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Review

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Psychological and physiological responses to smells from nature—potential health benefits for urban dwellers

Francesca Taufer[1] ✉, Anna María Pálsdóttir[2] & Marcus Hedblom[1]

An increasing number of studies explore the health benefits of nature exposure, yet few examine its effects through smells. This paper aims to review the literature on the psychological and physiological effects of smells emitted by natural sources. Findings from 30 studies show that smells from nature reduce stress, promote relaxation and enhance well-being. Their integration into cities can enhance nature exposure, urban satisfaction and promote healthier environments.

The majority of the global population dwells in cities[1], where rates of mental illness and stress disorders are higher than in rural areas[2,3]. Consequently, the need to integrate health and well-being into urban planning and governance is growing[4,5] and is highlighted in global policies and guidelines suggesting how to 'ensure healthy lives and promote well-being for all at all ages' for a more sustainable future[6]. Exposure to urban green spaces or nature is one potentially important way forward towards better health[7]. There is increasing evidence that exposure to nature can have positive effect on physical and mental health, promoting increased well-being[8,9], stress reduction[10,11] and positive long-term benefits for chronic diseases and cognitive functions[12]. However, the full extent of how different qualities of nature affect us, through self-evaluation or psychophysiological measures, is not fully understood. By investigating psychological and physiological responses elicited by natural stimuli, it is possible to better understand the details of what enhances potential health benefit in natural settings. This is crucial if we aim to design and manage healthy environments close to where we live. Health benefits include physiological changes in individuals, such as effects on blood pressure, the immune system, or the autonomic nervous system, as well as psychological benefits, such as supporting mental health and well-being by reducing stress levels or eliciting positive feelings[7,13]. Inputs from all our senses, such as hearing, sight, touch, taste and smell, play an important role in how humans experience the world and connect with nature. Sight is considered the dominant sense in humans, and processing visual information seems to dominate over the processing of information from other sensory modalities[14]. Accordingly, most research on urban green spaces and human health has primarily focused on the visual qualities of the surrounding environment[15], while less is known about the importance of sounds, smells, and tactile elements in the beneficial effects of experiencing nature[16–18]. However, the senses do not function independently but operate together, providing integrated multisensory information[17]. All senses influence mental health and well-being in various ways (e.g. reducing distress and monotony, fostering a sense of belonging and safety), emphasizing the need to consider multisensory experiences in urban planning to support mental health and well-being in cities[19].

Additionally, human senses are much more receptive to smell than previously thought[20]. Smells provide important information about potential hazards, social interactions, and strongly influence how people act, think and behave[21]. Smells also play a vital role in perceiving the surrounding environment (e.g. the smell of smoke), shaping how people interact with it[22]. The experience of smells is essential in people's everyday lives, and smells are often considered key elements for fully experiencing an environment, especially when combined with stimuli from other sensory modalities[23]. One way to describe the relationship between human experiences of smells and the surrounding environment is through the concept of "smellscape". Smellscape is defined as "the totality of the olfactory landscape as perceived and understood by an individual"[24]. Xiao et al.[25] reveal that smells are "spatial-emotional intermediary, bridging interpersonal experiences of smells and the social-spatial structure of place". Thus, smellscape are an intangible element of a place that contribute to creating place-identity for communities, enhancing space qualities, and valuing its cultural heritage[26,27]. Smellscapes play a vital role in experiencing a place and may induce a sense of belonging[28]. Different cultures have different traditions for creating and value smellscapes, as seen in the "One Hundred Sites of Good Fragrance" across Japan or the creation of odour-themed features in the streets of Grasse, France[24].

The sense of smell, or olfaction, stands out from other sensory systems. It is more potent than our other senses in evoking long-term memories, modulating the autonomic nervous system, and triggering both negative

[1]Swedish University of Agricultural Sciences – Department of Urban and Rural Development, Uppsala, Sweden. [2]Swedish University of Agricultural Sciences – Department of People and Society, Lomma, Sweden. ✉e-mail: francesca.taufer@slu.se

and positive emotions[29]. Much of these effects can largely be explained by the unique aspects of neuroanatomy, where the olfactory system has unfiltered access to the brain via its non-obligatory thalamic relay, as well as the fact that the amygdala (a brain structure implicated in processing saliency and emotion), hippocampus (memory encoding), hypothalamus (body homeostasis regulation) are all only two synapses away from the olfactory receptors[30]. The perception of smells is highly subjective, influenced by many individual aspects (e.g. age, gender, culture, past experiences, familiarity), as well as environmental features (e.g. weather, temperature), spatial patterns and human activities[31,32]. Looking on objective physiological measurement, smells seem to have even greater effects in facilitating physiological health benefits than other senses. In a multisensory study in a virtual reality comparing three different environments (a forest, a park and an urban area), Hedblom et al.[33] found that olfactory stimuli were more effective in reducing stress than visual or auditory stimuli. The stress-reducing effects were higher in the two natural environments compared to the urban area. The olfactory stimuli were congruent to the specific environment, such as smell of grass in the park, fir and mushrooms in the forest and tar and diesel in the urban area, thus smells from nature seem to be particularly important.

To date, smells in cities have mainly been highlighted for its negative effects, focusing on the elimination of bad odours and control of odour pollution rather than for their potential positive benefits[34]. Existing policies and legislation related to smells in cities focus on controlling odour emission of substances that result to be harmful to humans, or on management of air quality levels[24,35]. There´s no current distinction on how to managed smells perceived as pleasant or unpleasant[35]. Urban planning focusing on the elimination of smell pollution may result in a deodorization of places with a possible loss of sense of place and a collection of sensorial experiences[28]. Thus, by acknowledging in current policies the importance of positive aspects of smells, it is possible to design more meaningful environments[28]. Understanding the potential health benefit of experiencing smells in cities will permit us to use smells as a resource to create healthier and sustainable environments.

Research on the effects of exposure to smells have largely focused on stimuli that mainly include natural essential oils, aromatic, volatile liquids extracted from different parts of plants (e.g. flowers, stems, leaves or roots) or wood material[36,37] through various techniques and named according to the plant from which they are derived[38]. Inhalation of these essential oils has been shown to result in changes in brain activity[39] and autonomic nervous system responses[40], an increase in mental and physical relaxation[36,41], positive effects on the immune system[42], beneficial influence on several conditions such as anxiety, insomnia, stress and pain, with a general increase in well-being[43,44]. Although essential oils are products extracted from part of plants, they lack the complexity of smells of nature that we as humans experience from real settings. Furthermore, smells are perceived within a context, and smells may be tied to an individual´s sense of place, often calling to mind associations with, or memories of, specific landscapes[45]. The chemical profile of an essential oil varies depending on the technique used for extraction, and several elements can influence the quality, quantity and composition of the extracted product[46], making it almost impossible to reproduce the existing smells found in natural settings. Moreover, extracting essential oil requires large quantities of natural materials, equipment, energy and time, and using smells emitted directly from natural sources represents a more sustainable approach to creating healthier environments. Nonetheless, our main encounter with smell from nature is through exposure to the real natural sources (e.g. various plants, trees, water and soil) in daily life and not through perfumes or essential oils. Thus, this review focuses on smells that are non-artificial and undiluted. Although we acknowledge that animals and humans are considered to be part of nature, this paper does not focus on animal or human smells. Instead, the focus is on those smells of nature that can be implemented, modified, and managed in urban environments. Thus, in this paper, the term smells from nature covers all scents emitted by components and phenomena within vegetation (e.g. different species of plants, trees or flowers), water bodies (e.g. rivers, lakes, marshes, rain) and originated from the ground (e.g. soil, moss, decaying leaves…).

Nature is rich in various smells, which represent a significant component of the natural environment and delineate its unique smellscape. Smells from nature are greatly influenced by environmental factors such as weather conditions, temperature, wind, the different seasons and time of day. Elevated temperatures, for instance, cause more molecules to evaporate from their sources, increasing the production of smell[24]. Plants and flowers may emit smells spontaneously or after being triggered by an external stimulus, such as rain, wind, high temperature or physical touch[47]. The changing of seasons and day-night cycles also influence the amount, concentration and variety of smells from nature emitted by plants, with some species releasing more smells during different times of the day, morning, evening or night[31], or in specific seasons[47]. Smells from nature are not distinctive of natural environments but can also be found in urban environments, within different spaces such as gardens, parks, flower beds, trees or plants spread throughout the cities, as well as in plants, wood or flowers in indoor environments. This suggests that smells from nature are accessible and readily available in everyday life experiences. Smells from nature are commonly perceived positively[25,48] and are frequently associated with positive feelings[16]. However, not all smells from nature are considered to be pleasant, for example, the smells of decaying leaves or stagnant water, although the perception of smell pleasantness is highly influenced by individual preferences[49]. Investigating the effects of both pleasant and unpleasant smells will help to understand the possibilities in implementing smells from nature in cities. Urban planning should consider how to implement positive smells, but at the same time how to possibly control and manage negative smells by eliminating, blocking or masking those smells from nature that result to be harmful or unpleasant for human. Additionally, implementing smells that result to be positive will aid in identifying and selecting plant species whose integration into urban planning may better support mental health and well-being.

One common method for evaluating the perception of smells is self-reported assessments conducted during a smellwalk, a sensory walk where participants focus on identifying, describing and evaluating the perceived smells in their surroundings[24]. In-situ studies evaluating the experience of smells in cities, such as smellwalks, are more ecologically valid than indoor studies, meaning they are more generalizable to real-world situations, making them more relevant for understanding the practical implication of smells in everyday life. Smellwalks focus on the collection of various existing smells but, beyond rating the simple degree of pleasantness of individual smells, they do not further investigate the emotions connected with or elicited by these smells[50]. As Parker et al.[50] noted in their review, current studies on smellwalks are exclusively centred around the urban context, with some including urban parks or open spaces to create olfactory profiles of various places in cities. There are some studies evaluating people's experience of natural smellscapes, although these studies also highlight the need to fill this gap further[16,18,24].

Regularly experiencing smells from nature is important for people's daily lives and the occurrence of these smells is linked to the amount of greenery in the area[34]. It has also been argued that 'as humanity becomes ever more urban and experiences ever less nature[7], we are cut off from an evolutionary library of olfactory experiences'[22], highlighting the need to integrate smells from nature in the urban context. Recent studies suggest that, given the history of olfactory responses to natural environments during evolution, smells from nature may be more important for human well-being than previously thought[22,33]. Bratman et al.[22] propose a conceptual framework that integrates olfaction into the understanding of the effects of the natural environment on human well-being. In their work, they highlight the various individual and environmental factors that mediate olfactory perception and how exposure to nature through olfactory pathways may affect a range of well-being aspects, such as emotion regulation, quality of life, and dietary choices[22]. Exposure to smell from nature may, therefore, represent a unique and important pathway between nature and well-being[22].

Despite the growing acknowledgement of the importance of experiencing smells from nature, little is known about how different smells from nature influence psychological and physiological responses

across various environments. Bringing together expertise from multiple fields, Bratman et al.[22] propose the following consensus statement: ´A better understanding of the relationship of human beings with natural olfactory environments can promote appreciation and revitalization of the natural world—and can thereby contribute to human well-being´. Thus, this study intends to better understand the relationship between humans and smells from nature. This paper aim to review the existing scientific literature on the effects of exposure to smells from nature in both indoor and outdoor environments, and explore the different ways in which smells from nature can affect psychological and physiological responses. The overall objective is to highlight both the methodological and application challenges, as well as the potential health benefits associated with smells from nature, to strengthen their implementation in cities to create healthier ecosystems.

