Review

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The Multifunctional Role of *Salix* spp.: Linking Phytoremediation, Forest Therapy, and Phytomedicine for Environmental and Human Benefits

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Review

The Multifunctional Role of *Salix* spp.: Linking Phytoremediation, Forest Therapy, and Phytomedicine for Environmental and Human Benefits

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Abstract

Air pollution, soil contamination, and rising illness demand integrated, nature-based solutions. Willow trees (*Salix* spp.) uniquely combine ecological resilience with therapeutic value, remediating polluted environments while supporting human wellbeing. This review synthesizes recent literature on the established role of *Salix* spp. in phytoremediation and growing contribution to forest therapy through emissions of biogenic volatile organic compounds (BVOCs). As urbanization accelerates and environmental pressures intensify globally, *Salix* surprising adaptability and multifunctionality justify the utilization of this genus in building resilient and health-promoting ecosystems. The major points discussed in this work include willow-based phytoremediation strategies, such as rhizodegradation, phytoextraction, and phytostabilization, contribute restoring even heavily polluted soils, especially when combined with specific strategies of microbial augmentation and trait-based selection. *Salix* plantations and even individual willow trees may contribute to forest therapy (and 'forest bathing' approaches) through volatile compounds emitted by *Salix* spp. such as ocimene, β-caryophyllene, and others, which exhibit neuroprotective, anti-inflammatory, and mood-enhancing properties. Willow's significantly extended foliage season in temperate regions allows for prolonged 'forest bathing' opportunities, enhancing passive therapeutic engagement in urban green infrastructures. Famously, the pharmacological potential of willow extends beyond salicin, encompassing a diverse array of phytocompounds with applications in phytomedicine. Finally, willow's ease of propagation and adaptability make this species a convenient solution for multifunctional landscape design, where ecological restoration and human wellbeing converge. Overall, this review demonstrates the integrative value of *Salix* spp. as a keystone genus in sustainable landscape planning, combining remarkable environmental resilience with therapeutic benefit. Future studies should explore standardized methods to evaluate the combined ecological and therapeutic performance of *Salix* spp., integrating long-term field monitoring with mechanistic analyses of BVOC emissions under varying environmental stresses.

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1. Introduction

Global ecosystems are increasingly threatened by air pollution, soil contamination, biodiversity loss, and the rising incidence of environment-related diseases, all of which demand integrated, nature-based solutions capable of simultaneously restoring ecological balance and promoting human wellbeing. Although advances in environmental science and public health have provided important insights, a clear gap persists in connecting the phytoremediation [1] potential of plants with their therapeutic and cultural dimensions, since most studies have traditionally focused either on pollutant removal mechanisms or on psychosocial benefits of green spaces without integrating these perspectives. Willow trees (*Salix* spp.) emerge as particularly relevant in this context because they combine ecological resilience with pharmacological and sensory contributions: historically valued in traditional medicine, they are now recognized as effective bioindicators and agents of phytoremediation in contaminated soils and waters, while at the same time contributing to forest therapy [2] and nature-based healing through the emission of biogenic volatile organic compounds. By integrating environmental services with therapeutic outcomes, *Salix* species provide a model for sustainable landscape planning that addresses both ecological remediation and human health, thereby bridging the existing gap between environmental chemistry, restoration ecology, and wellbeing science, which constitutes the central focus of this review. Willow trees (Figure 1) are emblematic of riparian ecosystems and have been used for centuries in traditional medicine. In recent decades, their utility has expanded into environmental science, where they serve as bioindicators for air quality monitoring, since leaf traits such as stomatal density, stomatal pore surface, and stomatal resistance provide reliable indicators of atmospheric pollution levels [3] as well as agents of phytoremediation [1]. Simultaneously, the rise of forest therapy [2] and nature-based healing [4–6] has renewed interest in the sensory and biochemical contributions of willow to human wellbeing.


(A) **(B)**

Figure 1. Photographs illustrating: (A) a weeping willow (*Salix babylonica L.*) showing its full canopy and drooping branches; and (B) a twisted willow (*Salix matsudana 'tortuosa'*): tree with close-up of its characteristic contorted stems and foliage. Images (A) and (B) were captured in Pontelatone, Southern Italy (photo courtesy of G. N. Roviello).

Beyond these ecological and therapeutic roles, certain willow species such as *Salix babylonica* [7] (weeping willow, Figure 1A) are widely appreciated for their ornamental value in urban and garden landscapes. The weeping willow, with its graceful, pendulous branches, evokes tranquility and is often planted near lakes and reflective spaces for its aesthetic and emotional impact. Twisted cultivars like *Salix matsudana 'Tortuosa'* [8] (twisted willow, Figure 1B) add architectural interest with their contorted stems and curling foliage, making them popular choices in landscape design for visual drama and seasonal texture. These ornamental features not only enhance the visual appeal of green spaces but also contribute to the multisensory experience that supports psychological restoration. In the following review, the multifaceted roles of *Salix* species are examined in a holistic approach[9] through the lenses of ecological restoration, environmental chemistry, pharmacology, and human health. Drawing on recent findings, this synthesis explores how willow trees contribute to phytoremediation [10] through mechanisms such as rhizodegradation, phytoextraction, and phytostabilization, and how these same systems can be optimized via physiological trait selection, microbial augmentation, and integrated land management. Additionally, the review investigates the biogenic volatile organic compounds [11] emitted by willows, particularly in short-rotation coppice plantations, and their dual relevance to ecological interactions and therapeutic outcomes. Beyond their environmental services, *Salix* species are evaluated for their pharmacologically active compounds, such as salicin, and for their broader chemical diversity, which suggests promising multi-targeted applications in wellness and medicine. The cultural and sensory dimensions of willow are also considered, including traditional American Indigenous knowledge systems and the sensory enrichment offered by willow trees in urban landscapes.

