways, enhancing mood and motivation. These biochemical shifts are further reinforced by changes in autonomic nervous system activity. Forest bathing (*Shinrin-yoku*) has been shown to significantly increase parasympathetic nervous activity (which promotes relaxation and recovery) while reducing sympathetic activity (associated with stress and anxiety). Heart rate variability (HRV) studies demonstrate

that time in a forest can boost the high-frequency HRV component—a marker of vagal (parasympathetic) activation—by 56.1% after viewing and 102% after walking (Park et al., 2009). Simultaneously, the ratio of low-frequency to high-frequency HRV—an indicator of stress-related sympathetic dominance—drops significantly during forest walks (Park et al., 2009).

Another evidence of nature's impact on stress physiology comes from neuroimaging research. A recent study in Germany used functional MRI (fMRI) to compare brain activity before and after a one-hour walk in either an urban shopping district or a forested area on the city outskirts (Sudimac, Sale, & Kühn, 2022). The researchers focused on the amygdala—the brain region that regulates stress and fear responses. Their findings suggest that amygdala activation significantly decreased after the forest walk but remained unchanged (or even slightly elevated) after the city walk. In other words, a brief immersion in nature calmed the brain's stress center, whereas urban exposure did not (Sudimac, Sale, & Kühn, 2022).

This neural evidence aligns with hormonal data, reinforcing the idea that nature quiets the body's stress circuits. Another example involves gardening and community green spaces, which have been linked to improved mental well-being, better sleep quality, and enhanced mucosal immunity—especially in older adults (Shen, Hung, & Fang, 2022). In high-stress occupations, regular exposure to green environments has been associated with lower diurnal cortisol levels and improved mood (Jones, Tarter, & Ross, 2021). These endocrine and autonomic effects explain the widespread anecdotal reports of feeling mentally clearer and physically more relaxed after time in nature. Subjectively, people experience a sense of calm and restoration; objectively, cortisol drops, serotonin rises, blood pressure eases, and the neuroendocrine system shifts toward equilibrium (Park et al., 2009; Adewuyi et al., 2023). Over time, these physiological shifts can reduce the risk of stress-related ailments, including hypertension, chronic anxiety, and burnout.

By providing environments that engage our biophilia—our innate affinity for nature—urban plants can serve as a natural "stress relief valve," promoting both immediate well-being and long-term health.

Psychological and Cognitive Mechanisms

Attention Restoration Theory (ART)

Urban environments place high demands on directed attention—navigating traffic, filtering out sirens and billboards, or multitasking at work. Over time, this cognitive effort leads to mental fatigue. Attention Restoration Theory (ART), developed by Rachel Kaplan and Steven Kaplan, suggests that nature provides an ideal respite for our overworked brains (Kaplan & Kaplan, 1989). According to ART, natural settings effortlessly engage attention through "soft fascination" (e.g., rustling leaves, drifting clouds) in a bottom-up manner, allowing the top-

down directed attention system to rest and recover. In contrast, urban environments—dominated by honking cars, flashing ads, and crowded sidewalks—demand constant top-down focus, quickly depleting cognitive resources. Kaplan found that spending time in or even viewing, nature enhances performance on tasks requiring concentration (Kaplan, 1995). This insight underpins ART's core idea: exposure to natural environments restores attentional capacity fatigued by urban living (Liu et al., 2024).

ART identifies four attributes of restorative environments: being away (a mental escape from routine), extension (richness and coherence of the environment), fascination (effortless attention engagement), and compatibility (alignment with one's needs and desires) (Kaplan & Kaplan, 1989). Natural spaces often fulfill all these criteria—a quiet park offers a mental retreat from city noise, expansive stimuli (sky, trees, water) that engage the mind, gentle captivation (watching butterflies), and a setting conducive to relaxation (Rapuano et al., 2022).

ART is strongly supported by empirical research. In a classic experiment, participants took a walk either through a busy urban street or a lush arboretum. Those who walked in nature improved their working memory and attention by ~20%, while those in the city showed no improvement (Berman, Jonides, & Kaplan, 2008). Their memory span (tested by repeating sequences backward) and attention performance were significantly better after an hour in the botanical garden than after an hour in traffic. Notably, even viewing photographs of natural scenery produced smaller but similar benefits, suggesting that the content of natural stimuli—such as fractal patterns, gentle motions, or inherently engaging features—is key to restoring directed attention (Berman, Jonides, & Kaplan, 2008).