Methods

Search strategy

The search was conducted in a structured way, using a combination of search terms. This structure consisted of three lists of terms, each one within different domains of interest: one list with terms related to smell and olfaction (e.g. "Smell", "Scent", "Odour", "Odour" …), a second one with terms related to the natural and urban environments (e.g. "Nature", "Outdoor", "Landscape" …) and a third one with terms describing human experiences (e.g. "Perception", "Wellbeing", "Stress" …). Each search string was composed of one term from the first list, one term from the second list and all terms from the third list combined using Boolean operators. The full list of search terms and combinations is presented in the Supplementary Information file.

The electronic databases searched included *Web of Science* (All Databases selected), *Scopus* and *APA PsycINFO*. The search was performed within "Topic" (*Web of Science*), "Article title, Abstract, Keywords" (*Scopus*) and "Document title & abstract" (*APA PsycINFO*). Only accessible publications written in English were selected, without any limitations on the publication year. The literature search was conducted between December 2023 and January 2024. Considering the multidisciplinary nature of the topic, no specific research areas were initially selected. However, if the number of documents retrieved for each search string was substantial, then the search was refined by subject area with some exclusion criteria applied to simplify the process. The total number of strings searched was 92 (see Supplementary Information for the search strategy).

In order to achieve a more successful search strategy, the original database search was then complemented with a snowballing methodology[51], using the references cited in some articles that were deemed of interest for the research. In addition, a screening and selection of documents citing some of the most relevant publications were made to further refine the results.

Selection criteria

Studies fulfilling the following five criteria were included in the review: (1) The study focuses on smells from nature emitted by the real natural source; (2) The study is conducted in an indoor or outdoor environment, and the source of the smell is derived from the real natural component or part of it (e.g. plants, flowers, wood) or the study took place in an outdoor environment with the presence of smells from the natural surroundings; (3) The participants are humans; (4) There is a focus on psychological and/or physiological responses to the smells from nature in the analysis; (5) In multisensory contexts, there is an analysis of the specific influence of olfactory stimulation.

Following these criteria, studies were excluded if they: (1) Focused on artificial smells; (2) Used essential oils or odorants not derived from a real natural source (or part of it); (3) Involved animals as subjects; (4) Lacked an investigation about the human experience of smells, for example, studies that focus on creating a smell evaluation of the place, mapping an olfactory profile of a specific environment, or improving or evaluating marketing and tourism; (5) Evaluated the general effects of a multisensory setting without specific details on olfactory influence and experience.

Study selection

After an initial screening of titles and abstracts, publications deemed irrelevant to our research topic were excluded. The full text of the relevant studies was then reviewed by the first author and included if it full filled the inclusion criteria (Fig. 1). The final number of studies included in the review was discussed and confirmed by all authors.

Results

The database searches resulted in more than 4800 papers. After the abstract and title screening, 30 studies met the inclusion criteria (Fig. 1).

Publication year

Of the selected studies, six were published before 2014, with the earliest dating back to 2008; eight were published between 2015 and 2020, and the remaining 16 studies were published after 2021. This data trend indicates that research on smells from nature is relatively new and that interest in the topic has grown in recent years.

Sample and study design

Details about the sample of the reviewed studies (i.e. sample size, mean age, gender, and population) are provided in Table 1. Sample size across studies is diverse, spanning from 7[52] to 470 participants[53], which could be explained by differences in sample population (e.g. specific population clusters such as patients with dementia[52]) and the difference in time required depending on the methodology used (e.g. a single questionnaire compared to multiple physiological measurements).

The reviewed papers in an indoor setting are experimental studies. Of these, 12 out 18 include a control condition in their study design, thus increasing the validity and reliability of the findings (see Table 1). In the reviewed study in outdoor environments, there is greater diversity in the setting, structure, objectives and methodology. Thus, the typology of study is diverse and includes case studies and experimental research. In an outdoor setting, only 3 out of the 12 studies include a control condition[54–56]. Examples of control conditions used, in both settings, include the administration of air as an olfactory stimulus, a visually similar environment without the presence of smells, or a group of participants not taking part in the olfactory experience.

Aim and scope of the studies

Most of these studies evaluate psychological and physiological responses to exposure to the smell of a specific plant, flower or natural element[57–61], or from the comparison of different smells of various species[62–66]. Some studies further analyse differences in responses to varying concentrations or intensities of the same smell[67,68]. Other studies investigate the relationship between the natural smellscapes and participants' subjective perceptions[69–73], with a specific focus on the connection between smells from nature and affective states (any experience of feelings or emotions)[54], perceived restorative effects[73] or on how smells from nature contribute to human self-reported well-being[74]. Other studies examine the therapeutic effects of smells from nature within rehabilitation programmes or horticultural therapies, using these smells from nature as stimulation during nature-based interventions for healthy adults[75] or in specific population clusters, such as maladjusted soldiers[56,76], patients with mental stress-disorders[77] or patients with dementia[52]. Finally, some studies focus on the effects of olfactory stimuli in a multisensory environment, aiming to analyse both the combined and separate effects of stimulating different senses[52,53,55,78–81].

Countries

Of the 18 studies conducted in indoor environments using natural components, 17 were conducted in East Asia (China, Japan, South Korea, and Taiwan), except for one study conducted in Israel[69]. In contrast, the

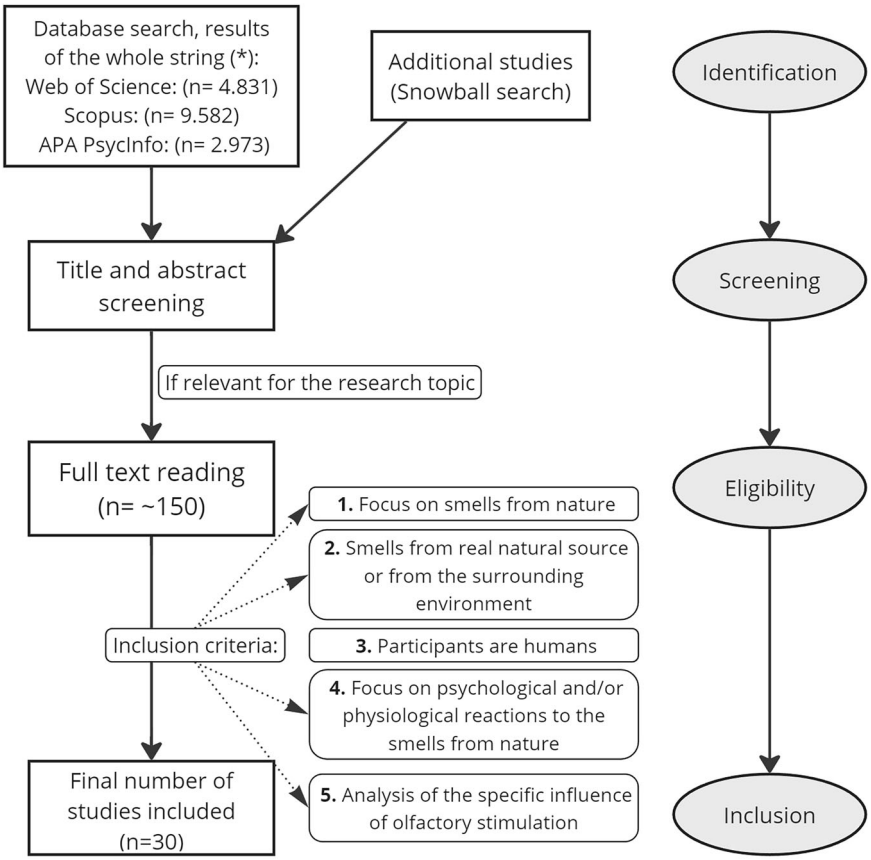

Fig. 1 | Literature search, selection process and inclusion criteria. (*) The numbers refer to the total results when searching the full combination of search terms and excluding non-relevant research areas (see Supplementary Information).

12 studies conducted in outdoor environments were more spread out among different countries, with a more balanced division between Asia (China, Korea, and Taiwan) and Europe (United Kingdom, Sweden, Poland, and Austria), unlike the indoor experiments.

Environments, setting, stimuli, smell source and time of exposure

Of the 30 studies, 18 were conducted in an indoor environment or in a laboratory. One indoor study[68] also included an outdoor condition, but the chosen scented area was a limited, enclosed space with features resembling a laboratory more than a real-world environment. Twelve studies were conducted in an outdoor environment, of which four took place in an urban context. The chosen environments for in-situ studies outdoors included woodlands, multisensory or rehabilitation gardens, and urban areas. Four of the outdoor environments were in an urban context, all conducted in China (see Table 1), specifically urban forest parks[73], urban parks[71,72] and an urban street with traffic noise[55]. Thus, very few studies exist on smell in-situ from nature within urban contexts.

In indoor environments, the sources of smells from nature are always clearly defined by selecting specific species of plants or flowers (e.g. "plants of lavender", "fresh rose flowers", "fresh herbs of geranium"), resulting in stimuli-specific responses. The natural smell sources used indoors include real plants (e.g. Lavender, pelargonium, primula), fresh flowers (e.g. Lily, rose, osmanthus), flower petals (e.g. Japanese plum blossom, jasmine, rose), tree needles (Pine tree), wood chips (Hinoki cypress), leaves (needle fir), fresh herbs (e.g. geranium, citrus, herbal tea) and even sediment from an urban riverbed (see Table 1). Of the four outdoor studies in an urban context, two studies investigate the effect of specific species, specifically lilac[55], magnolia, tree peony, syringa, osmanthus and wintersweet[71]. The other two studies[72,73] evaluate the effects from exposure to the whole smellscape, including an urban park with scents of e.g. flowers, grass, pine, bamboo, water, soil as well as three urban forests with e.g. pines, cypresses, ginkgoes, mountain apricots, maples and greasy pines. In other outdoor in-situ studies conducted in a natural context, the plants, trees or herbs that release the smells within the chosen environments are also specified. These include gardens (e.g. geranium, rosemary, pine, lemon balm, lavender)[52,54,65,77], as well as forests (e.g. coniferous forest, oak woodland, subtropical evergreen broadleaf trees)[53,74,76]. Some studies refer more generally to smells from nature, describing them as "forest smell" or "smells of plants"[56].

The time of exposure to various smell sources varies between 18 s[64] and 4 h[76,77], with most studies ranging from 5 to 30 min (see Table 1).

