

Scent of trees: Investigating the short-term effects of two tree essential oils on mood, psychological stress, and cognition

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ABSTRACT

The sensory experience of nature involves all senses, yet the olfactory pathway has been largely overlooked. Research shows that exposure to natural environments benefits mood, stress, and cognitive functioning. To explore this further, we conducted two studies to assess whether short-term exposure to essential oils from two trees, the Douglas fir (*Pseudotsuga menziesii*) and the Hinoki cypress (*Chamaecyparis obtusa*), influences these outcomes.

In both studies, participants (first study $n = 68$, second study $n = 34$) completed one mood and psychological stress assessment along with seven cognitive tasks on two separate days. During testing, an ultrasonic diffuser containing either essential oil from one of the trees or clear water was activated. Participants were randomised into one odorant group (Douglas fir vs. Hinoki) and experienced both exposure conditions in randomised order (odorant vs. placebo).

The initial study showed marginal evidence of an effect of the Douglas fir scent on vigilance, prompting a follow-up study to boost statistical power. However, combined analysis revealed no significant effects of either odorant group on mood, psychological stress, or cognitive performance. Interestingly, most participants could not reliably identify the odour, suggesting limited conscious awareness and/or semantic associations.

Our findings suggest that short-term exposure to these two tree essential oils does not produce immediate effects on the tested outcomes. Further research is needed to explore the role of conscious perception, semantic associations, individual odour preferences, and long-term exposure to forest scents in modulating emotional states and cognition.

1. Introduction

A deep inhale reveals the forest's scent as the wind rustles the green leaves. Even though nature engages all our senses, this experience is slowly fading from daily life due to urbanisation. With more and more people globally living in urban areas (United Nations D. o. E. a. S. A. Population Division, 2019), the opportunities to experience nature as a part of everyday life are decreasing. Meanwhile, meta-analyses have shown that exposure to natural environments positively impacts emotional well-being by enhancing positive affect and reducing negative affect (McMahan & Estes, 2015), as well as decreasing psychological and physiological stress (Gaekwad et al., 2023; Yao et al., 2021). Moreover, beneficial effects of nature exposure were also found for cognitive functioning (Nguyen & Walters, 2024; Ohly et al., 2016; Stenfors et al., 2019; Stevenson et al., 2018; Weeland et al., 2019),

especially in the domains of working memory, executive control, attentional control, and cognitive flexibility, as well as self-regulation. Many of the studies reviewed in the meta-analyses cited above investigated participants after a walk or an extended stay in nature. Considering the increasingly reduced accessibility of natural environments, it seems relevant to investigate the specific natural features that drive the beneficial effects of natural environments (Bratman et al., 2019) to understand which natural features should be integrated into urban everyday life. Most studies utilising this approach have focused on the visual pathway by studying virtual representations of nature, such as photos, videos, or virtual reality (Berry et al., 2015; Bourrier et al., 2018; Mostajeran et al., 2021). The beneficial effects of natural environments can also be observed from these purely visual stimuli, but are typically less pronounced than exposure to real-life nature (Stevenson et al., 2018). Regarding auditory stimuli, greater mood recovery from an

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unsettling video was reported after exposure to purely natural soundscapes than after exposure to natural sounds combined with anthropogenic sounds (human voices or motorized vehicles) (Benfield et al., 2014). Moreover, natural soundscapes, either in combination with visual stimuli or without, showed mixed effects on cognition (Emfield & Neider, 2014; Stobbe et al., 2023; Van Hedger et al., 2019).

Breath in. Another important sensory channel that plays a role in human perception is the sense of smell, which is strongly linked to brain regions associated with emotional processing (e.g., the limbic system), memories of experiences, and other senses (Gottfried & Dolan, 2003; Herz, 2004; Willander & Larsson, 2006; Zald & Pardo, 1997). Although the olfactory pathway is a key, albeit inconspicuous, part of our everyday lives, so far, research on the effects of nature has largely overlooked olfactory stimuli (Press & Mintz, 2000). However, natural environments such as forests produce a variety of volatile organic compounds (VOCs) and other airborne molecules that contribute to our experience of nature. Bratman and colleagues (2024) developed a conceptual framework with two primary olfactory pathways to research how these compounds affect humans. One olfactory pathway relies on the nonconscious processing of VOCs and other airborne molecules. Studies providing evidence for this pathway have investigated the mechanisms behind the health benefits of forest bathing (*shinrin-yoku*). These studies have demonstrated that exposure to terpenes (tree-derived phytoncides such as α -pinene and limonene) can produce short-term health effects, including anti-inflammatory responses and increased activity of natural killer cells (Andersen et al., 2021; Cho et al., 2017; Li et al., 2009). Furthermore, exposure to tree essential oils has been linked to reductions in stress-related physiological parameters, such as blood pressure, heart rate, parasympathetic nervous activity, and noradrenaline levels (Baik et al., 2018; Chen et al., 2015; Ikei et al., 2015; Kim et al., 2023; Li et al., 2009). It should be noted, however, that it remains unclear to what extent these effects are driven by unconscious neuro-immunological processes or by the conscious perception of smell (Bratman et al., 2024). The other olfactory pathway of plant-based VOCs involves the conscious perception of odour. In this complex process, an initial cross-cultural pre-linguistic, affective component appears to precede later cognitive processing of the odour (Majid et al., 2018). This subsequent cognitive evaluation is influenced by various moderating factors, such as individual preferences, prior experiences and associations, cultural influences, and multisensory context (Bratman et al., 2024). The overall finding that pleasant or unpleasant odours have an effect on mood and emotions (Kontaris et al., 2020) may primarily be linked to this pathway.

A significant number of these previous studies focused on the effects of essential oils derived from trees, such as the Hinoki cypress (Chen et al., 2015; Li et al., 2009; Shima et al., 2025; Yamada et al., 2011) and fir trees (Kim et al., 2023; Kim & Song, 2022). Both tree species contain a wide range of terpenes and have previously been linked to mood enhancement (Chen et al., 2015; Shima et al., 2025), psychological and physiological relaxation (Kim et al., 2023; Kim & Song, 2022), and health benefits (Li et al., 2009).