Methodology

A systematic literature search was carried out to identify scientific publications on the multifunctionality of *Salix* species, with particular attention to phytoremediation, ecosystem services, biogenic volatile organic compounds, and therapeutic or wellbeing applications. Search terms included: “Salix phytoremediation”, “willow ecosystem services”, “volatile organic compounds”, “VOC”, “BVOC”, “forest therapy”, “nature-based solutions”, and combinations of them. Searches were performed across Google Scholar, PubMed, Scopus, and Web of Science. The initial pool consisted of 202 articles. Duplicates across databases, retracted publications, and non-English texts were excluded during screening. After applying these criteria, the final dataset comprised 108 articles suitable for review. Of the 108 articles included, 59 were published between 2020 and 2025, representing ≥ 50% of the total dataset, reflecting the growing scientific interest in willow research within the frameworks of human health benefits, ecosystem services and nature-based solutions.

2. Phytoremediation Potential of Willow Species

Willow species (*Salix* spp.) have been extensively studied for their capacity to remediate contaminated environments through phytoremediation [12–14], a plant-based strategy for mitigating pollution [15,16]. In fact, phytoremediation is a sustainable, plant-based strategy that uses vegetation to remove, stabilize, or transform environmental contaminants from soil, water, and air [17,18]. As for phytoremediation mechanisms, phytodegradation [19] is the process by which plants enzymatically break down organic contaminants into less harmful compounds, while phytovolatilization [20] refers to the uptake and transformation of pollutants that are subsequently released into the atmosphere through transpiration. Due to their high biomass production, rapid growth, deep-rooting system, and tolerance to pollutants, willows are particularly effective in the phytoremediation of soils contaminated with heavy metals and organic compounds. *Salix* species exhibit high potential due to their extensive root systems that stimulate rhizospheric microbial activity, rapid growth rates that ensure continuous biomass turnover, and elevated transpiration that facilitates contaminant mobilization. However, substantial differences exist among clones such as *S. viminalis* ‘Orm’, *S. alba*, *S. matsudana* × *alba*, *S. miyabeana* ‘SX61’, and Tangoio, which vary in their capacity for heavy-metal accumulation, biomass yield, and tolerance to stressors. These genotypic distinctions are critical for site-specific selection and for predicting long-term remediation outcomes. Equally important is the distinction between laboratory experiments and field-validated studies on *Salix* spp.: while controlled conditions often report higher efficiencies, long-term field trials reveal the complex dynamics of pollutant persistence, bioavailability, and system management.