Beyond attention restoration, nature exposure may enhance creativity. In one study, participants who spent four days backpacking in the wilderness, completely unplugged from technology, scored 50% higher on a creativity problem-solving test than a control group (Atchley, Strayer, & Atchley, 2012). While extended wilderness immersion is rare in urban life, even brief nature interactions can help. Research shows that as little as a 10-minute break in a garden or gazing at trees through a window can reduce mental fatigue and improve focus in office workers.

Thus, ART offers a compelling psychological framework: urban parks and green spaces function as cognitive recharge stations, allowing directed attention to rest while involuntary attention gently engages with natural stimuli (Liu et al., 2024). This restorative process replenishes cognitive capacity, improving focus, problem-solving, and creativity upon returning to demanding urban settings (Berman, Jonides, & Kaplan, 2008). The implications for city design are significant—green micro-oases near schools could enhance learning and academic performance, while integrating nature into workplaces could reduce job stress and burnout, ultimately boosting productivity (Li & Sullivan, 2016; Sadick & Kamardeen, 2020).

Stress Recovery Theory (SRT)

While ART focuses on cognitive fatigue, Stress Recovery Theory (SRT) addresses nature's role in reducing affective and physiological stress. Developed by Roger Ulrich, SRT proposes that humans have evolved a preference for natural environments that promote survival—such as forests or savannas with water—and that exposure to these settings triggers an immediate positive emotional response and stress reduction (Ulrich, 1984; 1991). In Ulrich's seminal studies, participants who viewed natural scenes, as opposed to urban settings devoid of greenery, showed lower physiological stress indicators—including reduced heart rate, muscle tension, and skin conductance—within minutes. They also reported improved mood (Ulrich, 1984).

SRT suggests that this calming effect is largely unconscious and hardwired. Even indirect exposure, such as a mural or a window view of trees, can engage the brain's emotion-processing circuits—like the amygdala—in a way that promotes interest and pleasure rather than alarm, thereby inhibiting the stress response (Gaekwad, Moslehian, & Roös, 2023). This aligns with the biophilia hypothesis, which posits that humans have an innate affinity for living systems (Wilson, 1984; Barbiero & Berto, 2021). From an evolutionary perspective, paying attention to natural elements (like greenery or water) would have been adaptive, signaling safe and resource-rich habitats (Beatley, 2020), thereby allowing early humans to relax momentarily and recover from threats (Williams, 2017). By contrast, urban environments—characterized by sharp angles, loud noises, and dense crowds—may subconsciously signal potential danger, keeping the stress response activated (Juneja, 2016; Graziano, 2017).

Neuroscientific evidence supports SRT's claims. Functional MRI (fMRI) and EEG studies show that viewing natural landscapes engages the anterior cingulate cortex and insula, regions associated with positive affect and emotional regulation. Conversely, urban scenes activate the amygdala, which is linked to fear and stress (Sudimac, Sale, & Kühn, 2022). One fMRI study found that participants viewing nature images exhibited increased activity in the prefrontal cortex (which governs executive functions and emotional control) and reduced amygdala activity compared to those viewing urban environments (Sudimac, Sale, & Kühn, 2022). Similarly, EEG studies indicate that watching nature videos enhances alpha wave activity—a neural pattern associated with relaxation—whereas urban videos do not (Grassini, Segurini, & Koivisto, 2022). These objective findings corroborate self-reports: people consistently describe feeling more peaceful, rejuvenated, and less stressed after spending time in green spaces (Roe & MacCay, 2021). In Scotland, over 90% of surveyed adults reported that outdoor visits helped them de-stress and improved their mental health (Souter-Brown, 2020).

Notably, stress recovery in nature happens rapidly—often within the first five minutes of exposure. Ulrich's well-known hospital study found that post-surgical patients with a view of trees recovered faster and required less pain medication than those with a brick wall view, demonstrating the clinical significance of nature's restorative power (Ulrich, 1984). Similarly, a short walk in an urban park during a lunch break can significantly lower stress levels for

the remainder of the day. One study found that a 90-minute nature walk reduced rumination (repetitive negative thoughts) and decreased neural activity in the subgenual prefrontal cortex, a brain region linked to depression (Bratman et al., 2015).

SRT provides a compelling explanation for why green spaces foster emotional well-being: they tap into an ancestral preference for environments that signal safety and opportunity, thereby rapidly reducing stress (Ulrich, 1984; 1991). Even small patches of urban greenery—a single tree on a street or a pocket park—contribute to this effect by integrating nature into otherwise artificial landscapes, offering residents frequent opportunities for micro-reprieves from stress (Wang et al., 2016). Cities that prioritize green infrastructure effectively build a natural stress management system, potentially lowering rates of stress-related disorders and enhancing overall well-being (Twohig-Bennett & Jones, 2018; Sudimac, Sale, & Kühn, 2022).