In the debate over whether the hedonic perception of odours is innate or learned, an experimental study demonstrated that when an unfamiliar odour was paired with an emotional event, hedonic odour perception was altered to reflect the associated emotion (Herz et al., 2004). This suggests that previous experiences with odours can play a significant role in their effects on mood and health benefits. The previously reported studies primarily exposed participants to essential oils derived from tree species typical of the region in which participants were tested. To investigate whether familiarity with an odour influences its effect, we examined the short-term effects of two essential oils, the Douglas fir (*Pseudotsuga menziesii*) tree and the Japanese native Hinoki cypress (*Chamaecyparis obtusa*) tree, on mood and psychological stress. For the German sample recruited in the present study, Hinoki is not a native species that they will have encountered in a German forest. The Douglas fir, on the other hand, constitutes an odour that German

participants will likely associate with forests they know.

In addition to personal experiences with odour, the semantic assignment of an odour to a specific category or origin also appears to influence its perception. A previous study showed that individuals' reactions to an identical smell (a mixture of isovaleric and butyric acids) varied significantly depending on whether it was labelled "cheese" or "vomit" (Herz & von Clef, 2001). Furthermore, an initial study using a neural network-based language model demonstrated that some nature-related words were significantly associated with mental health-related positive-versus-negative word pairs (such as relaxation-versus-stress or restoration-versus-burnout) (Gladwin et al., 2023). The authors argue that, regardless of their origin, semantic associations could play a role in the effects of nature on mental health. Against this background, we deliberately omitted mentioning the concepts "nature", "forest", and "tree", as was any mention of exposure to odorants in the present study.

Beyond the short-term effects on health and well-being, previous literature has investigated the effects of specific herbal essential oils on cognitive functioning (Johnson, 2011). In particular, the odorants sage/salvia, peppermint, and rosemary have been shown to facilitate memory and sustained attention (Kennedy & Scholey, 2006; Lopresti, 2017; Tildesley et al., 2003; Warm et al., 1991). However, essential oils from forest trees have rarely been studied. Exposure to essential oil from the Hinoki tree has shown inconsistent effects on cognitive performance. Two studies with a sample size of $n = 6$ participants each reported an improvement in an attention task (letter cancellation) when the participants were exposed to a Taiwan cypress wood oil (Miyazaki et al., 1992, 1994). Additionally, eight participants achieved significantly more correct calculations in the Uchida-Kraepelin test when seated in a test room with interior walls made from hinoki wood compared to a control condition without wood (Kishida et al., 2025). In contrast, Yamada and colleagues (2011) observed a reduction in a word-color Stroop task performance in response to intermittent Hinoki wood odour exposure ($n = 8$). The very small sample sizes in these previous studies limit the conclusions that can be drawn from these partly inconsistent results.

Our aim, therefore, was to investigate the short-term effects of the two tree odorants on cognitive performance in a larger sample. Since no specific cognitive domain has yet been definitively identified as particularly sensitive to forest odour exposure, we employed a broad battery of cognitive tasks. We selected the tasks based on relevant cognitive domains that have previously been shown to be sensitive to nature exposure or to the application of herbal essential oil (Johnson, 2011; Nguyen & Walters, 2024; Ohly et al., 2016; Stenfors et al., 2019; Stevenson et al., 2018; Warm et al., 1991; Weeland et al., 2019).

2. Material and methods

Two separate studies were conducted to investigate the effects of two tree odorants (Douglas fir and Hinoki) on mood, psychological stress, and cognitive performance. The overall sample size across both studies was $N = 102$ participants. In the first study, $n = 68$ participants were randomly assigned to one of the tree odorants ($n = 34$ Douglas fir; $n = 34$ Hinoki). The data from this initial study showed a marginal effect for the Douglas fir exposure on vigilance. To increase statistical power for detecting and possibly confirming this effect for Douglas fir exposure, a second study was conducted, which included only the Douglas fir odorant group. This second study included $n = 34$ additional participants, resulting in a total sample size of $n = 68$ participants in the Douglas fir odorant group ($n = 34$ first study and $n = 34$ second study; see Table 1). Both studies shared an almost identical procedure; the additions to the second study are detailed below.

2.1. First study

Based on the reported effect sizes of nature exposure on mood,

Table 1
Socioeconomic and demographic characteristics of the participant sample.

Characteristic	Odorant group			Hinoki
	Douglas fir			
	Study 1 (n = 34)	Study 2 (n = 34)	Study 1 & 2 (n = 68)	Study 1 (n = 34)
Age in years	28.34	28.15	28.24	28.23
Sex ^a	52.94 %	52.94 %	52.94 %	52.94 %
Years of education	17.82	17.98	17.90	18.40
POMS overall	48.64	51.72	50.18	45.12
PSS total score	23.54	22.76	23.15	22.62

Note. Total sample size = 102. Values represent means. ^aPercentage of female participants. POMS = Profile of Mood States, PSS = Perceived Stress Scale.

psychological stress, and cognitive performance ranging from small to medium (McMahan & Estes, 2015; Stevenson et al., 2018; Yao et al., 2021), the first study assessed 34 participants per odorant group, guided by an a-priori sample size calculation (ANOVA repeated measures, within factors, $f = 0.25$, $\alpha = .05$, power = 0.8) using G*Power (Faul et al., 2007). In total, seventy-two individuals were recruited via online advertisements and flyers. Four volunteers dropped out after the first session and were therefore excluded, leaving $n = 68$ participants in the final sample (see Table 1).

All volunteers received the study information, which described the experiment as an investigation of retest effects. According to the single-blinded design, forest odorant exposure was intentionally not explicitly mentioned. In this context, the exclusion criteria (uncontrolled asthma, allergic reaction to fragrances, and persistent lung disease) were verified by an additional questionnaire, which included various health measures (e.g. health condition in general, flu infection in the preceding weeks). The screening process was extended to include a COVID-19 symptom questionnaire from March 2, 2020 onwards due to the COVID-19 pandemic. Before the study debriefing, each participant was asked to speculate on the experiment's hypothesis and to report any odour

detected during the sessions. All participants provided written informed consent. The study was preregistered on [AsPredicted.org](https://aspredicted.org/#34486) (#34486; https://aspredicted.org/K1T_4J3).

2.1.1. Procedure

For the first study, participants were randomly assigned to one of two odorant groups (Douglas fir vs. Hinoki). Each participant was assigned to a single odorant group and thus experienced just *one* forest odorant. However, within each odorant group, participants attended two exposure conditions (odorant vs. placebo) in two distinct test sessions in a within-subject crossover design (see Fig. 1). The exposure conditions were applied in a randomised order. Half the participants experienced odorant exposure in the first session and the placebo in the second, while the other half received the exposure conditions in reverse order.