2.1. Phytoremediation Mechanisms of Willow

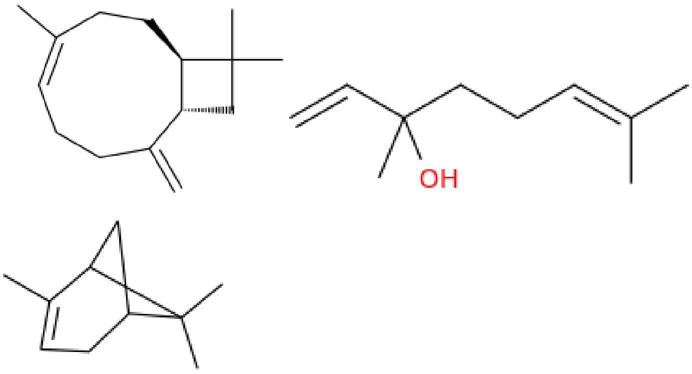
One key mechanism through which willows contribute to remediation is rhizodegradation [21,22], where root exudates stimulate microbial communities in the rhizosphere to degrade organic contaminants. For instance, a field study involving *Salix viminalis L.* ‘Orm’ planted in dredged sediment showed that mineral oil concentrations decreased by 57% in planted plots, compared to only 15% in fallow sediment. Notably, in the willow root zone, mineral oil degradation reached up to 79%. In contrast, polycyclic aromatic hydrocarbons (PAHs) [23] decreased more in fallow soils (32%) than in those with willow (23%), suggesting a selective effect based on pollutant type. Although willow demonstrated moderate uptake of heavy metals such as Cd, Cu, Pb, and Zn, the potential for phytoextraction was limited in this context [24].In addition to soil-based applications, willow-based systems are increasingly recognized for their capacity to remediate wastewater streams, particularly as these systems not only enhance plant growth and biomass yield but also efficiently remove nutrients such as nitrogen and phosphorus, thereby improving groundwater quality and maintaining ecological balance [25]. Willow-based systems are also employed in constructed wetlands and short-rotation coppice (SRC) plantations, particularly in Sweden, where nutrient-rich wastewaters (e.g., landfill leachate, sewage sludge, and industrial effluents) are applied to SRC willow to facilitate pollutant removal. The high evapotranspiration rates and frequent harvesting cycles contribute to the removal of heavy metals and organic compounds, while simultaneously enhancing biomass production for renewable energy. These systems offer a dual benefit: environmental cleanup and economic biomass valorization [26]. Long-term studies have confirmed the capacity of *S. viminalis* to remediate a variety of pollutants. Over a 10-year period at an industrially contaminated site, this species was shown to remove 21% of chromium, 30% of arsenic, 54% of cadmium, 61% of zinc, 62% of copper, 63% of lead, 87% of nickel, 53% of PCBs, and up to 73% of PAHs. The rate of pollutant removal was initially linear but plateaued over time, indicating variability in persistence and bioavailability among different contaminants [27]. Comparative studies between poplars and willows show that willow clones often accumulate more cadmium in shoot tissues. For example, the willow clone Tangoio accumulated up to 167 μg Cd g^{-1} dry matter, compared to 75 μg Cd g^{-1} in poplar clones. However, the application of chelating agents to enhance uptake must be approached cautiously, as some agents negatively impacted growth. Field extrapolations suggest that willow could potentially remove significant historical cadmium contamination from fertilized pasturelands in a single cropping cycle [28]. Genotypic variation within *Salix* species strongly influences phytoremediation success. Of 20 willow genotypes tested over two years on heavy metal-contaminated soils, 11 demonstrated favorable combinations of survival, biomass yield, and metal accumulation. Certain genotypes were more efficient at partitioning metals into wood tissues, which is preferable for post-harvest metal recovery and energy conversion [29]. In the United States, willow biomass research has evolved beyond energy production to encompass phytoremediation, snow fencing, and riparian buffers. Despite economic constraints tied to biomass pricing, policy incentives and improved yield through breeding and management continue to support willow deployment for environmental services, including site remediation [30]. Willow clones also exhibit distinct physiological responses to nutrient and water availability, which influence their efficiency in pollutant uptake. Studies have revealed significant inter-clonal variation in nitrogen and water-use efficiency, biomass allocation, and leaf retention, critical traits for selecting suitable genotypes for phytoremediation in diverse environmental conditions [31].

2.2. Salix Ecological Adaptability Economic Benefits and Microbial Synergies

From an ecological perspective, *Salix* spp. are well-suited for restoring polluted ecosystems. Their fast growth, tolerance to heavy metals, and adaptability across ecological niches make them potent candidates for remediation of heavily degraded sites [32]. Phytoremediation also offers quantifiable economic benefits. In cadmium-contaminated regions near Freiburg, Germany, willow cultivation allowed for land revaluation, enabling the return to high-value vegetable production within six years. The phytoremediation function was estimated to provide economic value up to €14,850 ha^{-1} over 20 years using hedonic pricing models [33]. Trait-based approaches to willow selection have further refined phytoremediation efficiency. Studies have shown that willow traits related to the “fast–slow” plant economics spectrum, such as specific leaf area and root investment, predict contaminant uptake across multiple elements. These findings support the development of predictive, ecophysiologically grounded phytoremediation strategies [34]. However, high evapotranspiration rates in mature willow plantations may induce a "contaminant pumping effect," concentrating pollutants near root zones rather than eliminating them. For example, higher levels of hydrocarbons and PAHs were observed under intact *Salix miyabeana* 'SX61' stands than in cut controls, suggesting complex spatial dynamics in pollutant migration and potential need for careful system management [35]. Willows have also shown efficacy in boron removal when used in constructed wetlands. In simulated wastewater, *S. anatolica* and *S. alba* removed up to 65% of boron, with more efficient phytostabilization than phytoextraction. Boron-loaded biomass was further utilized in the production of fire-resistant panels, offering a secondary valorization pathway [36]. Enhancing phytoextraction through microbial support has also yielded promising results. Bioaugmentation with beneficial bacteria (e.g., Rahnella sp.) and compost addition increased both biomass and metal uptake in *S. viminalis* grown in Cd-Zn-Pb contaminated soils. Despite some inconsistencies, combining high-performing clones with rhizospheric bacteria shows potential for improving metal extraction [37]. Experimental plots planted with willow microcuttings (e.g., *Salix matsudana* × *alba*) demonstrated successful establishment and moderate Zn removal (estimated at 300 g ha^{-1} $year^{-1}$) even under artificial contamination with Pb and Cu, particularly when supported with organic composts [38]. The role of rhizospheric microbial communities in metal uptake is further demonstrated by studies showing genotype-specific microbial assemblages that influence phytoextraction efficiency. Plant growth-promoting bacteria (PGPB) and mycorrhizal fungi are key players in modulating both biomass production and metal accumulation in willow genotypes [39]. Recent advances also focus on microbial inoculants, such as *Stenotrophomonas maltophilia* strain SaRB5, which enhanced willow biomass by 72% and cadmium uptake by 129%. This strain also reshaped the rhizosphere microbiome by recruiting beneficial nitrogen-fixing and metal-mobilizing microbes, thus improving phytoextraction via both direct and indirect mechanisms [40]. Endophytic fungi such as *Serendipita indica* have similarly enhanced Cd uptake by altering the rhizosphere chemistry, increasing nutrient availability, and supporting beneficial microbial networks. Such mutualistic systems between microbes and willow represent a significant frontier in improving phytoremediation outcomes [41]. In summary, *Salix* spp. exhibit substantial potential in phytoremediation through a variety of mechanisms and the integration of physiological trait selection, microbial augmentation, and system-level management strategies, that can significantly enhance the environmental and economic outcomes of willow-based remediation systems. Overall, willow species (*Salix* spp.) demonstrate remarkable versatility in phytoremediation, combining mechanisms such as rhizodegradation, phytoextraction, phytostabilization, phytodegradation, and limited phytovolatilization with different phytoremediation applications. Their fast growth, high biomass, and tolerance to pollutants, together with advances in genotypic selection, microbial augmentation, and system-level management, highlight willows as sustainable and economically valuable tools for restoring contaminated environments and enhancing ecosystem resilience.