Mental Health and Emotional Resilience

Urban nature profoundly benefits mental health. Regular exposure to green spaces is linked to lower rates of depression, anxiety, and other psychiatric conditions. Large-scale epidemiological studies reveal these patterns. A nationwide study in Denmark tracking nearly one million people found that children who grew up with the least green space had up to a 55% higher risk of developing mental disorders in adulthood compared to those raised in greener environments (Engemann et al., 2019). This dose-response relationship—where greater childhood exposure to greenery corresponds with lower lifelong mental illness risk—remained significant even after controlling for socioeconomic status and urbanization level. Such findings suggest that early-life exposure to nature fosters emotional resilience that endures into adulthood.

Several mechanisms may explain this effect. Green spaces provide opportunities for play and social interaction, buffer against childhood stress, and expose individuals to beneficial microbiomes that influence brain development. In adults, proximity to parks and tree-lined streets is consistently associated with lower rates of depression and anxiety (Twohig-Bennett & Jones, 2018; Sudimac, Sale, & Kühn, 2022). A meta-analysis of over 140 studies worldwide found that people with high levels of green space exposure were significantly more likely to report good mental well-being, life satisfaction, and lower stress levels (Twohig-Bennett & Jones, 2018). While correlation alone does not establish causation, longitudinal studies support a causal link. Moving to a greener neighborhood is associated with sustained improvements in mental health, whereas relocating to a less green area predicts declines. These findings underscore the vital role of urban nature in promoting psychological well-being.

Urban greenery plays a crucial role in mental health, not only passively through stress reduction but also as an active therapeutic tool. "Green care" or ecotherapy programs use natural settings for structured therapy, while nature-based activities support mental well-

being. Therapeutic horticulture, for instance, has shown promise for individuals with post-traumatic stress disorder (PTSD), dementia, and autism spectrum disorders (Roe, 2016). Veterans with PTSD who participate in gardening programs often report fewer nightmares, improved mood, and increased sociability. Engaging with plants and soil in a communal garden provides grounding sensory experiences and a sense of purpose. Studies show that horticultural therapy can reduce depression and stress symptoms, improve sleep, and aid in social reintegration for veterans (Mottershead & Ghisoni, 2021).

Similarly, incorporating gardens into dementia care helps alleviate agitation and enhance emotional well-being. A meta-analysis of horticultural therapy in dementia patients found significant reductions in agitation and increased engagement in activities, demonstrating how plants can reconnect even those with cognitive impairment to a calmer state of mind (Lu et al., 2019). For individuals on the autism spectrum, gardens and nature activities offer a multi-sensory yet non-overwhelming environment, supporting social skill development, anxiety reduction, and improved attention (Mogren, 2019; Anas, 2023). Case studies indicate that youth with autism in gardening programs become more communicative and show fewer self-stimulatory behaviors over time, suggesting improved self-regulation (Dami & Esmaeeldokht, 2023).

Beyond structured therapies, nature-based interventions—ranging from wilderness programs to green schoolyards—have been linked to higher self-esteem, reduced ADHD symptoms, and greater emotional resilience across diverse populations, from at-risk teens to the elderly (Taylor et al., 2022; Ramalho & Petrica, 2023). The key factor is that natural environments are low-stress, engaging, and meaningful, providing an ideal setting for therapy and personal growth (Schreibman et al., 2015).

Communities with abundant greenery often exhibit stronger social cohesion and support networks, further benefiting mental health (Jennings & Bamkole, 2019). Green spaces serve as gathering places for social interaction, exercise, and community events, fostering a sense of belonging and reducing loneliness—protective factors against mental illness. Studies have linked tree-lined neighborhoods and community gardens to lower crime rates and greater perceptions of safety and social connectivity (Weinstein et al., 2015). Conversely, a lack of nature in dense urban areas can contribute to sensory overload and feelings of confinement, fueling what some researchers call “nature-deficit disorder” (Nikkhou & Tezer, 2020).

Taken together, the evidence underscores that urban plants are not mere decorations but essential infrastructure for mental health. By mitigating risk factors such as chronic stress and social isolation while promoting joy, calm, and connection, urban greenery fosters a more resilient and happier population (Roe & McCay, 2021). In this sense, parks and trees serve as vital public health assets, helping prevent psychiatric disorders and enhance the overall quality of life in cities (Engemann et al., 2019; Sudimac, Sale, & Kühn, 2022).