Timeframe and season

Only a few studies investigate changes in the perception of smells from nature across different times and seasons. Xiong et al.[60] examined the effects of smells from nature at different times of the day (morning, afternoon, and evening). They found that exposure to certain smells from nature in the afternoon reduces negative emotions more significantly, while evening exposure to the smell enhances physiological relaxation. Weber and Heuberger[54] reported that the beneficial effects of smells from nature are more pronounced at night when vision stimulation is limited. Two in-situ studies investigated how the perception of smells from nature varies across seasons. Pálsdóttir et al.[77] conducted a five-year longitudinal study across different seasons, while Bentley et al.[74] investigated the changes in the smellscape of the same two forests in winter, spring, summer and autumn. Their results show that the intensities and types of smells from nature vary with the seasons, with less smells observed during winter. They also observed seasonal influences on participants' sensory experiences and perceived well-being, with smells of autumn contributing the most across different domains of well-being (physical, emotional, cognitive, spiritual and global), followed by those of summer, spring, and winter. Song et al.[71] selected plants that bloom in all four seasons to cover the whole changes in the smellscape. Weber and Heuberger[54] had different experimental conditions in different months (from May to July) with smells elicited from different seasonal plants. Most of the remaining in-situ studies have been

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Table 1 | Overview of the major findings of the included reviewed articles linked to outdoor and indoor environments

INDOOR ENVIRONMENT

	Paper	Author	Country	Setting	Sample	Aim, purpose of the study	Odorant, smell source	Exposure time	Tests	Result	Additional information
1	Effects of volatile organic compounds (VOCs) of Cinnamomum burmannii in its natural state on physical and mental health	Liang et al.[68]	China	Indoor and outdoor	Sample size: 42 participants (18 males, age 18–24) Control condition: yes	Study the effect of different concentration of VOCs of Cinnamomum burmannii on human physiological and psychological health indexes	Plant of Cinnamomum burmannii with different concentrations (high and low)	30 min	**Physiological measures:** brain waves and electromyography (Neurobit Optima 4 biofeedback tester), blood pressure and Heart Rate (wrist monitor). **Psychological measures:** psychological indicator (SCL-90 self-assessment scale)	The inhalation of the smell has positive effects on human physical and mental health with stress relief and relaxation. Lower concentration Cinnamomum burmannii VOCs have larger effects than high concentration.	Experimental rooms and biological university garden
2	Human responses to flower fragrance of Lilium Siberia and Rosa Escimo	Jin et al.[62]	China	Indoor	Sample size: 31 students (58% female, age 18–22) Control condition: Yes	Study human physiological responses to flower fragrance of Lilium Siberia and Rosa Escimo	Flower branches with blooming flowers of rose and oriental lily	5 min	**Physiological measures:** Blood pressure, finger temperature, pulse rate, galvanic skin responses	The exposure to the fragrance of rose increases sympathetic nervous activity and decreases diastolic pressure, pulse rate and physiological arousal leading to relaxation and emotion alleviation. The exposure to the fragrance of lily increase sympathetic nervous activity and physiological arousal	
3	An experimental study on physiological and psychological effects of pine scent	Jo, Fujii & Cho [57]	Korea	Indoor	Sample size: 15 male subjects (27.5 mean age) Control condition: Yes	Evaluate the values of pine tree scent focusing on psychological and physiological aspects.	Pine tree needles	10 min	**Physiological measures:** Cerebral activity (NIRS), blood pressure, stress level (salivary amylase concentration). **Psychological measures:** subjective smell evaluation (Semantic Differential method) and mood assessment (Profile of Mood States).	The inhalation of pine scent activates cerebral areas in charge of judgement, feeling, motor activity of the frontal lobe and memory area of the temporal lobe. No significant activation for the autonomic nervous system. The experienced mood is higher in vigour and less confused feelings.	
4	Physiological and psychological response to floral scent	Jo et al.[61]	Japan	Indoor	Sample size: 26 male student (24 mean age) Control condition: No	Examine psychophysiological responses to Japanese plum blossom fragrance to better understand how fragrance may enhance human health.	Petals of Japanese Plum blossom	2 min	**Physiological measures:** cerebral activity (NIRS), Autonomic nervous system activity (finometer) **Psychological measures:** subjective mood evaluation (Profile of Mood States), stimuli evaluation (Semantic Differential Method)	Results show an activation in cerebral areas in charge of movement, speech and memory and stimulation of the sympathetic nervous system at the exposure of the smell from Japanese Plum blossom fragrance enhances positive feelings, decreases negative feelings and is positively evaluated.	
5	The effect of indoor plants on human comfort	Qin et al.[78]	China	Indoor	Sample size: 16 students (8 males, 8 females, mean age 23.5) Control condition: Yes	Investigate the effects of characteristics, such as colour, odour and size of plants on human comfort	Plants of Lavender (no odour), Mentha (slight-scented) and Pelargonium (strong-scented)	15–20 min	**Physiological measures:** EEG, electrocardiogram, oxyhemoglobin saturation, fingertips blood flow, skin resistance and respiration rate (Power Lab device). **Psychological measures:** Subjective evaluation of the environment, plants factors and layout (Survey questionnaire)	The degree of satisfaction is higher in the slightly-scented plants condition. The plants with slight scent led to highest ratio of alpha and beta EEG bands. When the intensity of the odour changes, the difference of oxyhemoglobin saturation is significant. Environments with plants can improve human comfort.	Plants with different odour, size and colour conditions

Table 1 (continued) | Overview of the major findings of the included reviewed articles linked to outdoor and indoor environments

INDOOR ENVIRONMENT											
	Paper	**Author**	**Country**	**Setting**	**Sample**	**Aim, purpose of the study**	**Odorant, smell source**	**Exposure time**	**Tests**	**Result**	**Additional information**
6	Effect of olfactory stimulation by fresh rose flowers on autonomic nervous activity	Igarashi et al.[58]	Japan	Indoor	Sample size: 19 female students (19–26 years old, mean age 21.6) Control condition: Yes	Examine the effects of olfactory stimulation by the strong fragrance of fresh rose flowers on heart rate variability	Fresh rose flowers	90 s	**Physiological measures:** Heart rate variability (ECG). **Psychological measures:** subjective evaluation of emotional effects (semantic differential method)	Fresh rose flowers induce physiological and psychological relaxation with a significant increase in the parasympathetic nervous activities and an increase in “comfortable” and “natural” feelings.	
7	Comparison of the effects of olfactory stimulation by air-dried and high-temperature-dried wood chips of hinoki cypress (Chamaecyparis obtusa) on prefrontal cortex activity	Ikei et al.[63]	Japan	Indoor	Sample size: 19 female students (mean age 22.5) Control condition: No	“Compare the physiological effects of olfactory stimulation by air-dried and high-temperature-dried wood chips of hinoki cypress”	Wood chips of Hinoki cypress	90 s	**Physiological measures:** Oxyhemoglobin concentration (TRS). **Psychological measures:** subjective evaluation of the emotional impact (semantic differential method)	The level of oxy-Hb concentration is significantly reduced by olfactory stimulation by air-dried wood chips while it remains unchanged with high-temperature-dried wood chips. Air-dried wood chips are perceived as more natural. No differences in feelings of comfort or relaxation between the two conditions.	Comparison of high-temperature dried wood chips with air-dried wood chips conditions
8	Psychophysiological effects of orchid and rose fragrances on humans	Kim et al.[66]	South Korea	Indoor	Sample size: 44 participants, 2 age groups (group 1: mean age 24.5, 11 males and 14 females; group 2 mean age 54.3, 10 males and 9 females) Control condition: Yes	Determine the effects of floral fragrances on human brain waves and moods.	Plants of Orchids and Roses	20 min	**Physiological measures**: brain activity (EEG) **Psychological measures:** subjects emotional responses to fragrances (Semantic Differential method)	Orchid scent enhanced absolute alpha and mid-range beta wave activities, conducive to relaxing mental tension, relieving stress, and facilitating concentration. Rose scent enhanced absolute beta activity, associated with alertness, conscious behaviour, and elevated concentration. Orchid scent was perceived as being elegant and refreshing, and the rose scent as aromatic.	Three odor conditions: odourless, orchid and rose fragrances.
9	Multisensory design of pocket gardens for reducing stress and improving well-being, performance and satisfaction	Bitterman & Simonov [69]	Israel	Indoor	Sample size: 20 participants (10 males and 10 females, ages 23–62) Control condition: Yes	Examine isolated effects of specific landscape elements (sound and smell) for relaxation, wellness and functionality	Fresh herbs of geranium, citrus, spices, herbal tea and roses	2 min	**Physiological measures:** heart rate, galvanic skin response, skin temperature and blood pressure. **Psychological measures:** subjective preference and satisfaction (questionnaire and interviews) Functional parameters: errors on the PASAT test	No significant effect are find in the functional, subjective and physiological parameters with only a borderline significant difference in the galvanic skin responses with beneficial effect after exposure to smell	Stress induction by PASAT test
10	Effects of fragrance components of Abies holophylla Max. on stress relief and improvement of vascular function	Baik et al.[59]	South Korea	Indoor	Sample size: 15 healthy males and females (age 30 s and 40 s) Control condition: Yes	Investigate the effects of the fragrance of Abies holophylla Max on stress relief, vascular function and autonomic nervous system	Plant leaves of Abies holophylla Max.	20 min	**Physiological measures:** autonomic nervous system (Blood pressure, heart rate variability), vascular function (arterial stiffness (Aix), function of endothelial cells (FMD))	Decrease in the systolic blood pressure and heart rate. The fragrance components of A. holophylla Max. have positive effects on the autonomic nervous system and improve vascular function	

Table 1 (continued) | Overview of the major findings of the included reviewed articles linked to outdoor and indoor environments

INDOOR ENVIRONMENT											
	Paper	Author	Country	Setting	Sample	Aim, purpose of the study	Odorant, smell source	Exposure time	Tests	Result	Additional information
11	Olfactory effect on landscape preference	Zhao et al.[70]	China	Indoor	Sample size: 120 students (72 males, 48 females, mean age 21.1) Control condition: Yes	Investigate olfactory effects on landscape preference	Flowers from Osmanthus and Lily and sediment from an urban riverbed	Until task completed	**Psychological measures:** subjective judgement of odors and landscape photographs	Natural flower fragrances are preferred. Natural odours can increase landscape preference scores.	
12	Effect of fragrant Primula flowers on physiology and psychology in female college students: an empirical study	Jiang et al.[67]	China	Indoor	Sample size: 50 female students (mean age 22.32) Control condition: Yes	Explore the effects of fragrant and non-fragrant Primula flowers on physiological and psychological states of female college students	Plants of Primula	10 min	**Physiological measure:** Blood pressure, pulse rate (sphygmomanometer), brain waves (EEG). **Psychological measures:** subjective perception of the smell (Semantic differential method) and mood perception (Profile of mood states)	No significant differences in blood pressure and heart rate. Results show higher attention score and relaxation score after the exposure to the fragrant condition. Mood evaluation shows higher scores on the positive scale in the experimental condition. Smells from fragrant Primula improve physiological and psychological states with stronger restorative effects.	Fragrant and no-fragrant Primula condition
13	The impact of landscape plant fragrance on emotion and brain responses	Wu & Chang[64]	Taiwan	Indoor	Sample size: 38 participants (13 males, 25 females; mean age 25) Control condition: No	Explore the effects of different plant fragrance on the subjects 'brain activation responses and mood by using functional magnetic resonance imaging (fMRI)	Petals of Jasmine, Rose and Lily	18 s/ condition	**Physiological measures:** brain activity (fMRI). **Psychological measures:** subjective emotional response to odors (ScentMove questionnaire)	Brain activation area is mainly located in the Occipital Lobe, which is responsible for processing visual information tasks. The various flowers are perceived differently and elicit different emotions. Smelling Jasmine has refreshing feelings, Rose has pleasant feelings and Lily is perceived with more negative feelings	
14	Comparative study on birdsong and its multi-sensory combinational effects on physio-psychological restoration	Qi et al.[79]	China	Indoor	Sample size: 308 participants (13% male; mean age 22.92) Control condition: Yes	Examine effects of multi-sensory combination in the restoration and the perceived quality in different independent landscapes	Leaves from the lawn, flowers from rose and osmanthus and needles from pine trees, cut and minced.	2 min	**Physiological measure:** Skin temperature, Skin conductance level, brain activity (EEG). **Psychological measures:** perceived quality evaluation (semantic differential survey), psychological state (State Trait Anxiety Inventory questionnaire)	Adding olfactory stimuli to birdsong have an adverse physiological restoration and no significant effects on the psychological restoration and overall preference. Smells enhance the perceived overall sense of harmony. Combination stimuli led to increased physiological restoration but no significant effect psychologically. Health benefits from multi-sensory environments are complex.	Adding multisensory stimulation (visual and smell) to birdsong in a virtual reality setting
15	Psychophysiological responses of cut flower fragrances as an olfactory stimulation by measurement of electroencephalogram in adults	Wu et al. [75]	South Korea	Indoor	Sample size: 30 participants (mean age 34.87) Control condition: No	"Investigate adults' brain activity and emotional state during flower arrangement with different flowers in an Horticultural therapy program"	Trimmed flowers of Chrysanthemum, Lily, Hoary stock, Rose and Carnation	90 s	**Physiological measure:** brain activity (EEG). **Psychological measures:** subjective evaluation of emotional state (profile of mood states and semantic differential method), subjective scent strength (Labeled Magnitude Scale)	The activation of the prefrontal cortex was different among the five flowers. Different flowers have different results, with increase in concentration, calmness, relaxation but also higher arousal. Participants felt different emotional states among the various flowers (from more relaxed to higher tension). Different levels of strength of the smells are perceived.	

