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Indoor plants produce negative air ions: a comparison across species, temperature and humidity

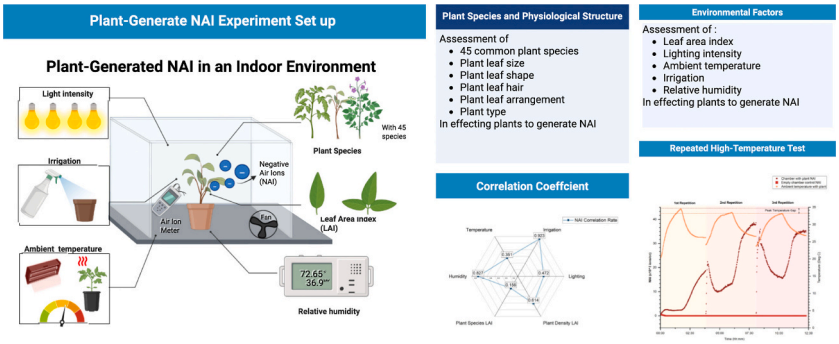
Luowen Lyu [a], Stephen Matheson [b], Nic C. Surawski [a], Peter J. Irga [a,*], Fraser R. Torpy [b]

[a] Plants and Environmental Quality Research Group, School of Civil and Environmental Engineering, University of Technology Sydney, Australia
[b] Plants and Environmental Quality Research Group, School of Life Sciences, University of Technology Sydney, Australia

HIGHLIGHTS

- 45 plant species were evaluated for their NAI release capacity.
- Plant physiological structures influenced NAI release.
- Temp, humidity, light intensity, irrigation also influence plant NAI production.
- High-temperatures caused thermal stress which enhanced NAI release.

GRAPHICAL ABSTRACT



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ABSTRACT

Negative air ions (NAI) are negatively charged gas ions, commonly released within the natural environment via plant metabolic activity. Exposure to NAI-enriched environments has been shown to provide substantial health benefits, and the ability to charge particulate matter (PM) and precipitate it from the airstream, leading it to be proposed as potential contributors to indoor botanical air purification systems. Current literature indicates low levels of NAI production by indoor plants, while there is a general consensus that reasonable levels of NAI can be produced by plants under correct physiological and microclimate conditions, the mechanisms of plant NAI generation remain insufficiently studied. Here we assess the ability of 45 plant species and their physiological structures to produce NAI's within a simulated indoor environment, to determine whether specific characteristics are correlated with higher NAI release. *Spathiphyllum wallisii* was revealed as the most effective NAI producer over 15-min. Further environmental factor assessments, revealed humidity and temperature to have the strongest correlations with NAI production, followed by increased plant density. Following high-temperature exposure, an adaptive "rapid NAI surge" was observed, resulting in NAI production at significantly greater levels than before high-temperature exposure. These results provide significant novel insights into the factors affecting plant NAI

Abbreviations: HVAC, Heating, ventilation, and air conditioning, in context with building ventilation; NAI, Negative air ions; PM, Particulate matter, defined by the diameter of the particle, measured in micrometres (μm).

* Corresponding author.
E-mail addresses: stephen.matheson@uts.edu.au (S. Matheson), Nicholas.Surawski@uts.edu.au (N.C. Surawski), Peter.Irga@uts.edu.au (P.J. Irga), Fraser.Torpy@uts.edu.au (F.R. Torpy).

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production, although future research is needed in combination with current indoor green infrastructure systems to provide a more comprehensive understanding of the optimal capabilities of indoor plant NAI generation.