Practical Applications of Green Spaces

A growing body of empirical research highlights the health benefits of urban greenery. Meta-analyses, which synthesize findings from multiple studies, provide the strongest evidence. A comprehensive meta-analysis by Twohig-Bennett & Jones (2018), covering data from over 290 million people across 20 countries, found that greater exposure to green space is associated with lower all-cause mortality, reduced rates of type II diabetes and cardiovascular disease, and improved self-rated health. Notably, individuals living in the greenest areas had significantly lower death rates—one analysis estimated a 12% reduction in mortality risk for those with abundant neighborhood vegetation compared to those in sparsely vegetated areas (Rojas-Rueda et al., 2019). Another review by Rojas-Rueda et al. (2019) confirmed that people who spend more time in green spaces tend to have lower mortality rates, reinforcing the idea that urban greenery can be life-saving at a population level.

Beyond correlational studies, intervention research strengthens the case for greenery as a causal factor in health improvements. For instance, when a vacant lot in a disadvantaged Philadelphia neighborhood was transformed into a pocket park, researchers observed declines in local residents' heart rates and depression levels compared to those living near unchanged vacant lots (Montes, 2023). Such "natural experiments" provide compelling evidence that access to green space actively enhances well-being.

This knowledge is increasingly shaping healthcare and urban policy. One emerging approach is the "green prescription," in which medical professionals prescribe time in nature to help manage conditions like anxiety, depression, and hypertension (Adewuyi et al., 2023). Programs in New Zealand, the UK, and several U.S. cities integrate healthcare with parks, where doctors prescribe nature walks—often 30 minutes, three times a week—as part of treatment (Brockis, 2024). Early evaluations show promising outcomes: patients who follow nature prescriptions report reduced stress, improved mood, and measurable health benefits such as lower blood pressure and decreased anxiety scores (Nguyen et al., 2021). In one California study, participants in an eight-week nature walk program exhibited significantly reduced depression symptoms compared to a control group (Kolster et al., 2023).

Urban policymakers are also recognizing green space as a public health resource. Strategies include setting tree canopy coverage targets (e.g., 30% in all neighborhoods) and ensuring every resident has a park within walking distance (Przewoźna et al., 2024). The World Health Organization recommends that all urban residents have access to at least 0.5–1 hectare of green space within 300 meters of their home, reflecting a global consensus on the importance of nearby nature (Rahman & Zhang, 2018). Some municipalities use "park desert" maps to prioritize new green spaces in underserved areas, promoting both health equity and environmental justice (Jennings et al., 2017).

Innovative urban greening efforts, such as green roofs and school gardens, further enhance city environments. School gardens, in particular, provide multiple benefits: children who participate tend to increase physical activity, improve nutrition knowledge and vegetable intake, and exhibit better focus and teamwork (Chan, Tan, & Gong, 2022). These gardens

function as outdoor classrooms, fostering curiosity and reducing stress—California studies have linked them to improved science scores and social skills, likely due to greater student engagement and reduced anxiety (Wells et al., 2015).

City case studies highlight the diverse benefits of urban greenery. In Singapore, a city-wide greening strategy—including roadside tree planting and skyrise greenery—has not only enhanced aesthetics but also mitigated the urban heat island effect and improved residents' well-being (Hamnett & Yuen, 2019). In Philadelphia, the Green City, Clean Waters initiative integrates rain gardens and green infrastructure to manage stormwater while creating pocket parks and curbside gardens. These spaces offer residents both recreational opportunities and mental health benefits, leading to reduced stress and increased community pride (Fitzgerald & Laufer, 2017). Toronto provides another compelling example. Researchers found that residents who moved to areas with more trees experienced significant improvements in self-reported health—comparable to the benefits of being a few years younger or earning several thousand dollars more annually. This suggests urban greenery can help offset socio-economic health disparities (Apparicio, Landry, & Lewnard, 2017; Barona et al., 2023).

Public health agencies are increasingly recognizing the value of green spaces. In the U.S., Park Rx programs allow doctors to prescribe free national park passes to patients, integrating nature into healthcare (James, Christiana, & Battista, 2019). These examples underscore a crucial realization: integrating greenery into cities is one of the most cost-effective wellness strategies available. While building more hospitals is expensive, planting trees and creating parks is not only cheaper but also helps prevent illness in the first place. By embracing greening interventions, cities are making nature-based healing a cornerstone of public health policy (Van den Bosch & Sang, 2017), fostering both healthier residents and more sustainable, livable urban environments.