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Table 1 (continued) | Overview of the major findings of the included reviewed articles linked to outdoor and indoor environments

INDOOR ENVIRONMENT											
	Paper	**Author**	**Country**	**Setting**	**Sample**	**Aim, purpose of the study**	**Odorant, smell source**	**Exposure time**	**Tests**	**Result**	**Additional information**
16	Benefits of Jasminum polyanthum's natural aromas on human emotions and moods	Xiong et al.[60]	China	Indoor	Sample size: 48 participants (50% male; mean age 22.1) Control condition: Yes	Study the effects of the natural aroma of the flower of Pink Jasmine on human health	Plants of Pink Jasmine	30 min	**Physiological measure**: brain waves (EEG). **Psychological measures:** Mood state (Profile of mood states)	The aroma emitted by Pink Jasmine flowers has a positive impact on physiological and mental health, with stress and anxiety reduction and improved memory. There is a decrease in negative emotions and an increase in positive emotions. The time of the exposure during the day influences the results.	Different groups were tested in different times during the day (morning, afternoon, and evening)
17	Physiological effects of a garden plant smellscape from the perspective of perceptual interaction	Zhang et al.[80]	China	Indoor	Sample size: 95 students (24 males, 71 females; age 18–26) Control condition: Yes	"investigate the physiological recovery effects of olfactory, visual and olfactory–visual stimuli associated with garden plants"	Flowers from Osmanthus	2 min	**Physiological measure:** autonomic nervous system activity (Blood pressure, pulse, skin conductance), central nervous system activity (alpha brain waves and beta brain waves)	The single olfactory stimulation has no significant effect on the autonomic nervous system indexes, while there are changes in the visual and combined condition. Olfaction stimulation shows an increase in the alpha and beta brainwaves amplitude. The combined stimulation has greater physiological health effects.	Multisensory setting with olfactory stimulation, visual stimulation and a combined condition
18	Biophilic environment with visual-olfactory stimuli contributes to psychophysiological restoration and cognitive enhancement	Li et al.[81]	China	Indoor	Sample size: 48 (24 males, 24 females; mean age 22.66) Control condition: Yes	Analyse the impact of visual, olfactory, and combined stimuli from coriander plants on psychophysiological restoration and cognitive performance	Plants of Coriander	30 min	**Physiological measure:** electrocardiogram (HR, HRV), brain activity (EEG), electro dermal activity, salivary stress marker (cortisol), proinflammatory cytokines, untargeted metabolomics. **Psychological measures:** mood state (Profile of Mood States), cognitive performance (psychomotor vigilance task, spatial working memory span task (SWMS)	Visual stimulus elicited a greater response from the nervous system, while olfactory stimulus elicited a greater response from the endocrine and immune systems. Olfactory stimuli alleviate negative emotion and inhibit the activity of the sympathetic nervous system. Olfactory stimulation shows an improvement in spatial working memory. The combined stimulus is the best in promoting psychophysiological restoration and improving cognitive performance	Multisensory setting with olfactory stimulation, visual stimulation and a combined condition
OUTDOOR ENVIRONMENT											
	Paper	**Author**	**Country**	**Setting**	**Sample**	**Aim, purpose of the study**	**Odorant, smell source**	**Exposure time**	**Tests**	**Result**	**Additional information**
19	The impact of natural odors on affective states in humans	Weber & Heuberger [54]	Austria	Outdoor: Fragrant garden and waterfront	Sample size: 32 participants (74% female; mean age 24.3) Control condition: Yes	Measure the relationship between complex, natural odors and affective states (calmness, alertness, mood) in the field	Fragrances of blooming plants from the fragrant garden. Different species among the seasons (list of the species available) Waterfront: Danube water	15 min	**Psychological measures:** affective responses to odours (mood, alertness, calmness) and subjective odor pleasantness and intensity rating (Questionnaire)	Complex natural odors from blooming plants have beneficial long lasting effects to increase calmness, alertness and mood in humans in a natural outdoor setting. Natural odors improve affective states in humans independent of visual input	Various experiments in different seasons, times and locations each with a control condition

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Table 1 (continued) | Overview of the major findings of the included reviewed articles linked to outdoor and indoor environments

OUTDOOR ENVIRONMENT

	Paper	Author	Country	Setting	Sample	Aim, purpose of the study	Odorant, smell source	Exposure time	Tests	Result	Additional information
20	Effects of horticultural therapeutic garden on autonomic nervous system among elderly people with dementia and the value of people-plants relationships	Koura & Ikeda[52]	Japan	Outdoor: Horticultural therapeutic garden	Sample size: 7 elderly people with dementia (5 males, 2 females; mean age 76.2) Control condition: No	"Investigate the effects of horticultural therapeutic garden on the autonomic nervous system among people with dementia and the value of people-plant relationship"	Herb plants: apple mint, lemon balm, rosemary, lavender	3–5 min	**Physiological measures:** Heart rate, Heart rate variability (electrocardiogram)	Smelling the fragrance of a favourite herb increase the activity of the parasympathetic nervous system	
21	Effect of a fragrant tree on the perception of traffic noise	Ba & Kang[55]	China	Outdoor: Urban streets with traffic noise	Sample size: 426 participants (53.9% female; mean age 48) Control condition: Yes	"Study the influence of odour on subjective evaluation of traffic noise of urban streets"	Trees: Lilac (Syringa oblata and Syringa amurensis).	Within 5 min	Psychological measures: subjective assessment of overall comfort, visual/ auditory/ olfactory satisfaction perceived. Congruence between odour and environment, fragrance familiarity, preference and intensity. (Questionnaire)	The perception of the street traffic is affected by fragrance. There is an increase in the overall comfort and a decrease in noise annoyance in the fragrant condition. The congruency smell-environment leads to more comfortable feelings.	Two conditions. A road with fragrant trees and one with not fragrant trees
22	The stress-reducing effects of forest healing activities in maladjusted military force members	Kim et al.[56]	Korea	Outdoor: Forest	Sample size: 52 soldiers (mean age treatment 22; control group 23 years) Control condition: Yes	"Investigate changes in psychological and physiological stress by conducting forest healing activities along with plant scent treatment for soldiers participating in a green camp."	Smells of the environment: Scent of plants	110 s	Physiological measures: Stress level (salivary cortisol samples). Psychological measures: subjective evaluation of stress (Stress response inventory-modified form), stress-coping techniques (stress coping scale).	The results show a reduction of experienced stress, significant differences in the stress-coping techniques and reduction in the cortisol level after the forest therapy.	Forest healing program for maladjustment soldiers. Control condition
23	Physiological and psychological effects of forest healing focused on plant fragrance therapy for maladjusted soldiers	Kim et al.[76]	Korea	Outdoor: Camp garden and nearby forest	Sample size: 62 soldiers (mean age 22.84) Control condition: No	"Verify the physiological and psychological effects of plant fragrance therapy to analyse whether the therapy has a forest healing effect on maladjusted soldiers"	Smell of the environment: Plant fragrances. Forest with coniferous and deciduous species (listed the species within it) *(+ a condition with Plant-derived essential oil)*	4 h	Psychological measures: Stress coping mechanism (stress coping scale) Physiological measures: brain wave measurement (NeuroHarmony S neurofeedback system)	Plant fragrance therapy on maladjusted soldiers helped positively stabilize their negative psychological and behavioral dispositions, and stabilization of brain waves lowered physical and mental stress and improved self-regulation and immunity. Plant fragrances are used as a mechanism to effectively cope with stress.	Forest healing program for maladjustment soldiers.

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Table 1 (continued) | Overview of the major findings of the included reviewed articles linked to outdoor and indoor environments

OUTDOOR ENVIRONMENT											
	Paper	**Author**	**Country**	**Setting**	**Sample**	**Aim, purpose of the study**	**Odorant, smell source**	**Exposure time**	**Tests**	**Result**	**Additional information**
24	Garden Smellscape-experiences of plant scents in nature-based intervention	Pálsdóttir et al.[77]	Sweden	Outdoor: rehabilitation garden	Sample size: 59 participants (50 females, 9 males; between 25–62 years old; mean age 45.5) Control condition: No	"Explore how participants suffering from stress-related mental disorders describe their perception, interaction, and lived experience of garden smellscape during their nature-based rehabilitation"	Smells from the plants in the garden (e.g. Pelargonium, Thymus, Aloysia)	4 h	Psychological measures: association with smells from nature, emotions and physical responses (semi-structured interviews)	The experience with smells from plants in the garden facilitate stress reduction, increase pleasant feelings and support mental recovery.	Longitudinal case-study for participant with stress-related mental disorders in a nature based-rehabilitation program
25	Urban sensory gardens with aromatic herbs in the light of climate change: therapeutic potential and memory-dependent smell impact on human wellbeing	Krzeptowska-Moszkowicz, Moszkowicz & Porada[65]	Poland	Outdoor: Sensory garden	Sample size: 73 participants Control condition: No	"Investigate the way respondents perceived the smells of various aromatic herbs in urban sensory garden and determine whether specific herbs had positive memory-dependent significance to respondents"	Aromatic herbs (e.g. Mentha, Lavender, Nepeta, Hyssop, Oregano, Lemon balm, Salvia, Lovage, Rosemary)		Psychological measures: subjective perception of smell and its association with memories (Survey)	The general perception of smells from nature is positively evaluated. Smells elicit personal and highly positive association (like home, childhood and vacation season)	Six multisensory gardens with different plants
26	Study on smellscape perception and landscape application of fragrant plants	Song & Wu[71]	China	Outdoor: Urban park	Sample size: 30 students (15 males, 15 females; mean age 19.5) Control condition: No	"Explore the relationship between smellscape and perception and provide a reference for smellscape map drawing and landscape application of fragrant plants"	Aromatic plants (with different blooming season): Magnolia, Tree peony, Syringa, Osmanthus, Wintersweet	Time of walking	Psychological measures: subjective evaluation of each plant (Semantic differential method)	The subjective evaluation of fragrance perception is positive. The various species are evaluated differently, with highest values for osmanthus followed by magnolia, wintersweet, and finally by syringa and tree peony.	
27	Nature, smells, and human wellbeing	Bentley et al.[74]	United Kingdom	Outdoor: Woodland	Sample size: 194 participants Control condition: No	Investigate how the experience of smells from nature in woodlands contribute to different domains of human wellbeing across four season	Smells of the environment: oak woodland and a mixed deciduous and coniferous plantation woodland	1 h	Psychological measures: subjective evaluation of wellbeing in the biopsychosocial model (recorded focus group discussion)	The perception of smells from nature influences multiple wellbeing domains: physical (relaxation and comfort), emotional (positive emotion), global, cognitive (restorative) and spiritual (peace and calmness). Found a link between smells from nature and participants´ memories. There´s also an influence from past experiences, the ecological setting and season.	Four visit of two woodlands in the different seasons