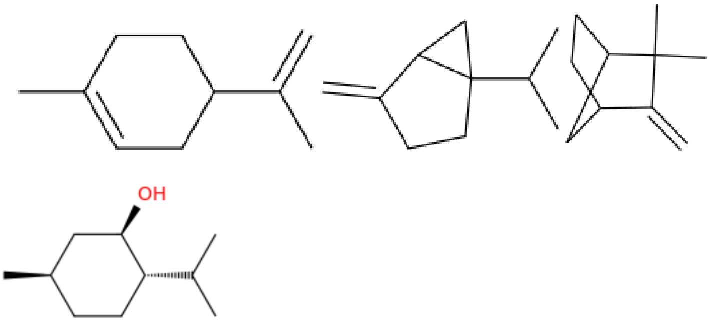
3. Volatile Emissions and Forest Therapy: Willow-Derived Biogenic Volatile Organic Compounds

Willow species, widely cultivated in Europe for bioenergy, are known for their substantial emissions of biogenic volatile organic compounds (BVOCs). These compounds, while sometimes raising concerns about atmospheric reactivity and potential impacts on air quality, as in the case of isoprene that can contribute to ozone formation and elevate concentrations by several tens of ppb [42], also hold promise for forest-based therapeutic benefits due to their bioactive properties [43]. A wide range of chemical classes, terpenoids, aldehydes, alcohols, esters, and other organic volatiles [44], are emitted by willows under different environmental and biological conditions, and some, such as α-pinene, have been identified as possessing potential health-promoting properties [45]. Most of these molecules share key structural features: they are predominantly nonpolar, which facilitates volatility and membrane permeability; many possess cyclic or bicyclic frameworks, contributing to their stability and receptor binding specificity. Leaf-scale studies across two growing seasons in Swedish managed willow plantations have revealed that BVOC emissions are dominated by isoprene, accounting for over 96% of total emissions by mass [46]. However, other compounds with more direct biological and ecological functions are also emitted as discussed below (Figure 2, Table 1) [47].



β-caryophyllene linalool

α-pinene



limonene sabinene camphene L-menthol

Figure 2. Chemical representations of selected volatile compounds emitted by willow species endowed with therapeutic properties discussed in this work [47–49].

Table 1. Volatile organic compounds from willow and therapeutic potential of some of these molecules.

Compound	*Salix* species	Reference	Beneficial effect	Reference
Isoprene	*Salix viminalis*, *Salix myrsinites*	Karlsson et al. 2021, Swanson et al. 2021	–	–
β-caryophyllene	*Salix viminalis*, *Salix nigra*	Karlsson et al. 2021, Braccini et al. 2015	Anti-inflammatory, anxiolytic, immune-modulating	Dahham et al. 2015, Bilbrey et al. 2022
Ocimene (cis- and trans-)	*Salix viminalis*, *Salix nigra*	Karlsson et al. 2021, Braccini et al. 2015	Pleasant scent, neuroprotective	Suresh, Sood and Vellapandian 2024
α-farnesene	*Salix spp.*	Karlsson et al. 2021	–	–
Hexanal	*Salix viminalis*	Toome et al. 2010	Calming scent, stress reduction	Pino and Trujillo 2021
Nonanal	*Salix babylonica*	Shaoning et al. 2023	–	–