The first study involved two test sessions, separated by one or two nights. Both were conducted at the same time of day for each participant. To realise the exposure condition (odorant vs. placebo) an Ultrasonic Oil Diffuser HM004 (VicTsing, Sunnyvale United States) was placed centrally in the testing room, approximately 19 square meters in size (see Fig. S1 in the Supplementary Material). Fifteen minutes before each session, the test room was ventilated for 10 min. This was followed by a 5-min pre-test period during which the diffuser was activated. The diffusion rate was 30 – 50 ml per hour and the diffuser remain activated for the entire testing duration. In the placebo condition, the diffuser contained 150 ml of clear water, while in the odorant conditions three drops of the respective essential oil were added. One hundred per cent natural essential oil was used for the Hinoki odorant, extracted through steam distillation of heartwood from the *Chamaecyparis obtusa* (Essence pur, Lohmar Germany). The Douglas fir condition consisted of a natural steam-distilled essential oil used from *Pseudotsuga menziesii* (Primavera, Oy-Mittelberg Germany). An overview of the components of both essential oils' obtained by mass spectrometry data, along with information about the diffuser and the testing environment, can be found in the Supplementary Material (see Tables S1–S2 and Fig. S1). Regardless of the exposure condition (odorant or placebo), the experimenter introduced the diffuser as a humidifier. During the testing session, the

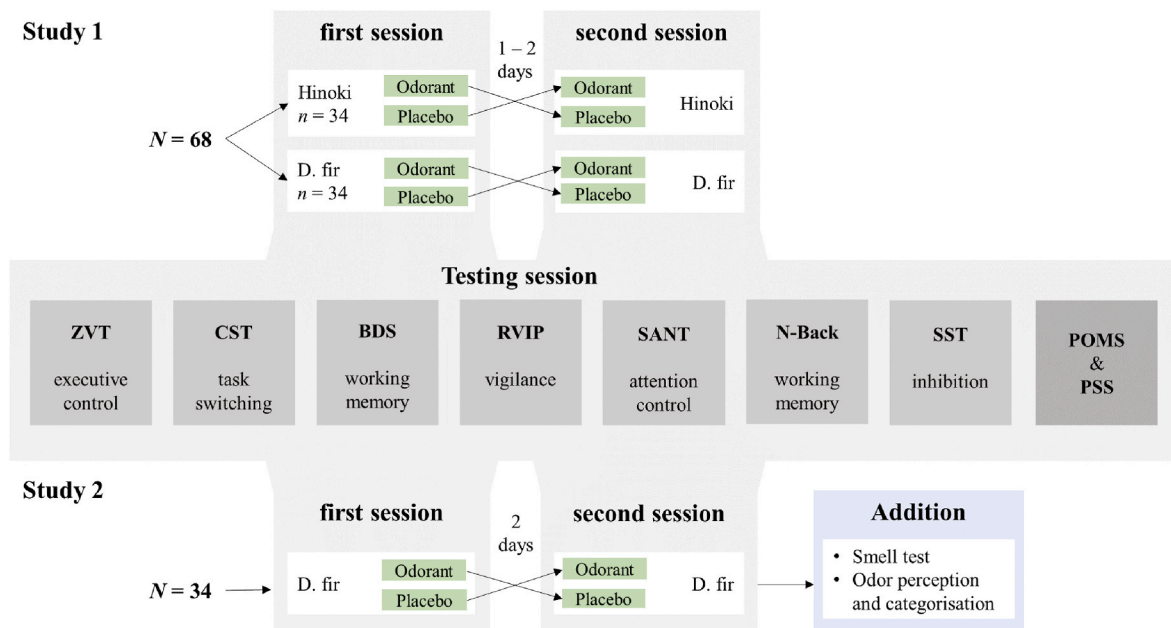


Fig. 1. Study design and procedure.

Note. All participants in the first study were randomised to *one* of the two odorant groups (Hinoki vs. D. fir = Douglas fir), whereby each participant performed the same measurements under *both* exposure conditions (odorant vs. placebo). In the second study, only the Douglas fir group was assessed and two additional measurements were performed at the end of the second study (highlighted in blue). The tasks and questionnaires used are listed in the performance order. ZVT = Zahlen Verbindungstest [German version of a trail making task], CST=Category Switch Task, BDS=Backwards Digit Span, RVIP=Rapid Visual Information Processing, SANT=Short Attentional Network Task, N-Back = N-Back Task, SST= Stop Signal Task, POMS=Profile of Mood States, PSS=Perceived Stress Scale.

diffusor stayed active and the windows remain closed. While the room temperature between participants varied between 17.9 and 23.6 °C, the temperature within the same participant between the two test sessions varied by an average of 0.78 °C. During both sessions, the same experimenter was seated in the room with one or two participants. All participants were instructed to wear noise-cancelling headphones while completing the computer-based test battery.

2.1.2. Measures

The session started with the German paper-pencil version of a trail making task, the Zahlen Verbindungstest (ZVT, Oswald & Roth 1987), before a computer-based task battery (Inquisit software 4.0.5) was performed. The task battery took approximately 75 min to complete. All computer tasks involved stimuli that were presented in a randomised order to prevent predictable sequences. Since our participants performed the same tests twice, this randomization ensured that the stimuli appeared in different sequences during each session, even though the task itself was familiar. As the ZVT is a paper-pencil task, we used parallel version A or B for the two test time points. The task battery was followed by the German versions of the Profile of Mood States (POMS, McNair et al., 1981) and the 10-item Perceived Stress Scale (PSS, Cohen, 1988; Schneider et al., 2020). Following the second testing session, participants answered a short questionnaire assessing the assumed purpose of the study and their perception of odour during the sessions.

2.1.2.1. Mood. To assess participants' current mood, the short version of the Profile of Mood States (POMS; McNair et al., 1981) was administered in German. Participants answered 35 POMS items on a 7-point Likert scale (1 = not at all; 7 = very strong) with the instruction to refer only to the last 60 min. The four subfactors of the POMS (depression/anxiety, fatigue, vigor and anger) were calculated according to the manual.