1. Introduction

Negative air ions (NAI) are negatively charged gas ions, typically formed when oxygen molecules acquire electrons, and are also known as "oxygen-based negative ions" (Goldstein, 2002; Goldstein and Arshavskaya, 1997). NAIs are formed within the natural environment through water shear forces from flowing water (Iwama, 2004), solar ultraviolet rays (Harrison and Carslaw, 2003), lightning discharges (Borra et al., 1997), and plant activities (Wang and Li, 2009). NAI's have been proposed as potential contributors to botanical air purification, due to their ability to charge particulate matter (PM) pollution, leading to faster deposition onto plant foliage (Jiang et al., 2018; Wu and Lin, 2012; Qiu et al., 2015; Berry et al., 2007). Similarly, some studies have also shown that NAIs can attach to airborne bioparticles, including dust, mould spores, and other allergens (Jiang et al., 2018; Berry et al., 2007; Grinshpun et al., 2005a; Mayya et al., 2004). Naturally, NAIs are stable and readily abundant within natural environments like forests, near water sources such as lakes or waterfalls (Jiang et al., 2018; Li et al., 2021). "Fresh air" as defined by the World Health Organization (WHO) has NAI concentrations above 1000 ions/cm^3 (Jiang et al., 2018; Lazzerini et al., 2018; Mitchell and King, 1994). However, urban outdoor and indoor environments regularly exhibit NAI concentrations significantly lower than this "fresh air" threshold (Guo et al., 2023; Wang et al., 2020). Research has demonstrated that NAI concentrations exceeding 1000 ions·cm^{-3} are associated with positive health effects in humans (Jiang et al., 2018; Perez et al., 2013). While the specific threshold at which NAIs efficiently remove particulate matter (PM) from indoor air remains undetermined, studies involving artificially generated NAIs suggest that their charged nature enables immediate particle capture. In sealed environments, over 80 % of PM can be removed within 30 min, and complete removal (up to 100 %) may be achieved within 1.5 h (Grinshpun et al., 2005b).

It is well known that plants can remove air pollutants, and harnessing this phenomenon has led to plant-based air purification as an emergent technology (Han et al., 2022; Irga et al., 2020; Kim et al., 2018). Unlike conventional mechanical air filtration systems, bioremediation achieves multiple environmental goals, including biophilia, sustainability, and low energy consumption (Coma et al., 2017; Irga et al., 2017). Indoor ornamental plants are known to naturally produce NAIs under standard growing conditions, representing one of the few controllable natural resources for non-artificial NAI production (Wang and Li, 2009; Jiang et al., 2018).

Yet, the underlying mechanisms of plant NAI generation and its potential still remain insufficiently studied. It has been hypothesised that the source of plant-derived NAIs originates from the electron transfer processes involved in photosynthesis and other enzyme-mediated physiological reactions (Jiang et al., 2018; Aubrecht et al., 2000). Current literature has indicated that the NAI concentration produced by plants is mostly suboptimal for indoor air filtration purposes ($<$ 200 ions/cm^3) (Jiang et al., 2018; Luo et al., 2020; Zhang et al., 2021), however, not all plants species have been tested and it is possible that environmental conditions may help to increase plant NAI generation. Some studies have attempted to verify that factors such as environmental temperature, humidity, light intensity, and other microclimatic conditions may influence a plant's ability to produce NAIs (Li et al., 2022; Luo et al., 2020; Zhang et al., 2021; Goel et al., 2005; Liu et al., 2017; Wallner et al., 2015). In an outdoor forest ecosystem study, Li et al. (Li et al., 2022) demonstrated that NAI levels fluctuate diurnally and seasonally, correlating with temperature and humidity. J. Wang & Li (Wang and Li, 2009) also confirmed the diurnal variation in plant-generated NAI levels and, through light intensity experiments, emphasising that specific species modify their NAI production in response to light exposure. The research further established a negative correlation between NAI, particulate matter (PM), and ozone concentrations, further supporting the role of NAIs in air purification (Jiang et al., 2021; Li et al., 2022). To date, research concerning plant-based NAI has primarily been restricted to outdoor environments or forest ecosystems. There is a clear lack of studies addressing these dynamics within indoor environments, particularly under systematically controlled and interacting environmental factors.