Compound	***Salix* species**	**Reference**	**Beneficial effect**	**Reference**
Linalool	*Salix viminalis*	Karlsson et al. 2021	Sedative, anxiolytic, mood-enhancing	dos Santos et al. 2022, Linck et al. 2010
(E)-4,8-dimethyl-1,3,7-nonatriene	*Salix myrsinites*	Swanson et al. 2021	—	—
α-pinene	*Salix cinerea, Salix spp.*	Mezzomo et al. 2024, Morrison et al. 2015	Anti-inflammatory, bronchodilatory, cognitive support	Rahimi et al. 2023, Allenspach and Steuer 2021, Gardiner 2025
Delta-3-carene	*Salix spp.*	Morrison et al. 2015	—	—
β-pinene	*Salix spp.*	Morrison et al. 2015	—	—
Limonene	*Salix phylicifolia, Salix spp.*	Hakola et al. 1998, Morrison et al. 2015	Antidepressant, stress reduction	Alkanat and Alkanat 2024, d'Alessio et al. 2014
Sabinene	*Salix phylicifolia*	Hakola et al. 1998	Antioxidant, anti-inflammatory	Ozah et al. 2025, Park et al. 2019
Camphene	*Salix phylicifolia*	Hakola et al. 1998	Respiratory stimulant, antimicrobial	Ambroziak 2020
1,4-dimethoxybenzene	*Salix caprea, Salix atrocinerea*	Füssel 2007	Floral scent, mood-enhancing	Karimi et al. 2015
Lilac aldehyde	*Salix caprea, Salix atrocinerea*	Füssel 2007	Floral aroma, calming effect	Dacho and Szolcsányi 2021
Decanal	*Salix babylonica, Salix nigra*	Shaoning et al. 2023, Braccini et al. 2015	Soothing scent, insect-repellent	Kim et al. 2019
Undecane	*Salix nigra*	Braccini et al. 2015	—	—
Cis-3-hexenyl acetate	*Salix suchowensis*	Ling et al. 2021	Calming, masking other scents	Pino and Trujillo 2021
Cis-3-hexen-1-ol	*Salix babylonica*	Shaoning et al. 2023	Fresh green aroma, stress reduction	Bandiera et al. 2024
L-menthol	*Salix babylonica*	Shaoning et al. 2023	Cooling, analgesic, respiratory relief	Kanezaki et al. 2020, Eccles 2003
Azulene (chamomile blue)	*Salix babylonica*	Shaoning et al. 2023	Anti-inflammatory, calming	Ozah et al. 2025

Notably, monoterpenes (MTs) such as ocimene (cis- and trans-β-ocimene) and sesquiterpenes (SQTs) like β-caryophyllene and α-farnesene exhibited significant seasonal patterns [49]. The highest emissions of SQTs occurred during late summer (August), with canopy position playing a critical role: sun-exposed leaves emitted more MTs and SQTs than shaded foliage [49]. Additionally, non-terpenoid volatiles such as hexanal and nonanal increased during pathogen attack (e.g., *Melampsora* spp. infection), indicating a defensive or stress-induced response [49]. These compounds belong to the broader category of green leaf volatiles (GLVs), which are often involved in plant-insect and plant-human interactions [49,50]. Importantly, GLVs are primarily produced or emitted in response to mechanical injury, which can result not only from insects and human activity but also from a variety of other biotic and abiotic factors [50–52]. A study of four commercial willow varieties for bioenergy revealed interclonal differences in volatile emissions. Isoprene dominated, while MTs and SQTs (e.g., linalool, ocimene, β-caryophyllene) varied across clones. Younger plants emitted more non-isoprenoid VOCs than older ones, highlighting developmental and genetic influences on BVOC profiles [53]. In Arctic tundra, warming amplified isoprene emissions in *Salix myrsinites*. Specific insects induced GLVs (e.g., DMNT) and SQTs under ambient conditions, but warming suppressed these herbivore-driven volatiles, indicating temperature-dependent modulation of plant defense signals [54]. Willows produce both non-volatile phenolic-based defenses (e.g., tannins, flavonoids, salicinoids) and inducible VOCs [55]. Herbivore-specific induction patterns were observed, with compounds like α-pinene positively correlating with bird predation of herbivores on *Salix cinerea* [55]. Interspecific variation was stronger for non-VOCs (e.g., salicinoids), while VOCs such as monoterpenes and GLVs showed lower intraspecific variation, potentially enhancing indirect defenses by attracting herbivore enemies [55]. Biotrophic fungal infections (e.g., rust) markedly altered willow VOC emissions [56]. Isoprene emissions decreased, while stress-related volatiles such as (Z)-β-ocimene, various SQTs, and lipoxygenase (LOX) products (e.g., hexanal) significantly increased, by as much as 175-fold in the case of SQTs [56] with these changes exhibiting clear temporal patterns tied to infection progression and leaf necrosis [56]. Seasonal studies in boreal environments found that *Salix phylicifolia* emitted high levels of trans-β-ocimene, sabinene, camphene, and limonene, especially during early leaf development and flowering [57]. In addition, light hydrocarbon emissions such as 1-butene**,** ethene, and propene were observed during blooming periods [57]. Remarkably, these compounds may contribute to pollinator attraction or act as environmental signals [57]. Floral scent emissions from species such as *Salix caprea* and *Salix atrocinerea* were found to contain 1,4-dimethoxybenzene, lilac aldehyde, and trans-β-ocimene, with circadian rhythms influencing their abundance [58]. These compounds were electrophysiologically active in both diurnal (e.g., *Apis mellifera*) and nocturnal pollinators (e.g., *Orthosia gothica*), indicating roles in enhancing reproductive success, with gender differences in scent composition and nectar sugar content further influencing pollinator behavior [58]. Headspace analysis showed that volatile blends from *Salix triandra* deterred specific beetles, while *Salix suchowensis* emitted attractants such as o-cymene [59]. Notably, cis-3-hexenyl acetate was found to mask o-cymene's attractant effect, offering potential for biocontrol applications using plant-based semiochemicals [59]. **Behavioral assays showed sawflies preferred *Salix nigra* over *S. viminalis*, due to higher volatile levels (β-ocimene, β-caryophyllene, undecane, decanal), with cuticular waxes with alcohols, esters, and acids being also associated with oviposition sites** [60]. *Salix humboldtiana* inoculated with arbuscular mycorrhizal fungi showed reduced total VOC emissions, especially of SQTs, and lower herbivory rates by *N. oligospilus*. This highlights a functional link between microbial symbiosis and reduced defensive signaling costs via VOCs [61]. **UK field studies identified *Salix* spp. as major emitters of isoprene, α-pinene, δ-3-carene, β-pinene, and limonene, with α-pinene peaking at 803 μg g^{-1} h^{-1} with emissions varying across sites and years but exceeding those of conventional crops, which demonstrates willow's dual role as a renewable energy source and contributor to atmospheric chemistry** [62]. A comparative study in Beijing identified α-pinene, (Z)-3-hexenyl acetate, cis-3-hexen-1-ol, L-menthol, decanal, nonanal, and chamomile blue (azulene) among beneficial BVOCs emitted by *Salix babylonica*. Diurnal trends revealed maximum emissions around midday, and seasonal shifts showed olefins dominating in spring, aldehydes in summer, and alcohols in autumn. Such profiles suggest that *S. babylonica* may offer substantial therapeutic benefits, especially when incorporated into urban greening and forest therapy planning [48].