Research Gaps and Future Directions

Despite strong evidence for urban nature's benefits, key knowledge gaps remain. One major area of inquiry is the dose-response relationship: how much nature exposure—measured in frequency, duration, or intensity—is needed for specific health benefits? While 120 minutes per week in nature has been suggested as a general threshold for improved well-being (White et al., 2019), more precise guidance is needed. For example, is five minutes of gazing at a garden enough to restore attention? How large must a green space be to lower cortisol levels in nearby residents? Research is ongoing to quantify the "doses" of nature required for outcomes such as stress reduction, cognitive restoration, and lower blood pressure. Some studies suggest that even 10-minute "micro-breaks" in a park can improve mood (Bartmann, Probst, & Corbin, 2022), but do these short exposures yield lasting mental health benefits? Individual differences further complicate the picture—what works for one person (e.g., a quiet forest setting) may not work for another who prefers a vibrant

community garden. Future studies using wearable sensors and smartphone tracking could refine dose-response curves, enabling personalized nature prescriptions tailored to individual needs, much like exercise prescriptions.

Another critical research gap involves cultural and geographic differences (Vuong, 2023; Vuong, La, & Nguyen, 2022). Most studies on urban green space and health come from North America, Europe, and East Asia, leaving much unknown about its effects in arid cities, tropical megacities, or informal settlements, where "green space" takes different forms. Cultural perceptions of nature vary widely—some groups may find wild urban parks uninviting or even intimidating (Madge, 1997), preferring manicured gardens, while others may derive greater benefits from untamed green areas. How do these preferences influence the health impacts of exposure to nature?

Environmental justice is also a pressing concern. Low-income neighborhoods often have fewer parks and street trees, exacerbating health disparities (Bruton & Floyd, 2014). Future research should not only document these inequalities but also collaborate with communities to co-create green spaces that reflect their needs and traditions. For example, community gardens in immigrant neighborhoods can provide familiar medicinal plants and culturally significant foods (Hondagneu-Sotelo, 2017), offering both health and cultural benefits. Geographical context further modulates the effects of urban greenery. A city with year-round warmth may see greater health gains from green spaces than one with harsh winters, where outdoor activity is seasonal (Lee, 2020). Long-term international studies could help cities learn from one another, refining strategies to maximize the health and social benefits of urban nature.

Interdisciplinary research is expanding to address some of the deeper mysteries of nature's impact on human well-being. One emerging frontier explores the link between socio-psychological phenomena and quantum and informational theories, such as Granular Information Transfer Theory (GITT), to model cognitive-environment interactions (Vuong & Nguyen, 2024a, 2024b). These frameworks suggest that natural environments provide "informational richness" or microscopic stimuli that resonate with human cognition. While still theoretical, such ideas push boundaries by questioning whether fundamental physical mechanisms—beyond biological sensory input—underlie nature's benefits. For instance, the fractal patterns in nature may synchronize with neural firing patterns, or the Earth's electromagnetic frequency (Schumann resonance) may influence brainwave coherence (Miller & Miller, 2003). Although these hypotheses straddle psychology, physics, and philosophy, they reflect a broader effort to unify knowledge across disciplines. As technology advances, some of these ideas may become testable. Could virtual reality nature, designed to replicate fractal dimensions or frequency spectra, deliver similar benefits as real nature? Understanding how nature exposure is transduced into biological and psychological signals will likely require such innovative theoretical approaches.

On a practical level, AI and big data are revolutionizing urban planning. AI-driven models analyze vast datasets—from satellite imagery to health records—to identify where green

spaces would have the greatest impact (Patil et al., 2024). For example, machine learning can predict hypertension hotspots linked to low tree cover and high heat indices, similar to how weather data has been used to forecast acute coronary syndrome prevalence (Wlodarczyk et al., 2022). City planners can then strategically plant trees to mitigate heat stress and cardiovascular risks. “Smart cities” are increasingly incorporating AI to optimize green space allocation alongside traffic and energy use (Masoumi & van Genderen, 2024). One concept, an “Urban Green Space AI Planner,” could simulate different greening scenarios, predicting their effects on air quality, noise reduction, and public health outcomes (Ge, Feng, & Meng, 2024). Early applications include AI-guided tree-planting strategies in Melbourne and Singapore to maximize climate resilience, shade, and pollution absorption (Swaminathan, 2015; He & Chen, 2024).