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Table 1 (continued) | Overview of the major findings of the included reviewed articles linked to outdoor and indoor environments

OUTDOOR ENVIRONMENT											
	Paper	**Author**	**Country**	**Setting**	**Sample**	**Aim, purpose of the study**	**Odorant, smell source**	**Exposure time**	**Tests**	**Result**	**Additional information**
28	Multisensory stimuli, restorative effect, and satisfaction of visits to forest recreation destinations: a case study of the Jhihben National Forest Recreation Area in Taiwan	Chiang[53]	Taiwan	Outdoor: National forest recreation area (tropical monsoon forest)	Sample size: 470 participants (54.1% female) Control condition: No	Understand the association between multisensory stimuli, perceived restorativeness and satisfaction	Smells of the environment: native subtropical evergreen broadleaf trees (banyans, camphor trees, tung trees, and citrus trees), and introduced tropical species (large-leaved mahogany, albizia, camphor, and pomelo)	Time spent in the park. Average 2 h (42%) or 3 h (36.1%)	Psychological measures: Perceived restorativeness (Perceived Restorativeness Scale), Satisfaction (Satisfaction Scale), multisensory stimuli (Sensory Landscape Scale)	Sight, hearing, smell, and touch have significant positive effects on perceived restorativeness and satisfaction levels. All four stimuli separately affect the perceived restorativeness and satisfaction.	
29	How does the urban forest environment affect the psychological restoration of residents? A natural experiment in environmental perception from Beijing	Li et al.[73]	China	Outdoor: Three urban forest parks	Sample size: 41 participants (21 males, 20 females) Control condition: No	Investigate how the urban forest environment affect psychological restoration of residents	Smells of the environment: three forests with 1. pines, cypresses, ginkgoes and mountain apricots. 2. cypresses, ginkgoes and maples. 3. greasy pines, cypresses and Cotinus coggygria	30 min	Psychological measures: subjective perception of the environment (Perceived Sensory Dimension Scale), restoration (Restoration Outcome Scale)	Olfactory stimuli can have a notable impact on participant psychological restoration.	Stress induction with Stroop test before entering the experimental area
30	Smellscape characteristics of an urban park in summer: a case study in Beijing, China	Wang et al.[72]	China	Outdoor: Urban park with wooded grasslands, waterfront trestles, and ancient buildings	Sample size: 7 participants (mean age 22) Control condition: No	Create a smell map of the city and evaluate the subjective perception of the smells	Smells of the environment: plants (flowers, grass, pine, bamboo, lotus), water (water plant, water vapour, sewage), soil and artificial smells	Within 1 h	Psychological measures: subjective evaluation of the experience (Overall, visual and olfactory experience), subjective olfactory perception (intensity, perception, dominance, harmony, occurrence, preference) (Questionnaire)	Smells from nature have an important and positive role in the overall experience. Compared with artificial smells, smells from nature are more relevant. The influence of vision is the strongest but the sense of smell has still a great influence on the overall experience.	

conducted only during one season, specifically spring[55,73,76], winter[56], autumn[53], or summer[72].

Indoor environment studies

Most studies include both physiological and psychological measures in their experimental design, but three studies only examine physiological responses[59,62,80], and one study includes only psychological measurements[70].

The subjective evaluation of the perception of smells from nature in an indoor environment includes a positive effect on mood and emotions, an increased sense of satisfaction, greater human comfort and positive feelings, together with a decrease in negative feelings[58,60,61,67]. Smells from nature can therefore help alleviate psychological stress, induce relaxing feelings and improve mental states[68]. Moreover, they have been shown to enhance cognitive performances, with significant improvements in spatial working memory[81].

The physiological responses following exposure to smells from nature emitted from real natural sources in an indoor environment, measured using an electroencephalogram (EEG), show significant changes in brain activity. These include an increase in the ratio of α waves and β waves, and an increase in emotional relaxation, improved attention and better physiological states[66,67,78,80,81]. Significant effects are also observed in the autonomic nervous system, with an increase in both the sympathetic and parasympathetic systems[58,61,62]. These changes can produce positive effects, such as a decrease in heart rate, systolic pressure, and skin conduction, as well as inducing physiological relaxation and improving vascular functions[59,68]. Significant changes are also found in the oxyhemoglobin saturation level in the right prefrontal cortex, as measured by near-infrared time-resolved spectroscopy, contributing to physiological relaxation[63,78]. In addition, muscle comfort, as assessed by the surface electromyography index, increases following exposure to aromatic plants, indicating muscle and body relaxation[68]. Finally, the inhalation of smells from nature affects the functions of the immune and endocrine systems by reducing salivary cortisol and proinflammatory cytokines levels, which, in turn, decrease stress levels and reduce the body's inflammatory response. These two systems appear to be more influenced by olfactory stimulation than by visual stimulation, which instead elicits a greater response in the nervous system. This difference suggests that olfaction may have a more direct and significant effect on the immune and endocrine systems than vision[81].

Perception of smell in indoor environments

Changes have been observed in participants´ evaluation, arousal, attention levels, muscle comfort, oxyhemoglobin saturation level and the amplitude of α waves, caused by variations in the intensity and concentration of each smell, as well as by comparisons of smells from different varieties of plants or flowers[62,63,66,68,75,78]. General satisfaction was higher with a slightly-scented plant compared to the greater intensity of a strongly-scented plant[78]. Furthermore, various species of flowers (e.g. jasmine, rose or lily) can evoke feelings of happiness, relaxation, serenity, energy or refreshment[64,66,75], as well as produce contrasting effects on participants' arousal[62].

However, some studies do not show any significant effects from exposure to smells from nature. No significant results were found in participants´ evaluations of positive feelings or their satisfaction levels[69,79]. Moreover, in some studies, there was no significant effect on the physiological responses, with no activation of the autonomic nervous system, heart rate, blood pressure or skin conductance indices[57,61,67,69]. As explained in these studies, the lack of significant effects could be due to the short duration of exposure to the smell in the study design and its concentration.

Outdoor environment studies

The four studies conducted in an urban context were all subjective, including questionnaires without physiological measurements. In the study by Li et al.[73], vision, sound and smell were compared in three urban forest parks. While smell did not play a major role in psychological restoration as vision did, it was still beneficial to the human body. The second study by Wang et al.[72] emphasised a '*…remarkably strong association…between the degrees of olfactory, visual, and overall experiential satisfaction*', thus highlighting the importance of multisensory experiences. The third study[55] revealed more positive evaluations of street sounds with higher concentrations of lilacs (either *Syringa amurensis* or *Syringa oblata*). This study confirmed previous research on sound–odour interactions conducted in laboratory settings[82]. The fourth study[71] was conducted in a park and revealed that the evaluation of five different plants, magnolia, tree peony, syringa, osmanthus and wintersweet, showed that all had a distinct smell linked to its plant type.

Experiences of smells from nature were predominantly positively evaluated in outdoor settings, resulting in improved long-lasting emotional and affective states[54], eliciting highly-positive personal associations[65], evoking positive feelings and mental relaxation[77], affecting perceived restorativeness[53,73], and influencing physical, emotional and global well-being, leading to a general improvement in general health[74].

Only three of the 12 outdoor studies measure physiological responses while experiencing smells from nature in-situ. Koura and Ikeda[52] assessed the responses of the autonomic nervous system in people with dementia while walking in a horticultural therapeutic garden, measuring heart rate and heart rate variability. Their findings show an increase in the parasympathetic nervous system activity. Kim et al.[56,76] evaluated physiological responses, respectively, the salivary cortisol level and brain activity, at the end of exposure to smells from the forest during a therapy programme, showing a significant decrease in stress levels and tension.

Perception of smell in outdoor environments

Different species of plants and flowers (e.g. osmanthus, magnolia, and tree peony) emit distinctive smells, which participants evaluate with varying characteristics and ratings[71]. These differences can be influenced by individuals' personal experiences (sensitivity of the receiver) and the physical features of the environment, such as seasons, weather conditions, or ecological settings[74], as well as planting density, space size and openness[71]. Some smells are vaguely described, such as 'scent of plants'[56], or 'oak woodland and a mixed deciduous and coniferous plantation woodland'[74], while others are more precise, providing lists of species[54]. Remarkably, all the selected studies conducted in outdoor environments found some effect from exposure to smells from nature (this was not always the case in indoor environments). However, few of these studies compare the results with a control condition (see Table 1).

Discussion

This review found a total of 30 studies investigating smells from nature. Of these, only 12 studies were conducted in-situ natural settings, and 4 were conducted in urban areas, specifically an urban forest[73], urban parks[71,72] and a street with traffic[55]. Thus, studies on natural complex smellscapes in outdoor environments seem very rare, and there seems to be a lack of research on smells from nature.

Most people today live in urban areas, where nature experiences are constantly being reduced due to urbanisation[83]. Additionally, people living in more green areas report better mental health than those living in urban areas[84]. Here, we present findings indicating that smells from nature, in general, had positive effects on both psychological and physiological responses in humans, with potential benefits for health and well-being, regardless of whether the studies were conducted indoors or outdoors. Smells from nature can affect people´s experience of the environment and influence multi-sensory perception.

Cities 'do…not know how to incorporate nature and nature contribution to people into city planning'[85]. Currently, planning and design of urban green environments are dominated by visual aspects[86,87]. However, incorporating stimulation from all senses (vision, hearing, smell, touch and taste) in urban green planning could create a richer sensory experience of an environment increasing its overall satisfaction[72]. Thus, multisensory urban design represents a way to promote mental health and well-being[19] and create more restorative environments[53,73] by maximizing the positive effects of nature on human health[88]. One application could be seen in Singapore´s

initiative to create therapeutic gardens that stimulate all the senses, shifting the focus of garden design towards promoting mental health (https://www.nationalgeographic.com/travel/article/singapore-wellness-mental-health). As explained by Roe and McCay[19], one approach to multisensory design for mental health is to maximize salutogenic sensory design while minimizing exposure to negative sensations across all senses, both individually and in combination, integrating sensory stimulation in a cohesive yet engaging way.