3.1. Willow Volatiles Enhancing Forest Therapy and Human Wellbeing

Analysis of VOCs in *Salix matsudana* bark revealed a complex mixture of organic acids, esters, and alcohols, including compounds like 1,2-benzenedicarboxylic acid, bis(2-methylpropyl) ester, glycolaldehyde dimer, and catechol, suggesting a rich source of bioactive volatiles with potential therapeutic and industrial applications [63]. Interestingly, the human health benefits of some of the volatile compounds emitted by willow are well known and these compounds, released under varying environmental and biological conditions, contribute to the therapeutic potential of willow-rich environments and may enhance the experience of forest therapy and forest bathing [64–67]. Compounds such as linalool [68], limonene [69], and cis-3-hexen-1-ol [70] are associated with mood enhancement and stress reduction. Linalool [71] and limonene [72] are widely recognized for their calming and anxiolytic effects, while ocimene [73] and green leaf volatiles like hexenyl acetate [74] contribute to a fresh, soothing olfactory profile. These volatiles are emitted by species including *Salix viminalis*, *Salix babylonica*, and *Salix nigra*, and their release is influenced by seasonal dynamics, canopy exposure, and plant age. Volatiles with anti-inflammatory properties include β-caryophyllene [75], α-pinene [76], and sabinene [77], and azulene [77]. Β-caryophyllene, found in *Salix viminalis* and *Salix nigra*, interacts with cannabinoid receptors and may reduce inflammation [78]. α-pinene [79] and sabinene [80], emitted by *Salix cinerea* and *Salix phylicifolia*, support respiratory health and exhibit antimicrobial activity. Respiratory support is further provided by α-pinene [81], camphene [82], and L-menthol [83]. These compounds, released by *Salix babylonica*, *Salix phylicifolia*, and other willow species, are traditionally used to ease breathing and reduce airway irritation. L-menthol, in particular, offers a cooling sensation and mild analgesic properties that benefit respiratory comfort [84]. Floral volatiles such as 1,4-dimethoxybenzene [85], lilac aldehyde [86], and decanal [87] enhance the sensory experience of natural environments. Emitted by *Salix caprea*, *Salix atrocinerea*, and *Salix babylonica*, these compounds may contribute to emotional uplift and olfactory stimulation, engaging both diurnal and nocturnal pollinators and potentially influencing human mood through scent. Remarkably, the above mentioned ocimene has demonstrated neuroprotective properties in a rotenone-induced rat model of Parkinson’s disease [88], with the study revealing that ocimene treatment significantly reduced α-synuclein aggregation in brain tissue, lowered acetylcholinesterase (AchE) levels, and increased D2 receptor expression, all biomarkers associated with improved motor function and reduced neurodegeneration. Moreover, behavioral tests showed enhanced motor activity and reduced anxiety in ocimene-treated groups compared to controls. Overall, these findings suggest that ocimene may offer therapeutic potential in mitigating Parkinsonian symptoms and protecting dopaminergic neurons, positioning it as a promising candidate for further investigation in neurodegenerative disease treatment [88]. In summary, willow species emit diverse volatile organic compounds that support ecological functions and offer therapeutic benefits. Beyond their role in bioenergy and phytoremediation, these volatiles contribute to plant defense, pollinator attraction, and human wellbeing, including mood enhancement and stress reduction. Seasonal and genetic factors shape emission profiles, while stressors further modulate release. By combining pollutant removal with volatile-mediated sensory enrichment, willow plantations provide both ecological restoration and psychological restoration, positioning them as valuable components of integrated landscape design.