Another breakthrough is the creation of digital twins—virtual models of cities that integrate buildings, roads, and green infrastructure (Ketzler et al., 2020). These models allow urban planners to test interventions—such as adding parks or green corridors—and forecast their effects. When combined with public health data, digital twins enable designs that prioritize well-being, ensuring, for example, that every child can walk a green route to school or that hospitals have optimally placed healing gardens (Marcus & Barnes, 1999; Marcus, 2007). The future of urban design may evolve into a collaboration between human creativity and AI analytics (Quan et al., 2019), producing cities that are both aesthetically rich and health-promoting by design.

As climate change intensifies, the role of urban greenery will become even more crucial. Green spaces cool cities, reducing heat-related illnesses (Nazish, Abbas, & Sattar, 2024); they help manage floodwaters (Schuch, 2017); and they offer psychological refuge, as seen after the COVID-19 pandemic (Maury-Mora, Gómez-Villarino, & Varela-Martínez, 2022). Research must keep pace with these challenges, focusing on resilient urban nature and its protective benefits in an era of climate stress. The concept of “therapeutic landscapes” may expand—by integrating forest patches into health clinics or establishing “healing forests” at city edges (He et al., 2022). The future of urban nature and human health lies in interdisciplinary collaboration—requiring collaborations between ecologists, clinicians, urban planners, computer scientists, and community leaders. By addressing key gaps—dosage, context, and underlying mechanisms from microbiome interactions to quantum effects—and applying cutting-edge tools, we can ensure that future cities evolve into thriving ecosystems that nurture human well-being rather than mere concrete jungles.

Conclusion

Urban plants are not mere decorative elements—they are vital to the health and well-being of city populations. This review has underscored how green infrastructure, from sprawling parks to a single potted tree on a balcony, exerts profound, multidimensional benefits. Biologically, urban vegetation improves external environments by purifying the air, lowering

temperatures, and reducing noise pollution. In turn, these environmental changes promote internal physiological health—enhancing lung function, bolstering immune responses, and regulating stress hormones (Diener & Mudu, 2021). Psychologically, access to nature fosters relaxation, mental restoration, and social cohesion (Manvelyan, 2024). Scientific evidence, ranging from cellular studies on immune function to neuroimaging of forest walkers, confirms these benefits. Moreover, the positive impacts of urban greening translate into tangible public health outcomes—lower mortality rates, reduced disease burdens, and enhanced quality of life (Twohig-Bennett & Jones, 2018; Rojas-Rueda et al., 2019).

Given these findings, urban planners, public health officials, and policymakers must prioritize green spaces as essential infrastructure rather than optional amenities. Just as clean water and electricity are fundamental services, so too is access to nature. Integrating nature-based solutions into urban design can take many forms—expanding parks, planting street trees and rooftop gardens, developing green corridors, and incorporating natural elements into new constructions. Many cities now track green space per capita as a key metric of urban health, and some have appointed roles like “Chief Heat Officers” and “Urban Forest Managers” to lead greening efforts. The return on investment is clear: urban greening reduces healthcare costs and boosts workforce productivity. Even modest increases in tree cover can significantly lower rates of cardiovascular disease, yielding long-term economic benefits. Beyond the financial incentives, there is a deeper moral and ecological imperative—enhancing urban nature supports biodiversity, mitigates climate change, and secures a healthier future for generations to come (Nguyen et al., 2023; Nguyen, 2024). Human and environmental health are inextricably linked; by greening our cities, we heal both ourselves and our planet.

This review also underscores the need for continued interdisciplinary research. There is still much to uncover about the precise mechanisms through which nature promotes health and the most effective ways to implement these insights. Collaboration among experts in medicine, psychology, ecology, and technology can drive innovative solutions—such as therapeutic landscapes or AI-optimized urban greening strategies. Equally important is public engagement (Nguyen & Jones, 2022; Nguyen et al., 2023). When residents are informed about the benefits of urban nature and actively involved in shaping green spaces, they become advocates for their preservation. As cities expand, they must not grow apart from nature but integrate it into their fabric. The vision of “biophilic cities” is not merely an aesthetic or ethical aspiration—it is a public health necessity (Beatley, 2011; Vuong et al., 2024). Urban greenery is nature’s prescription for many of the challenges of city life. By embracing nature-based solutions, we can create urban environments where high-rises and parkland, technology, and trees, coexist harmoniously, enabling people to thrive both physically and mentally amid the bustle of modern life.

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