2.1.2.2. Psychological stress. The German adaptation of the Perceived Stress Scale (PSS; Cohen, 1988; Schneider et al., 2020) was assessed with ten items answered on a 5-point Likert scale (1 = never; 5 = very often). The items were introduced with the phrase: "In the last 60 min ...". The total PSS score was derived by combining the Perceived Helplessness and Perceived Self-Efficacy subscales.

2.1.2.3. Cognitive measures. Since no specific cognitive domain has yet been identified as particularly sensitive to forest odorant exposure, we employed a broad battery of cognitive tasks and focused on the relevant cognitive domains that have been associated with sensitivity to exposure to nature or herbal essential oils (see Table 2). Based on the assumption that the ability to restore concentration is a key mechanism behind the beneficial effects of nature on cognitive performance (Ohly et al., 2016), we decided to administer the cognitive tasks in a fixed order. This operational approach ensures that fatigue effects resulting from the demanding cognitive battery would be less variable across the different tasks. Instead, the approach was designed to facilitate the identification of any restoration effects if they existed.

The session started with the A or B variant of the Zahlen Verbindungstest (ZVT) (Oswald & Roth, 1978), to capture executive control. Participants were instructed to connect 90 digits (from 1 to 90) in ascending order by drawing a line as quickly as possible between them. Participants had 30 s to complete the task. The score equalled the total number of correctly connected digits.

Next, the Category Switch Task (CST) was performed (Friedman et al., 2008; Mayr & Kliegl, 2000). In each trial, participants had to perform one of two categorisation tasks by pressing the correct key response; they had to either (1) categorise the presented word according to whether it represented a living or non-living object, or (2) determine whether the presented word was bigger or smaller than a basketball. In each trial, one of the sixteen target words was randomly presented.

Table 2
Overview of the tasks, cognitive domains, and calculation of the dependent variables used.

Task	Cognitive domain	Included because of sensitivity to	Dependent variables	Calculation
ZVT	executive control	nature exposure (Nguyen & Walters, 2024; Ohly et al., 2016)	number correct	total number of correctly connected digits
CST	task switching	nature exposure (Stevenson et al., 2018)	mean rt SC	mean rt of switch trials - the mean rt of non-switch trials
BDS	working memory	nature exposure (Ohly et al., 2016; Stenfors et al., 2019; Stevenson et al., 2018)	accuracy SC	proportion of cr in switch trials - proportion of cr in non-switch trials
RVIP	vigilance/sustained attention	herbal odour exposure (Johnson, 2011; Warm et al., 1991)	two error ML	length of the last digit sequence reported correctly before making two consecutive errors
SANT	attention control	nature exposure (Nguyen & Walters, 2024; Stevenson et al., 2018)	consistency	number of trials before reaching the two-maximum error length
N-Back	working memory	nature exposure (Stevenson et al., 2018)	number false alarms	total amount of false alarms
			% correct	proportion of correct responses
			rt correct	mean rt of cr
			% correct	proportion of the cr across all conditions
			rt correct	mean rt of all cr across all conditions
			orienting effect	mean rt of cr in condition (a) - mean rt of cr in condition (b)
			conflict effect	mean rt of cr in the incongruent condition - mean rt of cr in the congruent condition
			maximum N	maximum achieved n-back level
			mean N	mean achieved n-back level
			number hits	the number of total hits
			number false alarms	number of total false alarms
			DV	proportion of total hits - false alarms
SST	inhibition	nature exposure (Faber Taylor et al., 2002; Weeland et al., 2019)	SSRT	mean stop-signal delay - mean reaction time of the go task

Note. ZVT = Zahlen Verbindungstest [German version of a trail making task], CST=Category Switch Task, rt = reaction time, SC = switch cost, cr = correct responses, BDS=Backwards Digit Span; ML = maximum length; RVIP= Rapid Visual Information Processing, SANT=Short Attentional Network Task, N-Back = N-Back Task, DV = proportion of total hits minus false alarms, SST=Stop Signal Task, SSRT = mean stop-signal reaction time.

Which categorisation task had to be performed was signalled by the symbol displayed directly above the word; a heart indicated the (1) categorisation task, whereas a cross indicated the (2) size task. A reminder of the key mapping was provided in the first eight trials as a practice block to familiarise participants with the tasks. In 50% of the test trials the same categorisation task as the previous trial (non-switch) was required; the other 50% required a switch of the categorisation task compared to the previous trial (switch). The average reaction time of switch trials minus the average reaction time of non-switch trials constitutes a measure representing the switch cost reaction time. The switch cost in proportion to correct responses was calculated (proportion of correct responses in switch trials - the proportion of correct responses in non-switch trials).

The Backwards Digit Span Task (BDS) is a visual implementation of the Digit span procedure (Woods et al., 2011). All participants were required to repeat a previously presented random number sequence in backwards order. In the number presentation phase, each digit was shown for 1 s in the middle of a white computer screen. The test block started with a two-digit sequence. It was adapted based on a 1:2 staircase procedure, in which the sequence was increased by one digit if participants responded correctly. In the case of two consecutive errors, the sequence length was decreased by one. A fixed number of fourteen sequence trials was conducted. The two-error maximum length (length of the last digit sequence reported correctly before making two consecutive errors), and the measure of consistency (number of trials before reaching the two-maximum error length) were the outcome variables we focussed on.

To assess vigilance, the Rapid Visual Information Processing (RVIP) was performed (Wesnes & Warburton, 1984). In this task, pseudorandomised digits series (ranging from 1 to 9) were presented with a rate of 100 digits/min (1 digit/600 ms). Participants were instructed to press the response key as soon as they detected a series of three consecutive odd or even digits. The total amount of false alarms, the proportion of correct responses, as well as the mean reaction time (milliseconds) for correct responses, were used as outcome measures.

The Short Attentional Network Task (SANT) was used to assess orienting and executive attention (Fan et al., 2002). In this task, five arrows were presented in a row, pointing either in the same (congruent condition) or in different directions (incongruent condition). The participants were instructed to indicate the direction of the middle arrow by pressing the correct response key as quickly and accurately as possible. Every trial started with a black fixation cross presented for a random duration of 400 to 1600 ms before one of three condition cues was shown for 100 ms. In each of these condition cues, an asterisk was displayed either (a) in the middle of the screen to alert the participants that the target arrows were about to be shown or (b) above or below the fixation cross to indicate where the target arrows were to be presented or (c) not at all. After the cue, the fixation cross was shown for 400 ms before the target arrows appeared above or below the fixation cross. The proportion of correct responses and the mean reaction time across all conditions, as well as the orienting effect (mean reaction time of correct responses in condition (a) - mean reaction time of correct responses in condition (b)) and the conflict effect (mean reaction time of correct responses in the incongruent condition - mean reaction time of correct responses in the congruent condition), were used as dependent variables.