4. Therapeutic Applications and Pharmacological Properties of Willow and its Bioactive Compounds

4.1. Historical Therapeutic Use of Willow

The bark of willow trees contains salicin [89], a glycoside that metabolizes into salicylic acid, the active compound in aspirin. Beyond salicin, willow species produce flavonoids, tannins, and polyphenols with biological properties [90]. Extracts from *Salix spp.* have been used in traditional and modern herbal medicine to treat pain, fever, and inflammatory conditions [91]. The willow tree holds an esteemed place in the history of medicinal plants, most notably for its association with the development of acetylsalicylic acid, commonly known as aspirin [91]. Early records dating back to Assyrian (4000 BC) and Sumerian (3500 BC) civilizations noted the therapeutic use of willow bark with the pharmacologically active compound salicin being first structurally characterized in 1838, which revealed a composition of D-glucose and salicyl alcohol, and ultimately laid the groundwork for aspirin synthesis [91].

4.2. Willow in Modern Medicine

Moreover, modern pharmacological investigations have reaffirmed willow bark's role as a natural source of salicylates [92]. Comprehensive phytochemical analyses of *Salix* species have identified over 320 secondary metabolites, encompassing a wide spectrum of bioactive compounds [93]. These include flavonoids (e.g., flavonols, flavanones, anthocyanins), phenolic glycosides, organic acids, terpenes, simple phenolics, and volatile compounds [93]. Collectively, these constituents contribute to willow's multifunctional pharmacological profile, which spans analgesic, antioxidant, anti-inflammatory, anticancer, cytotoxic, antidiabetic, antimicrobial, anti-obesity, neuroprotective, and hepatoprotective activities [93]. Among specific species, *Salix alba* (white willow) has been widely employed in traditional medicine for its anti-inflammatory, antipyretic, and analgesic effects [94]. Recent studies revealed its bark extract contains phenolic constituents such as salicin, salicylic acid, salidroside, saligenin, and tremulacin [94]. As for toxicity of willow products, its extracts exhibited low genotoxicity at moderate doses, and cytotoxic effects were observed at higher concentrations (≥200 μg/mL), with cell viability falling below 70% [94]. Genotoxic effects were more evident in the absence of liver enzyme metabolism, indicating the need for metabolic activation to modulate toxicity [94]. Furthermore, clinical trials administering 120–240 mg of salicin daily for up to 8 weeks reported no serious adverse effects in adults [92]. Minor adverse effects, including gastrointestinal discomfort and rare allergic reactions, have been documented [92]. However, caution is advised due to known risks associated with salicylates, particularly for children (due to the risk of Reye syndrome), pregnant or breastfeeding women, and individuals with aspirin sensitivity [92]. Therefore, the United States Pharmacopeia has consequently included cautionary labeling requirements in its *Salix* species monograph to address these concerns [92]. Beyond its role as an analgesic and anti-inflammatory agent, willow biomass, especially bark and wood, offers potential for high-value bioactive substance production. In a comparative study of ten willow genotypes, interspecific hybrids such as *Salix purpurea* × *S. daphnoides* UWM 029 and UWM 193 demonstrated both high biomass yields and elevated salicin concentrations. Notably, *S. purpurea* × *S. daphnoides* bark contained up to 29 mg/g salicin, with annual yields surpassing 92 kg/ha. These hybrids also delivered high energy yields, reinforcing their potential dual role in pharmacological and bioenergy applications [95]. Notably, willow-derived extracts have also demonstrated anticancer properties. In studies involving *Salix mucronata* (safsaf willow), aqueous leaf extracts significantly inhibited tumor growth in mice injected with Ehrlich Ascites Carcinoma Cells. Treated groups showed a 35-day delay in mortality, while in vitro assays revealed apoptotic cell death in up to 80% of malignant cells from leukemia patients (ALL and AML). DNA fragmentation patterns and cytological assessments supported apoptosis induction as the primary mechanism of action, suggesting that willow metabolites may serve as tumor inhibitors [96]. In summary, *Salix* species combine historical medicinal use with modern therapeutic promise. Beyond salicin, their diverse chemical profile suggests multi-targeted applications in both pharmaceutical and wellness contexts, warranting continued investigation. .

5. Urban Willows: Integrating Green Infrastructure and Public Health

In urban settings, willow trees play a vital role in green infrastructure by stabilizing soils, filtering runoff, and enhancing biodiversity. Their integration into urban green infrastructures [97,98] not only supports ecological restoration but also offers meaningful health benefits through passive exposure to nature. Urban willow plantations can be intentionally designed to serve dual purposes: environmental remediation (e.g., heavy metal uptake [99]) and human wellbeing. These restorative landscapes promote mental health, encourage physical activity, and foster social connection.