Among the various approaches for enhancing indoor bioremediation effectiveness, plant-derived NAIs represent a largely unexplored research area. Investigating their role in indoor plant-mediated air purification could provide novel insights into the underlying mechanisms and optimisation strategies (Han et al., 2022; Vinet and Zhedanov, 2006; Lee et al., 2020; Kumar et al., 2023). The current study provides proof of concept for the manipulation of ornamental indoor plant microclimates paired with plant physiological structure selection, as a possible way to enhance indoor environments' NAI concentrations. We investigated 45 plant species within a simulated sealed indoor environment, with the aim of assessing overall NAI production capability as-well as possible correlation between key plant physiological factors and NAI net change. The top-performing plant species for overall NAI production capacity was identified, and subjected to further assessments, including a systematic investigation of the correlation between planting density and environmental factors influence on plant NAI production.

2. Materials and methods

2.1. Experiment set-up

The plants used within this work were all common indoor and outdoor ornamentals in Australia ($n = 3$ independent plants per treatment). Details regarding the plant species are provided in Table 1. All plants were grown in standard 300 mm pots using ~2.26 L of standard potting mix consisting of composted hardwood sawdust, composted bark fines, and coarse river sand in a 2:2:1 ratio, supplemented with slow-release fertilizer granules (12:4.6:10 N:P:K). The plants were grown in a nursery for 6 months and visually examined to confirm their health and ensure that their sizes aligned with those typically used in commercial applications, before being transported to a research glasshouse which was maintained at a temperature of 23.7 ± 3.6 °C, relative humidity of 68.1 ± 16.0 % and a maximum mid-day light level of 90 ± 10 μmol m^{-2} s^{-1}. Plants were transported to a laboratory in the same building only for experimentation, then returned to the glasshouse. Although variations in biomass characteristics such as leaf area and height were observed both within and between species, the tested plants were considered representative of the expected performance of these species in practical applications. Prior to testing, all plants were watered to field capacity, allowed to drain for 1 h, before adjustment to achieve an average soil moisture content below 20 % *w*/w. Upon completion of each experimental sequence, plants were harvested for leaf area index (LAI) measurements.

2.2. Plant NAI generation

All experimental trials were conducted within sealed Perspex chambers (0.6 × 0.6 × 0.6 m; 216 L) (Fig. 1) with removable lids mounted on steel frames. The chambers were sealed with adhesive foam-rubber tape and secured with adjustable metal clips to only test stated environmental factors and eliminate all possible confounding variables. Each chamber contained a 2.4 W fan to promote atmospheric

equilibration, and an overhead light box (50 mm air gap) equipped with five 18 W fluorescent tubes tailored for plant growth (Wotan L 18/11 Maxilux daylight, Ozram, Germany). An AIC3Pro Air Ion Counter (by AlphaLab, Inc., U.S.A) was placed 1–3 cm from the plants, at the same height as the leaves, to maximise ion collection reproducibility among species. The air ion counter operates by using an internally charged panel to attract all charged particles in the air, and particle counts are determined by detecting variations in electrical current. To minimize experimental inaccuracies, each measurement was repeated three times ($n = 3$).

Except for the environmental parameters being specifically examined, all other conditions were kept constant in a controlled laboratory setting: temperature (23.7 ± 3.6 °C), relative humidity (68.1 ± 16.0 %), and average light intensity of 5–50 μmol m^{-2} s^{-1} of light on the leaf surfaces, where lower irradiances were detected on the shaded understory of the plant leaves. A blank 'empty chamber'control group ($n = 3$) and a "potting substrate only" procedural control ($n = 3$) was incorporated to allow quantification of any non-plant associated variation in the data. For NAI testing, plants were placed within the chamber and allowed to acclimate for 5 min before NAI monitoring began, NAI was recorded at 15-s intervals over the course of 15 min. Prior to testing, the soil moisture of each plant's substrate was measured to ensure it met the below 20 % threshold.