Looking at the influence of smells from nature on other senses in experiencing an environment shows mixed results[53,55,79–81], suggesting that the relationship between stimuli from different senses is a complex phenomenon. The reviewed in-situ studies suggest that, for example, smells can affect the perception of noisy urban environments, increasing both the auditory and olfactory qualities and improving overall street comfort[55]. However, a pleasant smell may not be perceived as positive if it clashes with other sensory stimuli in the environment, and the results may differ from that of the same smell within an environment with congruent stimuli. What appears clearer is that exposure to combined multisensory stimuli, including visual, sound, smell, touch and taste, results in more positive effects compared to single-sense stimuli alone, regardless of the specific sense involved[79–81], and these results are similar to the findings from other studies[89,90]. Therefore, attention must be given to the quality of these stimuli and how they interact with each other. Furthermore, according to Wang et al.[72], smells from nature '…are able to form an organic whole, rather than existing in fragments, interspersed with the industrial odours of the city…', suggesting that a complete smellscape integrates better with other sensory elements.

Emerging research explores how to incorporate smells from nature into the design of both indoor and outdoor environments[91,92] and highlights their importance to connect with nature within urban contexts[93]. Wang et al.[72] suggest a need to manage and construct smellscapes in urban parks, not only to control negative smells in cities but also to promote the creation of, for example, different gardens with positive smells that can enhance immersive, multisensory experiences that support relaxation and emotional well-being. Krzeptowska-Moszkowicz et al.[65] found that associating smells with positive memories can improve mood and perceived well-being for individuals in cities. Thus, experiencing smells in sensory gardens through various species of fragrant herbs can improve the quality of life for residents in big cities. However, numerous factors that can affect smell diffusion must be considered when allocating fragrant plants. The reviewed studies emphasize that, to enhance positive smell from nature in urban areas, city management and design should consider which species to plant, the density of trees to optimize smell diffusion, and the spatial size and openness of the area[71]. Previous research explains that designing with smell requires evaluating local plant species, their growing conditions, seasonality, environmental factors, functions, and bloom periods[91]. Human perception aspects should also be considered, such as the distance and height from the source, the physical context, and the engagement required to fully experience the smell[91]. However, attention must also be given to the possible harmful effects of certain fragrant plants, as they can increase the risk of allergic reactions or other individual issues[94]. Thus, investigating the harmful effects of various species is relevant to select those species that better mitigate these risks. Understanding the relationships between all these elements that shape the complexity of smell experiences is essential if we want to create sustainable environments that incorporate smells from nature.

Research on smells from nature is emerging, covering aspects from multiple disciplines. Thus, the methodology used is still under development and varies significantly depending on the quality of the study, its main purpose, and its objectives. The ephemeral aspects of smells, the complexity of their delivery, high subjectivity, and strong influence from environmental conditions and uncontrollable factors are some complications that arise when working with smells. Smellwalks, multisensory walks, and outdoor experiences represent important methods for collecting, mapping, and describing perceived smells and their connections to specific environments[53–55,71–74]. By using these methods, it is possible to identify the variety of smells present in an environment and how their perception may change over time depending on environmental factors (e.g. wind, temperature, rain). Smellwalks also help create an olfactory profile of cities, which can serve as a tool for designing and managing urban green spaces. Rehabilitation and therapeutic programs provide insight into the healing properties of smells from nature emitted by various plants and highlight the value of the relationship between patients and smells from nature[52,56,65,76,77]. Increasing knowledge about the therapeutic properties of smells by exploring how smells from nature may affect the rehabilitation process, can help classify the effects of fragrant plants and support their implementation in therapeutic gardens. Additionally, experimental studies in controlled settings provide insights into the effects of inhaling smells from specific and defined species to understand the differences among them. Adding in these study design the evaluation of physiological changes provide an objective and complementary approach to exploring the underlying mechanisms and potential health benefits of inhaling smells from nature. Since the perception of smell is highly subjective, the inclusion of physiological measurements can be even more crucial to identify physiological substrates involved when experiencing smells from nature that are common among different subjects. It would also help evaluating the subconscious changes that cannot be investigated through subjective assessments, as these do not always reach human awareness. For example, in an indoor laboratory experiment, Hedblom et al.[33] found that people subjectively rated visual features as more important than smell features. However, the objective physiological measurements showed the opposite, with smell being the most strongly correlated with stress reduction. Several of the reviewed indoor studies have shown that exposure to smells from nature in a laboratory setting increases physiological relaxation and reduces stress levels[59,66–68,80,81]. However, investigating whether these physiological responses occur when experiencing smells from nature in-situ may be more ecologically valid than indoor studies. Ecologically valid studies to in-situ smells exposure, may also be more relevant for understanding the practical implications for people´s everyday life experience. Additionally, such studies can help identify environmental qualities that influence the human body at a physiological level, aiming to enhance health and well-being. Only three of the reviewed studies were found in this context[52,56,76], none of which were conducted in urban settings. These in-situ studies explored the effects of smells during therapeutic activities, showing that exposure to the smells of a forest[56,76] or favourite herbs (i.e. apple mint, lemon balm, rosemary and lavender[52]), respectively, reduces physiological stress and increases parasympathetic nervous activity. However, while Koura and Ikeda[52] measured changes in heart rate in participants walking in the garden, Kim et al.[56,76] evaluated physiological responses before and after the therapy in a pre-post design, rather than while experiencing forest smells. This aligns with the dominance of self-reported measurement over physiological responses in current studies on the benefits of nature exposure. Conducting in-situ studies in urban settings presents numerous challenges, including unpredictable occurrence, the use of portable devices, and the difficulty of isolating the effects of smells from other sensory stimuli. However, two recent studies demonstrate the feasibility of conducting in-situ research in urban nature combining physiological and subjective measurements, although their focus is not on smells. Korpilo et al.[95] investigated multisensory restorative experiences in real-life environments by combining soundscape perception with physiological measurements of stress recovery across different urban settings. Similarly, Olszewska-Guizzo et al.[96] examined the effects of passive exposure to urban green spaces with varying visual qualities using portable EEG devices.

The duration of exposure to the smells represents an additional element to consider when studying smells. Olfactory adaptation is the phenomenon in which olfactory receptors stop responding to an odorant, and the olfactory stimuli are no longer detected[97]. The time for adaptation to occur usually ranges from 1 to 20 min, although it depends on several factors, including the qualities of the smell (e.g. intensity, concentration) and on the individual perceiving it (e.g. perceived danger of the odorant, current mood)[97,98]. Thus, phenomena such as olfactory adaptation and cognitive

habituation (i.e. the psychological process by which an individual no longer detects a smell after long-term exposure[97] need to be considered when implementing smells from nature into urban design, as well as in the setup of studies investigating smells. Some considerations might include factors such as smell intensity, concentration, duration of exposure, or intermittently dispense the smell.

While olfactory stimuli used in laboratory studies mainly consist of smells from nature emitted by specific plants, outdoor studies focus mainly on the effects of the overall smellscape of the environment rather than analysing single stimuli-response effects of different smells. Although one might be walking in a forest with various tree species, Kim et al.[56] describe the experience of smell only as "smells of forest" or "scent of plants", without mentioning the specific species. Some studies, instead, define the species present in a forest environment more specifically (e.g. evergreen broadleaf tree, tropical species, pine, cypresses (See Table 1) but without going into further details about the precise effects due to different species within the environment. However, Bentley et al.[74] found that the smells of an oak woodland were described differently and more frequently than those of a mixed deciduous and coniferous woodland, suggesting that smellscapes of different forest types are experienced differently. The results from various studies[62,64,66,70,71,74] suggest that not all smells from nature are experienced in the same way, with some smells being preferred over others and potentially eliciting different emotions and feelings. Ba and Kang[55], for example, revealed that the fragrance on streets planted with double rows of lilac was stronger than on the streets with single rows, and that the fragrance of *Syringa amurensis* was more intense than that of *Syringa oblata* at the same planting density. Considering the above, there is a need to specify plant species in in situ outdoor environments. In the more formal environments such as urban parks or gardens (compared to the less formal environments as e.g. forests), existing reviewed literature often provide more detailed descriptions of the species present, and it usually includes trees and shrubs (e.g. lilac, magnolia, osmanthus) or aromatic herbs (e.g. mentha, salvia, lemon balm). Weber and Heuberger[54], for instance, used the smells of seasonal blooming plants of selected species in a fragrant garden as stimuli, showing that complex and natural smells increase calmness, alertness and mood in humans. Song et al.[71] analysed the subjective perception of five different species of fragrant plants in an urban park, with an additional analysis of their main fragrance compound, type and diffusion process, and showed how these perceptions changed by species within the same park. For example, osmanthus exhibited a strong, sweet smell and received the highest positive perception rate, while tree peony was perceived as least pleasant with a woody and light medicinal fragrance. Krzeptowska-Moszkowicz[65] defined the aromatic herbs in six different gardens and observed that lavender and mint were the preferred plants, and their smells elicited highly positive associations, while salvia brought to mind special memories for only a few respondents. However, few studies have investigated multiple defined species in cities, and these studies are limited to only a few species. Some smells from nature may target specific human states or cognitive functions (e.g. memory, emotions, stress…) more than others, but the characteristics and effectiveness of these mechanisms are not well understood. Additionally, little is known about how the complexity of overall olfactory perception of smells from numerous species is formed, and whether these combinations can provide additional benefits for human well-being. This is also something that Ba and Kang[55] highlighted, acknowledging that they only examined one species in an urban setting and suggesting that other species might have similar effects, highlighting the need for further research.

Due to COVID-19, many people suffered a reduced or temporary loss of the sense of smell, with a significant reduction in their quality of life, revealing how important smell is in everyday experiences[99]. Currently, the treatment with the greatest degree of supporting evidence for loss of smell is olfactory training[100], which involves a twice-daily exposure to different sets of smells over 12 weeks, mainly conducted indoors with artificial smells. However, having access to nature close to where one lives might play an important role not only in promoting well-being and reducing stress but also in facilitating naturalistic olfactory training by using smells from nature. Moreover, due to the need to reduce transportation during the pandemic, close access to nature has gained increased importance for the health of the population[101]. Importantly, physical access to urban green is not equal among the population. Thus, smells from nature can represent a way to easily access nature within an urban context, even for people with reduced mobility, decreasing the need for travel to reach natural environments, hence promoting more sustainable cities. It is, therefore, of utmost importance to identify and define smells from individual plant species or perhaps dominant vegetation by family or genus if we are to create outdoor environments with the idea of improving the quality of an environment, user experience and promote health and well-being by increasing contact with nature through smells in cities.

Future research

The current number of studies on smells from nature is generally limited, leaving many knowledge gaps. The reviewed literature on smells from nature comes from several disciplines, including Landscape Architecture, Horticulture, Plant Studies, Health, Environmental Studies, Design, Forestry, Management, and Environmental Psychology. A multidisciplinary approach is needed to understand the details and health benefits of the smell experience, and the way smells from nature can potentially be integrated in urban nature.