An adaptive version of the single N-Back Task (Jaeggi et al., 2010) was used to assess working memory performance. A sequence of eight different yellow shapes (Vanderplas & Garvin, 1959) was presented on a black background. Each shape was presented for 500 ms and was followed by a 2500 ms inter-stimulus interval before the next shape was shown. The participants were instructed to respond when the current stimulus was identical to the stimulus presented n trials before. The test started with $n = 1$ and was adapted based on the individual participant's performance. Feedback was presented after each test block. When at least 90% of the responses were correct, n increased by one; when

performance dropped to 75% or below, n was decreased. In the remaining trials, n stayed at the same level. In addition to the maximum achieved and mean n -back level, the number of total hits, number of total false alarms, as well as the proportion of total hits minus false alarms (DV), were outcome measures we selected.

The Stop Signal Task (SST) was used to assess inhibitory control (Logan, 1994; Verbruggen et al., 2008). After a fixation cross, a right- or left-pointing arrow was presented in white on a black background for a maximum of 1250 ms. Participants were instructed to press the correct response key as quickly and accurately as possible, depending on the arrow's direction (go task). Randomly and in 33% of the trials, an auditory stop signal was presented, indicating that participants should refrain from pressing the button (stop task). The stop-signal delay between the go and the stop signal stimulus started at 250 ms and was continuously adjusted by a 50 ms increase or decrease, depending on individual success at inhibiting the response (staircase procedure). The mean stop-signal reaction time (SSRT) was estimated by subtracting the mean stop-signal delay from the mean reaction time of the go task (Logan et al., 1997); this was used as the main outcome measure.

2.2. Second study

The second study assessed $n = 34$ additional participants (see Table 1) in the Douglas fir odorant group, to increase the statistical power of the first study. The study procedure was identical to study one, with only the following additions.

Because of the COVID-19 pandemic, all measurements were carried out with only one participant in the test room. The experimenter was present in the room next door. The odorant in the study was dosed with a pipette and comprised exactly 100 μ l of the same essential oil of Douglas fir, addressing inconsistencies from using three drops in the first study (see supplemental material for mass spectrometric data Table S2). Following each testing session, we asked participants whether they perceived an odour. If they reported any odour, we asked additional questions regarding the odour's perceived characteristics, including valence, intensity, familiarity, description, and assigned categories (see Supplementary Material Table S3). This alteration prevented us from asking participants in the last session about their assumptions regarding the study's hypothesis (as we did in study one). Having been asked about perceived odours already after the first test time point (regardless of the exposure condition), participants may have become more conscious of the possible presence of odours during the study. Nevertheless, we decided to include this additional assessment in the first study because we wanted to account for individual feedback on odour valence, familiarity, and categorisation.

At the end of the study, a threshold smell test with odour sticks (Odofin Sniffin' sticks, Germany) was carried out to capture the olfactory performance of the participants on the day of the examination (see Supplementary Material). As in study one, all participants provided written informed consent. The second study was preregistered in [AsPredicted.org](https://aspredicted.org/#91499) (#91499, <https://aspredicted.org/yt2x-7z9r.pdf>).

2.3. Statistical analysis

For all data, the outliers of the dependent variables were excluded using the median absolute deviation (MAD) with a deviation of 2.5 units (Leys et al., 2013), as this approach is more robust and less sensitive to extreme outliers and sample size. The number of removed outliers ranged from 0 to 19 datapoints. Moreover, the data of seven individuals who performed below the 10% percentile in the threshold smell test based on normative data of $N = 9139$ participants (Oleszkiewicz et al., 2019) were excluded. The observations used for each statistical model are presented in Table 3. Analysis of the dataset including the outliers and individuals who performed below the 10% percentile in the threshold smell test are presented in the Supplementary Material Table S5a and S5b. Linear mixed-effects models were performed using

Table 3

The estimates (Est), standard errors (std. E), confidence intervals (CI), and p-values of the within-subject factor exposure condition (odorant vs. placebo) in the linear mixed effect models of the frequentist approach as well as the Bayes factors (BF) are presented for the Hinoki odorant group and the combined dataset of study one and two for the Douglas fir odorant group.