5.1. Willow in Urban Parks as Multisensory Therapeutic Landscapes

Stanley Park in Vancouver, Canada, provides a compelling example of this dual functionality [100]. Within its classification of therapeutic plants, *Salix babylonica*, the weeping willow, is recognized for its sensory and therapeutic value across three of the five senses: sight, sound, and touch. Visually, its

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elegant, drooping branches create a calming aesthetic often associated with reflective environments, such as lakesides and gardens. This visual presence alone can reduce stress and promote relaxation. Auditorily, the tree's slender branches and narrow leaves produce soft rustling sounds when moved by the wind, contributing to a soothing natural soundscape that supports mindfulness and emotional regulation [100]. Tactilely, the texture of its bark and the pliability of its hanging branches invite gentle physical interaction, offering grounding sensory input that can be especially beneficial in therapeutic horticulture or for individuals with sensory processing needs. These qualities align closely with the broader role of urban forest parks (UFPs) [101] as essential components of urban development. UFPs are increasingly recognized as critical community resources that support physical activity and mental health across all age groups. During the COVID-19 pandemic, urban parks saw a dramatic rise in visitation, as people sought safe and restorative green spaces [102]. The multisensory engagement offered by therapeutic landscapes, through sight, sound, touch, smell, and even taste, has proven to be a powerful conduit for reconnecting people with nature. Canada, with its longstanding tradition of designing and conserving UFPs, offers valuable insights into this approach and the study conducted on Stanley Park revealed that the park's rich plant diversity contributes to a functional therapeutic environment perceived through all five senses, with visitors reporting high levels of satisfaction and a strong reliance on these sensory experiences [100]. In summary, *Salix* is suitable for the creation of sensory gardens which are also used in therapeutic practices. In fact, willow trees in urban green infrastructures aid ecological restoration and enhance wellbeing through multisensory experiences, making them a vital green infrastructure that strengthens social connection in urban parks, where diverse plant life supports a fully immersive sensory landscape perceived through sight, sound, and touch.

6. Conclusions

Willow trees embody a rare synergy between ecological utility and therapeutic potential. From remediating polluted landscapes to soothing the human mind and body, *Salix* species offer a model for integrated approaches to environmental and public health. Their role in phytoremediation is well-established, and emerging evidence supports their contribution to forest therapy through volatile emissions. As urbanization intensifies, climate changes affect plant health [103,104] and environmental challenges grow, willow's versatility makes it a valuable ally in designing resilient, health-promoting ecosystems. *Salix* species show strong potential in phytoremediation through mechanisms such as rhizodegradation, phytoextraction, and phytostabilization, with outcomes enhanced by trait selection, microbial support, and system-level management. Beyond ecological utility, willows emit diverse volatile compounds that aid plant defense, attract pollinators, and offer therapeutic benefits for human wellbeing, including stress reduction and forest therapy effects. Seasonal, genetic, and environmental factors shape these emissions, positioning willow plantations as dual-function systems that deliver ecological restoration and psychological enrichment. With their historical medicinal role and chemical diversity extending beyond salicin, willows represent promising candidates for integrated landscape design and future pharmaceutical and wellness applications. Taken together, willow plantations exemplify how ecological restoration and human wellbeing are interconnected, aligning their multifunctionality with established conceptual frameworks of ecosystem services and nature-based solutions. Shrub willow, for instance, has been developed as a bioenergy feedstock in temperate regions with marginal croplands, while simultaneously providing ecosystem services such as reduced nutrient loss and erosion, enhanced biodiversity, and improved climate resilience [105]. Likewise, streambank erosion control increasingly relies on nature-based solutions, particularly soil and water bioengineering techniques that employ living willow material to stabilize substrates and protect biodiversity. Distinct morphological traits among willow species highlight the importance of species-specific strategies, reinforcing their role in tailored ecosystem management [106]. As for urban environments, willow trees contribute not only to phytoremediation processes and biodiversity, but also to human wellbeing by offering multisensory therapeutic experiences, such as the calming visual presence of

Salix babylonica's drooping branches, the soothing rustle of its leaves in the wind, and the tactile engagement of its flexible limbs, making urban willow trees valuable components of green infrastructures that promote mental health, physical activity, and social connection. Moreover, the forest bathing contribution of willows in urban parks is also an important secondary effect of green areas enriched with this tree species, offering passive therapeutic benefits through their extended foliage season [107], calming visual presence, and aromatic emissions. Their ability to retain green leaves late into autumn in temperate regions [107] allows for prolonged engagement with restorative and forest bathing landscapes, making willow-lined paths and groves accessible for sensory immersion well into the late season. This seasonal advantage enhances the design of health-promoting ecosystems, where phytoremediation, biodiversity support, forest therapy, and psychological restoration converge in a single, low-cost, and easily propagated [108] solution. Concerning limitations of this study, current evidence on the therapeutic effects of willow-emitted molecules remains insufficiently characterized, and the direct impact of inhaled volatile compounds on human health is still unexplored. Future research should therefore establish standardized approaches to evaluate the dual ecological and therapeutic functions of *Salix* spp., integrating long-term field monitoring with mechanistic analyses of volatile organic compound emissions under diverse environmental stressors.aken together, the aspects explored in this work highlight the multifaceted value of willow as a keystone genus in sustainable landscape design. Whether in phytoremediation systems, urban green infrastructures, bioenergy plantations, or culturally significant ecosystems, *Salix* species offer a compelling blueprint for harmonizing ecological resilience with human health and wellbeing.

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