One limitation of existing literature is the lack of studies specifying the effects of smells from nature released by various species. The reviewed studies show that not all smells from nature are perceived in the same way, but is not clear which smells are most beneficial for human well-being. There is a need to investigate how human responses vary to different smells and how the natural smellscape changes in different types of green environments (e.g. lawns, gardens, forests that are prone to timber production, or primeval forests). Additionally, future studies should investigate temporal changes of natural smellscapes across different seasons and times of day. These results could provide more knowledge on the relationship between smells and different habitats. Previous studies reveal that the visual perception of high biodiversity of plants is perceived as more attractive that areas with lower species richness[102], and that a combination of singing by several bird species increase the positive perception of urban green areas more than singing by a single species[103]. It would be interesting to study if increased biodiversity of natural smells has similar effects as visual and soundscape features. Thus, future studies should investigate whether areas with a greater variety of smells from nature are perceived as being more positive than areas with fewer smells from nature. A practical implication would be to implement these findings considering local species, density, and spatial scale in the planning of public areas. By doing so, we can enhance the quality of life in cities and create healthier smellscapes in different types of natural and urban environments.

A limitation of current research is the limited number of in-situ studies that utilise smells emitted from real natural sources (e.g. plants, soil, water), incorporating physiological measurements using portable devices. More such studies are needed to enhance the generalizability and ecological validity of findings, and to better specify the complexity of smells in different types of urban green spaces. The reviewed laboratory studies measuring physiological responses reveal that smells from nature have positive effects, increasing relaxation and reducing stress levels[59,66–68,80,81]. Thus, there is a need to investigate whether the same effects occur in-situ in urban green spaces.

Another limitation of the existing literature is that, at the moment, studies on smells from nature seem to be centred towards Asia, especially the ones conducted in-situ within urban settings. Wang et al.[72] highlight that smellscapes should be integrated with the local culture context, which might have an effect on, for example, the perception of scented plants. Hence, future research should examine the influence of more cultures on experiencing smells from nature in various urban areas all over the world. Thus, cultural aspects need to be taken into account when designing and managing urban green spaces with smells, in order to preserve the cultural and heritage values of various smellscapes.

Conclusion

The results of the reviewed articles suggest that exposure to smells from nature, emitted from real natural sources, positively influences human psychological and physiological responses. These include reducing stress levels, inducing relaxation, and enhancing positive emotions and affective states. However, research on smells from nature is still limited, particularly in defining the smell from specific species found in cities, and in conducting in-situ studies analysing human physiological responses in both urban and natural environments. Working with smells from nature in-situ presents several challenges, both methodological and in their implementation, such as the strong influence of environmental factors, the high subjectivity of smell perception, and the need for portable devices. Still, the literature highlights that a comfortable smell experience in cities can enhance overall satisfaction. The reviewed studies indicate that smells from nature have potential benefits for human health and well-being. Therefore, integrating smells from nature into urban environments could enhance nature exposure, improve environmental quality and potentially contribute to the creation of healthier ecosystems in a sustainable way.

Data availability

No datasets were generated or analysed during the current study.

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References

1. United Nations. *Department of Economic and Social Affairs, Population Division, World Urbanization Prospects 2018: Highlights* (United Nations, 2019).
2. Lederbogen, F. et al. City living and urban upbringing affect neural social stress processing in humans. *Nature.* **474**, 498–501 (2011).
3. Peen, J., Schoevers, R. A., Beekman, A. T. & Dekker, J. The current status of urban-rural differences in psychiatric disorders. *Acta Psychiatr. Scand.* **121**, 84–93 (2010).
4. World Health Organization. *Global Report on Urban Health: Equitable Healthier Cities for Sustainable Development* (Geneva: World Health Organization, 2016).
5. UN-Habitat and WHO. *Integrating Health in Urban and Territorial Planning: A Sourcebook* (Geneva: UN-HABITAT and World Health Organization, 2020).
6. United Nations. *Transforming our World: The 2030 Agenda for Sustainable Development* (United Nations, 2015). https://sdgs.un.org/publications/transforming-our-world-2030-agenda-sustainable-development-17981.
7. Bratman, G. N. et al. Nature and mental health: an ecosystem service perspective. *Sci. Adv*. **5**, eaax0903 (2019).
8. Ross, M. & Mason, G. J. The effects of preferred natural stimuli on humans' affective states, physiological stress and mental health, and the potential implications for well-being in captive animals. *Neurosci. Biobehav. Rev.* **83**, 46–62 (2017).
9. van den Bosch, M. & Sang, A. urban natural environments as nature based solutions for improved public health - a systematic review of reviews. *J. Transp. Health* **5**, S79–S79 (2017).
10. Corazon, S. S., Sidenius, U., Poulsen, D. V., Gramkow, M. C. & Stigsdotter, U. K. Psycho-physiological stress recovery in outdoor nature-based interventions: a systematic review of the past eight years of research. *Int. J. Environ. Res. Public Health* **16**, 1711 (2019).
11. Ulrich, R. S. et al. Stress recovery during exposure to natural and urban environments. *J. Environ. Psychol.* **11**, 201–230 (1991).
12. Jimenez, M. P. et al. Associations between nature exposure and health: a review of the evidence. *Int. J. Environ. Res. Public Health.* **18**, 4790 (2021).
13. Tsunetsugu, Y. et al. Physiological and psychological effects of viewing urban forest landscapes assessed by multiple measurements. *Landsc. Urban Plan.* **113**, 90–93 (2013).
14. Hutmacher, F. Why is there so much more research on vision than on any other sensory modality? *Front. Psychol.* **10**, 2246 (2019).
15. Pallasmaa, J. *The Eyes of the Skin: Architecture and the Senses* (John Wiley & Sons, Incorporated, 1996).
16. Franco, L. S., Shanahan, D. F. & Fuller, R. A. A review of the benefits of nature experiences: more than meets the eye. *Int. J. Environ. Res. Public Health* **14**, 864 (2017)..
17. Spence, C. Senses of place: architectural design for the multisensory mind. *Cogn. Res-Princ. Implic.* **5**, 46 (2020).
18. Truong, M. X., Bonnefoy, B. & Prévot, A. C. About smells and nature: an exploratory study on the links between environmental identity, smell sensitivity, and sensory uses of natural spaces (Sobre los olores y la naturaleza: un estudio exploratorio sobre los nexos entre la identidad ambiental, la sensibilidad olfativa y los usos sensoriales de los espacios naturales). *Psyecology-Revista Bilingue De Psicologia Ambiental.* **11**, 7–20 (2020).
19. Roe, J. M. *Restorative Cities. Urban Design For Mental Health And Wellbeing* (Bloomsbury Publishing, 2021).
20. McGann, J. P. Poor human olfaction is a 19th-century myth. *Science* **356,** eaam7263 (2017).
21. Herz, R. S. *The Scent of Desire: Discovering our enigmatic sense of smell*. (Harper Perennial, 2008).
22. Bratman, G. N. et al. Nature and human well-being: the olfactory pathway. *Sci Adv*. **10**, eadn3028 (2024).
23. Vukovic, N. & Mingaleva, Z. Towards a sustainable city with a sensory garden in the context of urban well-being. *Sustainability.* **15**, 4762 (2023).
24. Henshaw, V. *Urban Smellscapes* (Routledge, 2014).
25. Xiao, J., Tait, M. & Kang, J. Understanding smellscapes: Sense-making of smell-triggered emotions in place. *Emotion Space Soc.* **37**, 100710 (2020).
26. Alqadrie, A. M. & Martokusumo, W. The other sensory approach on exploring urban heritage landscape. Case study: Chinese quarter of semarang. *J. Infrastruct. Facility Asset Manag*. **3**, 147–162 (2021)..
27. Ling, X., Guan, H., Peng, J. & Xiong, Z. Critical zone recognition of smellscape of a Chinese traditional market based on the sensitivity-coordination matrix. *J. Urban Plan. Dev.* **148**, 05022021 (2022).
28. Wankhede, K., Deshmukh, A., Wahurwagh, A., Patil, A. & Varma, M. An insight into the urban smellscape: the transformation of traditional to contemporary urban place experience. *J. Asian Archit. Build. Eng.* **22**, 3818–3831 (2023).
29. Herz, R. The role of odor-evoked memory in psychological and physiological health. *Brain Sci.* **6**, 22 (2016).
30. Soudry, Y., Lemogne, C., Malinvaud, D., Consoli, S. M. & Bonfils, P. Olfactory system and emotion: common substrates. *Eur. Ann. Otorhinolaryngol. Head Neck Dis.* **128**, 18–23 (2011).
31. He, J. H. et al. Sniff the urban park: unveiling odor features and landscape effect on smellscape in Guangzhou, China. *Urban For. Urban Green*. **78**, 127764 (2023).
32. Majid, A., Speed, L., Croijmans, I. & Arshamian, A. What makes a better smeller? *Perception* **46**, 406–430 (2017).
33. Hedblom, M. et al. Reduction of physiological stress by urban green space in a multisensory virtual experiment. *Sci. Rep.* **9**, 10113 (2019).
34. Quercia, D. Chatty, happy, and smelly maps. In *Www'15 Companion: Proceedings of the 24th International Conference on World Wide Web* 741–741 (Association for Computing Machinery, 2015).
35. Xiao, J. et al. Recent advances in smellscape research for the built environment. *Front. Psychol.* **12**, 700514 (2021).
36. Ikei, H., Song, C. & Miyazaki, Y. Physiological effects of wood on humans: a review. *J. Wood Sci.* **63**, 1–23 (2017).
37. Song, C., Ikei, H. & Miyazaki, Y. Physiological effects of nature therapy: a review of the research in Japan. *Int. J. Environ. Res. Public Health* **13**, 781 (2016).
38. Rios J. L. Essential oils: what they are and how the terms are used and defined. in *Essential Oils in Food Preservation, Flavor and Safety* (ed Preedy, V.) (2016).