Task	Dependent variable	Odorant group	Obs.	Frequentist approach				Bayesian approach
				Est	std. E	CI	p	BF
ZVT	number correct	D. fir	117	1.70	0.87	−0.03 – 3.42	0.054	0.061
		Hinoki	65	−1.43	1.06	−3.55 – 0.69	0.18	0.036
CST	mean rt SC	D. fir	122	19.89	17.33	−14.44 – 54.22	0.25	0.035
		Hinoki	67	4.67	17.27	−29.84 – 39.18	0.79	0.018
	accuracy SC	D. fir	111	−0.00	0.01	−0.02 – 0.02	0.91	0.023
		Hinoki	67	−0.00	0.01	−0.02 – 0.02	0.87	0.031
BDS	two error ML	D. fir	117	−0.14	0.18	−0.51 – 0.22	0.43	0.021
		Hinoki	65	−0.08	0.22	−0.53 – 0.37	0.73	0.023
	consistency	D. fir	111	−0.28	0.26	−0.80 – 0.23	0.28	0.043
		Hinoki	64	−0.27	0.32	−0.90 – 0.37	0.40	0.052
RVIP	number false alarms	D. fir	103	0.12	0.79	−1.46 – 1.69	0.88	0.015
		Hinoki	59	−1.05	1.22	−3.50 – 1.39	0.39	0.044
	% correct	D. fir	122	−0.00	0.01	−0.03 – 0.03	0.79	0.008
		Hinoki	68	0.03	0.02	−0.02 – 0.07	0.24	0.051
	rt correct	D. fir	118	10.50	6.59	−2.55 – 23.55	0.11	0.045
		Hinoki	67	1.44	11.35	−21.24 – 24.13	0.90	0.027
SANT	% correct	D. fir	118	−0.18	0.23	−0.64 – 0.27	0.43	0.021
		Hinoki	66	0.03	0.23	−0.43 – 0.49	0.89	0.014
	rt correct	D. fir	117	−0.54	3.23	−6.94 – 5.87	0.87	0.003
		Hinoki	62	−1.71	3.75	−9.21 – 5.79	0.65	0.009
	orienting effect	D. fir	121	0.61	3.16	−5.65 – 6.87	0.85	0.016
		Hinoki	66	3.21	3.97	−4.73 – 11.16	0.42	0.048
	conflict effect	D. fir	113	−3.86	2.44	−8.69 – 0.98	0.12	0.055
		Hinoki	65	0.36	3.70	−7.04 – 7.76	0.92	0.024
N-Back	maximum N	D. fir	120	0.17	0.13	−0.09 – 0.42	0.20	0.032
		Hinoki	67	0.11	0.25	−0.38 – 0.60	0.66	0.028
	mean N	D. fir	118	0.03	0.07	−0.10 – 0.17	0.61	0.012
		Hinoki	66	0.05	0.13	−0.22 – 0.32	0.71	0.025
	number hits	D. fir	122	−0.96	0.94	−2.83 – 0.90	0.31	0.014
		Hinoki	67	0.97	1.44	−1.91 – 3.84	0.51	0.027
	number false alarms	D. fir	120	−0.66	0.95	−2.55 – 1.23	0.49	0.009
		Hinoki	68	−0.26	1.28	−2.81 – 2.29	0.84	0.013
	DV	D. fir	117	−0.03	0.05	−0.12 – 0.07	0.60	0.017
		Hinoki	61	0.10	0.07	−0.04 – 0.24	0.16	0.078
SST	SSRT	D. fir	116	6.06	6.00	−5.82 – 17.95	0.31	0.034
		Hinoki	66	0.93	8.63	−16.32 – 18.17	0.92	0.031

Note. Obs. = observations, D. fir = Douglas fir, ZVT = Zahlen Verbindungstest [German version of a trail making task], CST=Category Switch Task, rt = reaction time, SC = switch cost, BDS=Backwards Digit Span, ML = maximum length, RVIP= Rapid Visual Information Processing. SANT=Short Attentional Network Task, N-Back = N-Back Task; DV = proportion of total hits minus false alarms, SST= Stop Signal Task, SSRT = mean stop-signal reaction time (mean stop-signal delay - mean reaction time of the go task).

the lmer(.) function from the lme4 package (version 1.1-35.5; Bates et al., 2015) in R (version 4.3.2; R Core Team, 2023). The participants' ID was used as a random intercept to control for within-subject effects, while the exposure condition (odorant vs. placebo) was included as a fixed factor. The variable test time point (first vs. second) was integrated as a covariate to control for order effects:

$$H1 \leftarrow \text{lmer}(X \sim \text{exposure} + \text{test time point} + (1 | \text{ID}))$$

The model was applied for each dependent variable and each odorant group. According to Glickman et al. (2014) the Benjamini-Hochberg correction (BH; Benjamini & Hochberg, 1995) was used to control for multiple testing within each odorant group. This statistical approach calculates the false discovery rate (FDR) as the

probability of a false positive (null hypothesis is incorrectly rejected), given the total number of rejected hypotheses (true positive and false positives).

The data of the first study was analysed first and revealed a significant result in the vigilance task for the Douglas fir odorant group (Table S6, Supplementary Material). Note that this result did not survive the correction for multiple testing. Therefore, the second study was conducted to increase statistical power. The data of both studies from the Douglas fir odorant group was then combined and analysed together. The analysis of the data from the second study alone is summarised in the Supplementary Material Table S7a and S7b.

This study initially employed a frequentist approach, which limits the interpretation of observed null effects of the exposure condition

(odorant vs. placebo). In contrast, the Bayesian approach allows for the quantification of evidence in favour of the null hypothesis, as it directly compares the evidence supporting both the alternative and null hypotheses based on the analysed data. Therefore, we conducted Bayesian generalised linear models using the *rstanarm* package, version 2.32.1 (Goodrich et al., 2024): $H1 \leftarrow \text{stan_glmer}(X \sim \text{exposure} + \text{test time point} + (1 | \text{ID}))$. Given the limited research on the impact of tree essential oil on cognitive performance, we used weakly informative priors (see Tables S9 and S10 in the Supplementary Material). The Bayes factors (BFs) were then computed and are reported in Table 3. Values lower than 1 can be interpreted as evidence in favour of the null hypothesis, suggesting that the exposure variable does not have a significant effect on the dependent variable in our model. The complete R script is available at <https://github.com/DjoFischer/ScentoofNature>.

3. Results

In first study, participants did not differ significantly in the PSS total score or in any of the cognitive tasks between the odorant groups at the first test session. Regarding the mood assessments, only the POMS subscale for anger was significantly higher among participants in the Douglas fir group compared to participants in the Hinoki odorant group (see Table S4a and S4b in the Supplementary Material). The detection of an odour during the test sessions was reported by $n = 7$ in the Hinoki and $n = 8$ in the Douglas fir group, whereby only three participants, all in the Douglas fir group, were able to describe the odour correctly as tree odour. The results of a chi-square test showed no significant differences between the detection of an odour in the two experimental odour conditions, $\chi^2(1) = 0.043$, $p = .87$, $N = 136$.

In the second study, the exposure condition (odorant or placebo) was correctly identified by $n = 16$ participants. Furthermore, only 14.71% ($n = 5$) specifically identified the odour as a tree or forest scent, while 11.76% ($n = 4$) described the smell as earthy, fresh, or woody. Most participants (73.53%, $n = 25$) described the odour in other ways, such as

citrusy, flowery, fruity, or like a cleaning agent. In addition, two participants were able to correctly classify the odour category from a list (see Table S3). Results of analyses including only this subgroup of participants who either identified the odour correctly as originating from a tree or were able to assign the odour to the correct label (first study $n = 3$ and second study $n = 11$; total $n = 14$) showed a significant effect for the fatigue subscale of the POMS as well as an effect in the mean stop-signal reaction time measuring inhibition. Both results indicate a beneficial effect from Douglas fir exposure compared to the placebo, suggesting less fatigue and enhanced inhibition performance. However, it must be noted that neither of these effects remain significant after the correction for multiple comparisons (see Table S8a and S8b in the Supplementary Material).

3.1. Mood and psychological stress

In the first study, no differences were found in the four POMS subscales or the PSS total score for either the Hinoki or the Douglas fir exposure. In the analysis of the combined data (first and second study, $n = 68$), none of the four POMS subscales nor the PSS total score differed significantly between the Douglas fir exposure and the placebo. The estimated effects and error bars for the exposure condition (exposure vs. placebo) on the four POMS subscales and the PSS total score, separated by dataset are presented in Fig. 2. The respective BFs can be found in the supplementary material.

3.2. Cognitive performance

In the Hinoki condition, no significant differences were found in the ZVT, CST, BDS, RVIP, SANT, adaptive N-Back, or in SST performance (see Table 3). In the analysis of the first study, no significant differences were found in either the ZVT, CST, BDS, SANT, adaptive N-Back, or SST performance in the Douglas fir group (see Supplementary Material Table S6). Only in the test to assess vigilance did the Douglas fir odorant

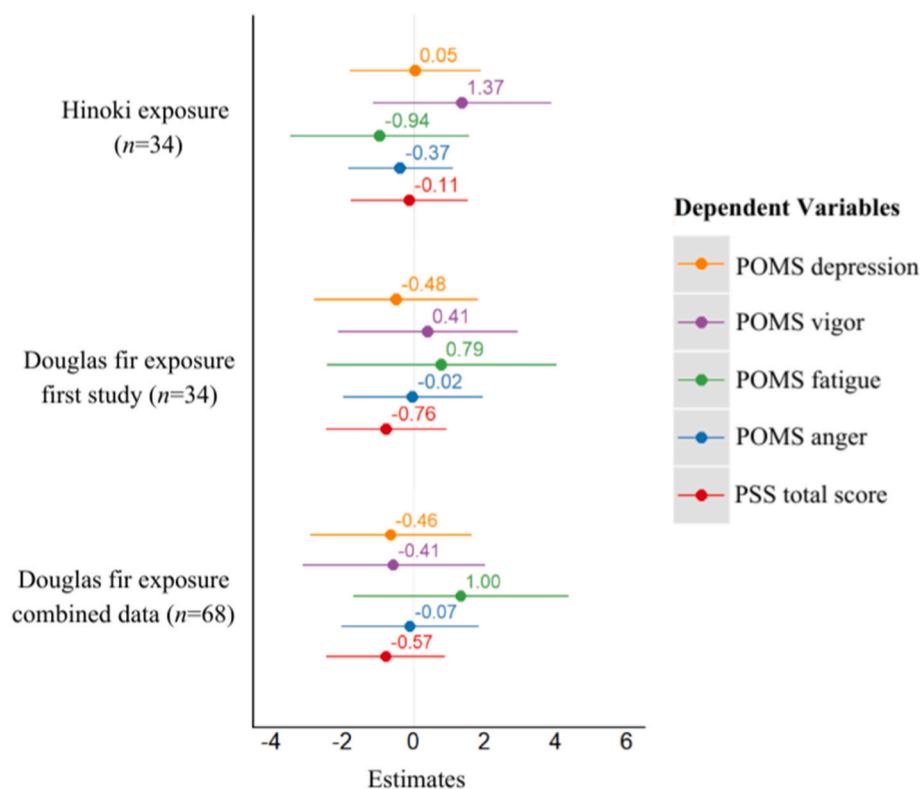


Fig. 2. Estimated effects and error bars for the exposure condition (exposure vs. placebo) on mood and psychological stress variables, separated by dataset. Note. None of the estimated effects were found to be significant. PSS= Perceived Stress Scale, POMS= Profile of Mood States.

exposure lead to a significantly reduced mean reaction time ($b = 18.73$, $CI = 2.95 - 34.50$, $p = .02$) for correct responses of the RVIP. However, this effect did not survive the Benjamini-Hochberg correction ($p_{\text{corrected}} = 0.36$).

The analysis of the dataset which combined participants from the first and second study ($n = 68$) showed that the effect did not remain significant ($b = 10.50$, $CI = -2.55 - 23.55$, $p = .11$). There was no significant result in any of the dependent variables in any of the cognitive tests (see Table 3).

4. Discussion

The present study aimed to explore the short-term effects of two different essential oils from trees on mood, psychological stress, and cognitive performance. In the first study, the Hinoki essential oil exposure showed no effect on any of the assessed mood variables, stress, or cognitive measures. In the Douglas fir group, odorant exposure did not affect the mood or stress measures. No significant effects were found for cognitive tasks assessing working memory, cognitive flexibility, inhibition, attention control, and executive control. Only in the task measuring vigilance did the Douglas fir exposure elicit shorter mean reaction times of the RVIP. On average, participants showed significantly faster reaction times when exposed to the Douglas fir oil compared to the placebo condition. Considering the exploratory nature of the study and the effect failing to withstand multiple comparison correction, a second study was performed to validate this finding by increasing statistical power. After merging the datasets of both studies for the Douglas fir group ($n = 68$), the analysis no longer revealed any significant effect in the vigilance task. In addition, there were no significant effects in the other cognitive domains, nor in the mood or stress measures. The Bayesian approach further supported the Frequentist model results. The Bayes Factors ranged from 0.003 to 0.078 and indicated strong to very strong evidence against the alternative hypothesis (Kass & Raftery, 1995). These additional results provide evidence that the analysed data clearly reveal no effect of odorant exposure and that this is not due to an insufficient sample size.

Our results show no effects of either odorant group on mood and psychological stress, regardless of whether the odour was from a familiar (Douglas fir) or an unfamiliar tree (Hinoki) for the German sample. This contrasts with previously reported beneficial effects of tree odours on mood (Chen et al., 2015; Kim & Song, 2022; Shima et al., 2025). It is important to note that these studies exposed the odorants during a specific period (known as inhalation phase) of approximately 3 to 5 min, without any cognitive demands. In contrast, our study featured continuous odorant exposure without such an inhalation phase. Additionally, a demanding cognitive task battery (lasting on average 75 min) was conducted. The resulting cognitive fatigue must be considered when interpreting the results, as it may have masked potential minor effects on mood and psychological stress. Moreover, we did not record physiological stress parameters, which have been previously associated with tree odour exposure (Chen et al., 2015; Ikei et al., 2015; Kim et al., 2023; Li et al., 2009). Measuring such parameters in future studies, especially those incorporating inhalation phases and varying cognitive load, would be valuable.