39. Sowndhararajan, K. & Kim, S. Influence of fragrances on human psychophysiological activity: with special reference to human electroencephalographic response. *Sci. Pharm.* **84**, 724–751 (2016).
40. Tsunetsugu, Y., Park, B. J. & Miyazaki, Y. Physiological effects of visual, olfactory, auditory, and tactile factors of forest environment. in *Forest Medicine* (Nova Science Publishers, 2012).
41. Igarashi, M., Ikei, H., Song, C. & Miyazaki, Y. Effects of olfactory stimulation with rose and orange oil on prefrontal cortex activity. *Complement. Ther. Med.* **22**, 1027–1031 (2014).
42. Angelucci, F. L. et al. Physiological effect of olfactory stimuli inhalation in humans: an overview. *Int. J. Cosmetic Sci.* **36**, 117–123 (2014).
43. Farrar, A. J. & Farrar, F. C. Clinical aromatherapy. *Nurs. Clin. N. Am.* **55**, 489–504 (2020).
44. Thangaleela, S. et al. Essential oils, phytoncides, aromachology, and aromatherapy-a review. *Appl. Sci.* **12**, 4495 (2022).
45. Brozzo, C. Perfumes and the aesthetic appreciation of nature. in *Theoretical Perspectives on Smell* (Routledge, 2022).
46. Bakkali, F., Averbeck, S., Averbeck, D. & Idaomar, M. Biological effects of essential oils - a review. *Food Chem. Toxicol.* **46**, 446–475 (2008).
47. Kaiser, R. *Meaningful Scents Around The World: Olfactory, Chemical, Biological, And Cultural Considerations* (Wiley-VCH, 2006).
48. Xiao, J., Tait, M. & Kang, J. A perceptual model of smellscape pleasantness. *Cities* **76**, 105–115 (2018).
49. Arshamian, A. et al. The perception of odor pleasantness is shared across cultures. *Curr. Biol.* **32**, 2061–2066.e3 (2022).
50. Parker, M., Spennemann, D. H. R. & Bond, J. Methodologies for smellwalks and scentwalks-a critical review. *Chem. Senses* **49**, bjae005 (2024).
51. Wohlin, C., Kalinowski, M., Romero Felizardo, K. & Mendes, E. Successful combination of database search and snowballing for identification of primary studies in systematic literature studies. *Inf. Softw. Technol.* **147**, 106908 (2022).
52. Koura, S. & Ikeda, A. Effects of horticultural therapeutic garden on autonomic nervous system among elderly people with dementia and the value of people-plants relationships. In *Proc. Xxix International Horticultural Congress on Horticulture: Sustaining Lives Livelihoods and Landscapes (Ihc2014): Xii International People Plant Symposium: Hortic. Human Comm*. 1121, 27–31 (2016).
53. Chiang, Y. J. Multisensory stimuli, restorative effect, and satisfaction of visits to forest recreation destinations: a case study of the Jhihben National Forest recreation area in Taiwan. *Int. J. Environ. Res. Public Health* **20**, 6768 (2023).
54. Weber, S. T. & Heuberger, E. The impact of natural odors on affective states in humans. *Chem. Senses* **33**, 441–447 (2008).
55. Ba, M. & Kang, J. Effect of a fragrant tree on the perception of traffic noise. *Build. Environ.* **156**, 147–155 (2019).
56. Kim, J. et al. The stress-reducing effects of forest healing activities in maladjusted military force members. *J. People Plants Environ.* **23**, 377–385 (2020).
57. Jo, H. J., Fujii, E. & Ho, T. D. An experimental study of physiological and psychological effects of pine scent. *J. Korean Instit. Landsc. Archit*. **38**, 1-10 (2010).
58. Igarashi, M., Song, C., Ikei, H., Ohira, T. & Miyazaki, Y. Effect of olfactory stimulation by fresh rose flowers on autonomic nervous activity. *J. Altern. Complement. Med.* **20**, 727–731 (2014).
59. Baik, H. J., Kim, H. J., Jae, S. Y. & Yi, B. Y. Effects of fragrance components of Abies holophylla Max. on stress relief and improvement of vascular function. *J. People Plants Environ.* **21**, 223–232 (2018).
60. Xiong, X. et al. Benefits of Jasminum polyanthum's natural aromas on human emotions and moods. *Urban For. Urban Green.* **86**, 128010 (2023).
61. Jo, H. et al. Physiological and psychological response to floral scent. *Hortscience* **48**, 82–88 (2013).
62. Jin, Z., Li, X., Zhang, Q., Pan, H. & An, X. Human responses to flower fragrance of Lilium 'Siberia' and Rosa 'Escimo'. *For. Stud. China* **11**, 185–189 (2009).
63. Ikei, H., Song, C., Lee, J. & Miyazaki, Y. Comparison of the effects of olfactory stimulation by air-dried and high-temperature-dried wood chips of hinoki cypress (Chamaecyparis obtusa) on prefrontal cortex activity. *J. Wood Sci.* **61**, 537–540 (2015).
64. Wu, Y. C. & Chang, C. Y. The impact of landscape plant fragrance on emotion and brain responses. *Acta Hortic.* **1313**, 53–58 (2021).
65. Krzeptowska-Moszkowicz, I., Moszkowicz, Ł & Porada, K. Urban sensory gardens with aromatic herbs in the light of climate change: therapeutic potential and memory-dependent smell impact on human wellbeing. *Land* **11**, 760 (2022).
66. Kim, S. M., Park, S., Hong, J. W., Jang, E. J. & Pak, C. H. Psychophysiological effects of orchid and rose fragrances on humans. *Korean J. Hortic. Sci.* **34**, 472–487 (2016).
67. Jiang, S. et al. Effect of fragrant primula flowers on physiology and psychology in female college students: an empirical study. *Front. Psychol*. **12**, 607876 (2021).
68. Liang, R. et al. Effects of Volatile Organic Compounds (VOCs) of Cinnamomum burmannii in its natural state on physical and mental health. *Polish J. Environ. Stud.* **32**, 133–144 (2023).
69. Bitterman, N. & Simonov, E. Multisensory design of pocket gardens for reducing stress and improving well-being, performance and satisfaction. *Des. J.* **20**, S2418–S2425 (2017).
70. Zhao, J., Huang, Y., Wu, H. & Lin, B. Olfactory effect on landscape preference. *Environ. Eng. Manag. J.* **17**, 1483–1489 (2018).
71. Song, X. & Wu, Q. Study on smellscape perception and landscape application of fragrant plants. *Urban For. Urban Green.* **67**, 127429 (2022).
72. Wang, C. et al. Smellscape Characteristics of an Urban Park in Summer: A Case Study in Beijing, China. *Sustainability,* **16**, 163 (2024)..
73. Li, S., Chen, T., Chen, F. & Mi, F. How does the urban forest environment affect the psychological restoration of residents? A natural experiment in environmental perception from Beijing. *Forests.* **14**, 1986 (2023).
74. Bentley, P. R. et al. Nature, smells, and human wellbeing. *Ambio* **52**, 1–14 (2023).
75. Wu, Y. T., Lee, A. Y., Choi, N. Y. & Park, S. A. Psychophysiological responses of cut flower fragrances as an olfactory stimulation by measurement of electroencephalogram in adults. *Int. J. Environ. Res. Public Health* **19**, 11639 (2022).
76. Kim, J. et al. Physiological and psychological effects of forest healing focused on plant fragrance therapy for maladjusted soldiers. *J. People Plants Environ.* **24**, 429–439 (2021).
77. Pálsdóttir, A. M., Spendrup, S., Mårtensson, L. & Wendin, K. Garden smellscape-experiences of plant scents in a nature-based intervention. *Front. Psychol*. **12**, 667957 (2021).
78. Qin, J., Sun, C., Zhou, X., Leng, H. & Lian, Z. The effect of indoor plants on human comfort. *Indoor Built Environ.* **23**, 709–723 (2014).
79. Qi, Y. et al. Comparative study on birdsong and its multi-sensory combinational effects on physio-psychological restoration. *J. Environ. Psychol.* **83**, 101879 (2022).
80. Zhang, X., Guo, J., Zhang, X. & Zhang, Q. Physiological effects of a garden plant smellscape from the perspective of perceptual interaction. *Int. J. Environ. Res. Public Health* **20**, 5004 (2023).
81. Li, Z. et al. Biophilic environment with visual-olfactory stimuli contributes to psychophysiological restoration and cognitive enhancement. *Build. Environ.* **250**, 111202 (2024).
82. Ba, M. & Kang, J. A laboratory study of the sound-odour interaction in urban environments. *Build. Environ.* **147**, 314–326 (2019).

83. Hartig, T., Mitchell, R., de Vries, S. & Frumkin, H. Nature and Health. *Ann. Rev. Public Health* **35**, 207–228 (2014).
84. van den Berg, M. et al. Health benefits of green spaces in the living environment: A systematic review of epidemiological studies. *Urban For. Urban Green.* **14**, 806–816 (2015).
85. IPBES, Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. *E. S. Brondizio, J. Settele, S. Díaz, and H. T. Ngo IPBES secretariat, Bonn, Germany*. 1148 pages (p. 466) https://doi.org/10.5281/zenodo.3831673 (2019).
86. Bratman, G. N., Hamilton, J. P. & Daily, G. C. The impacts of nature experience on human cognitive function and mental health. *YearEcol. Conserv. Biol.* **1249**, 118–136 (2012).
87. Deng, L. et al. Effects of integration between visual stimuli and auditory stimuli on restorative potential and aesthetic preference in urban green spaces. *Urban For. Urban Green.* **53**, 126702 (2020).
88. Lee, J. et al. Effect of forest bathing on physiological and psychological responses in young Japanese male subjects. *Public Health* **125**, 93–100 (2011).
89. Song, C., Ikei, H. & Miyazaki, Y. Physiological effects of forest-related visual, olfactory, and combined stimuli on humans: an additive combined effect. *Urban For. Urban Green.* **44**, 126437 (2019).
90. Schebella, M. F., Weber, D., Schultz, L. & Weinstein, P. The nature of reality: human stress recovery during exposure to biodiverse, multisensory virtual environments. *Int. J. Environ. Res. Public Health* **17**, 56 (2019).
91. Henshaw, V., McLean, K., Medway, D., Perkins, C., Warnaby, G. *Designing with Smell. Practices, Techniques and Challenges* (Routledge, 2017).
92. Spence, C. Using ambient scent to enhance well-being in the multisensory built environment. *Front. Psychol*. **11**, 598859 (2020).
93. Antonelli, M. et al. Forest volatile organic compounds and their effects on human health: a state-of-the-art review. *Int. J. Environ. Res. Public Health* **17**, 6506 (2020).
94. Gibbs, J. E. M. Essential oils, asthma, thunderstorms, and plant gases: a prospective study of respiratory response to ambient biogenic volatile organic compounds (BVOCs). *J. Asthma Allergy* **12**, 169–182 (2019).
95. Korpilo, S. et al. Landscape and soundscape quality promote stress recovery in nearby urban nature: a multisensory field experiment. *Urban For. Urban Green.* **95**, 128286 (2024).
96. Olszewska-Guizzo, A., Sia, A., Fogel, A. & Ho, R. Can exposure to certain urban green spaces trigger frontal alpha asymmetry in the brain? Preliminary findings from a passive task EEG study. *Int. J. Environ, Res. Public Health* **17**, 394 (2020).
97. Wolfe, J. et al. *Sensation & Perception* (Sunderland, Massachusetts, USA, 2015)
98. Pellegrino, R., Sinding, C., de Wijk, R. A. & Hummel, T. Habituation and adaptation to odors in humans. *Physiol. Behav.* **177**, 13–19 (2017).
99. Elkholi, S. M. A., Abdelwahab, M. K. & Abdelhafeez, M. Impact of the smell loss on the quality of life and adopted coping strategies in COVID-19 patients. *Eur. Arch. Oto-Rhino-Laryngol.* **278**, 3307–3314 (2021).
100. Wu, T. J., Yu, A. C. & Lee, J. T. Management of post-COVID-19 olfactory dysfunction. *Curr. Treat. Options Allergy.* **9**, 1–18 (2022).
101. Ugolini, F. et al. Effects of the COVID-19 pandemic on the use and perceptions of urban green space: An international exploratory study. *Urban For. Urban Green.* **56**, 126888 (2020).
102. Lindemann-Matthies, P., Junge, X. & Matthies, D. The influence of plant diversity on people's perception and aesthetic appreciation of grassland vegetation. *Biol. Conserv.* **143**, 195–202 (2010).
103. Hedblom, M., Heyman, E., Antonsson, H. & Gunnarsson, B. Bird song diversity influences young people's appreciation of urban landscapes. *Urban For. Urban Green.* **13**, 469–474 (2014).

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Author contributions

All authors contributed to the conceptualization of the study. F.T. literature review, writing - original draft. A.M.P. supervision, writing - review and editing. M.H. supervision, writing - review and editing. All authors reviewed the final manuscript.

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Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Francesca Taufer.