No significant effects of either odorant group were found on cognitive performance. The absence of any effects from tree odour exposure contrasts with previous studies of Hinoki odour, which reported a negative effect (Yamada et al., 2011) or an enhancing effect (Miyazaki et al., 1992, 1994). However, these studies used very small sample sizes, investigated odour exposure in relation to only one cognitive task, and employed different exposure frequencies (intermittent exposure or continuous exposure). As mentioned earlier, it is important to recognise that in our study, the odour exposure took place during a demanding cognitive battery.

Overall, we found no effect of either tree odour on any of the assessed variables, suggesting that odour familiarity had no influence. It is

important to note that only a small proportion of participants in the Douglas fir group were able to correctly identify the odour. This limits the interpretation of the potential influence of odour familiarity on mood, psychological stress, and cognitive performance.

The fact that we did not observe any effects contrast with a substantial body of environmental psychology research showing that exposure to nature can enhance mood, reduce psychological stress and improve cognitive functioning (McMahan & Estes, 2015; Nguyen & Walters, 2024; Stenfors et al., 2019; Stevenson et al., 2018). While tree essential oils contain relevant VOCs, they do not cover the total breadth of molecules found in actual forest (Antonelli et al., 2020). Nevertheless, when comparing such results, it is important to consider that the olfactory pathway is unique among the senses: detecting a smell is straightforward, but identifying and naming even familiar scents can be challenging (Smeets & Dijksterhuis, 2014). This process of identification and classification significantly influences odour perception. The study mentioned earlier showed that individuals' reactions to an identical smell varied significantly depending on whether it was labelled as "cheese" or "vomit" (Herz & von Clef, 2001). In contrast, visual stimuli (such as images of forests or trees) can be immediately recognised and labelled.

Turning to the results of the second study, even though half of the participants noticed the smell when directly questioned, only 14.71% identified the familiar Douglas fir odorant as originating from a forest or tree, while 11.76% described it as earthy, fresh, or woody. Most participants (73.53%) described the perceived odour differently, such as citrusy, flowery, fruity, or like a cleaning agent. This is especially important considering that the odour-induced effects of different herbal odours on behaviour may be explained by semantic associations (Johnson, 2011) and/or the conscious olfactory pathway (Bratman et al., 2024). Experiments by Holland and colleagues (2005) demonstrated that exposure to the citrus scent of an all-purpose cleaner affected cognitive performance in a lexical decision task and resulted in faster responses to cleaning-related words in comparison to a control condition. Furthermore, citrus scent exposure influenced participants' actual behaviour; the participants displayed more cleaning behaviour while eating a crumbly biscuit. The authors suggested that the odour triggered semantic associations contributed to the observed behaviours. Applied to the present study, we argue that since the majority of the participants were unable to correctly categorise the odour, no or only invalid and likely unsystematic semantic associations may have been activated. We found marginal effects in the fatigue subscale and the inhibition task among the very small subsample ($n = 14$) who correctly identified the Douglas fir odour. Due to the limited sample size and the fact that these results did not withstand control for multiple comparison, the results cannot be interpreted definitively. However, they provide preliminary evidence that warrants further examination to better understand how exposure to nature odours influences cognition and behaviour through activated semantic associations. Future studies may want to focus on directing participants' attention to the origin of the odour during inhalation phases. This might help to deepen our understanding of the role of smell in the effects of nature exposure on humans.

Another important difference lies in the diversity of the stimuli presented. A natural environment such as a forest comprises a variety of elements, including olfactory and visual elements. This diversity is easier to represent in visual stimuli than in scents. In this study, essential oils from two trees were separately applied. However, it is important to acknowledge that these odorants cannot fully reflect the complexity and diversity of actual forest air. Further studies utilising more realistic forest odours could provide valuable insights into the effects of forest scents on variables such as mood, psychological stress, and cognitive performance.

4.1. Limitations

Unlike other studies that presented the odorants or placebos only

during inhalation phases when participants were not performing tasks, our study administered the odours continuously throughout the entire testing session. Given the exploratory nature of the study, we employed a broad cognitive test battery that lasted approximately 75 min. Due to this length, participants likely experienced a decline in concentration and signs of fatigue. Because the tasks were performed in a fixed order, these fatigue effects were not evenly distributed across the different tasks. Additionally, unlike in previous studies, we did not measure physiological stress parameters, which have been linked to exposure to tree odours. Given these differences, future studies should investigate odour exposure during inhalation phases without any cognitive demands. They should also examine physiological stress responses to better understand the effects of odour exposure.

Furthermore, the experiment was conducted in a neutral white test room located in an old medical building. Considering that context has a strong influence on odour perception, the location of the experiment must be taken into account. Moreover, while tree essential oils do contain relevant VOCs, they do not cover the total breadth of molecules found in actual forest air. Additionally, the study did not include measurements of the amount of volatilized essential oil and its components before, during, and after the experiment. In future studies, these measures are important for comparing the observed findings with other research.

In order to minimize the influence of preexisting mental associations with consciously perceived odours, we did not explicitly mention the odour to the participants. This operationalization might have resulted in most participants failing to identify the odour accurately, which may have diminished potential effects mediated by semantic associations. Further research should experimentally manipulate and investigate the impact of semantic associations triggered by more diverse and realistic forest odours.

4.2. Conclusion

Overall, the study showed no significant short-term effects of essential oil exposure from two different trees types (Douglas fir and Hinoki) on mood, psychological stress, or cognitive performance. Whether the scent was from a familiar tree or not made no difference. Importantly, the majority of participants failed to detect or correctly identify the odour. Further research is needed to understand how exposure to natural odours may influence cognition and behaviour through activated semantic associations when the origin of the odorant is communicated.

CRediT authorship contribution statement

Djo Juliette Fischer: Writing – original draft, Visualization, Software, Project administration, Investigation, Formal analysis, Data curation. **Simone Kühn:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

Ethical approval

The local psychological ethics committee of the University Medical Centre Hamburg-Eppendorf, Germany, approved the experiment (LPEK-0048 and LPEK-0418).

Declaration of generative AI and AI-assisted technologies in the writing process

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvp.2026.102962>.

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