2.3. Environmental and physiological effects

After the NAI generation experiments of the 45 plant species, *Spathiphyllum wallisii* (3 plants per trial, LAI = 1.41 ± 0.2 m^2/m^2 per plant), was selected to investigate the effects of plant density, leaf area index, light intensity, soil irrigation, humidity and temperature on natural NAI production. *S. wallisii* is a common ornamental indoor plant, which has been extensively studied within the literature for its ability to phytoremediate common indoor pollutants and act as an efficient plant species within green wall botanical biofiltration systems (Torpy et al., 2017; Paull et al., 2019; Irga et al., 2019). Plant density was adjusted through placing 1, 2, 3 or 4 potted S. wallisii plants evenly with the experimental chamber. The experiment comprised five treatment groups corresponding to varying levels of LAI: Group 1 (1 plant, LAI = 2.94), Group 2 (2 plants, LAI = 3.80), Group 3 (3 plants, LAI = 4.20), Group 4 (4 plants, LAI = 5.60), and Group 5 (4 plants, LAI = 6.60).To investigate the effects of light intensity, we measured NAI emissions under six lighting conditions: all five lights (276.13 lx), four lights (235.53 lx), three lights (181.03 lx), two lights (122.03 lx), one light (75.00 lx), and no light (30.77 lx). The light intensity was measured with an LI-250 A Light Meter (LI-COR, Inc., Lincoln, Nebraska).

Four irrigation condition experiments were conducted on potted *S. wallisii*: pre-irrigation, post-irrigation, irrigated pots without plants,

Table 1
Plant list and related plant structural properties.[a]

Type	Plant Species	Leaf Size	Leaf Shape	Hairy Leaves	Leaf Arrangement
Monocots	*Agapanthus orientalis 'Blue'* (blue lilly)	Medium	Linear	No	Basal
	Aloe marlothii arborescens (Sea Urchin Aloe)	Large	Lanceolate	Yes	Rosette
	Anigozanthos (Kangaroo Paws)	Small	Linear	No	Alternate
	Carex brunnea (Greater Brown Sedge)	Medium	Linear	No	Clump
	Chlorophytum comosum (Spider Plant)	Small	Lanceolate	No	Rosette
	Dianella caerulea (Blue Flax Lily)	Medium	Linear	No	Alternate
	Dianella congesta (Flax Lily, Beach Flax Lily)	Medium	Linear	No	Alternate
	Dianella tasmanica (Blue Flax Lily, Tasman Flax lily)	Medium	Linear	No	Alternate
	Dietes grandiflora (wild iris)	Small	Linear	No	Alternate
	Dracaena fragrans (Cane Deremensis)	Large	Lanceolate	No	Rosette
	Dracaena trifasciata (Snake Plant)	Medium	Linear	No	Rosette
	Epipremnum aureum (Devil's Ivy)	Medium	Heart-shaped	No	Alternate
	Festuca glauca (Blue Fescue Grass)	Small	Linear	No	Clump
	Lomandra longifolia x confertifolia spp. *pallida* (Lomandra Lime Tuff)	Medium	Linear	No	Alternate
	Neomarica northiana (Walking Iris)	Medium	Lanceolate	No	Basal
	Phormium tenax (New Zealand Flax)	Large	Linear	No	Basal
	Spathiphyllum wallisii (Peace Lily)	Medium	Lanceolate	No	Alternate
	Zamioculcas zamiifolia (Zanzibar Gem)	Medium	Lanceolate	No	Alternate
Dicot Woody Plants	*Acacia stricta* (Straight Wattle)	Small	Linear	Yes	Alternate
	Acmena smithii (Lilly Pilly)	Medium	Obovate	No	Alternate
	Coprosma repens (Pacific Sunset)	Small	Obovate	No	Opposite
	Elaeocarpus Prima Donna (Blueberry Ash)	Medium	Obovate	No	Alternate
	Ficus insipida (Umbrella Tree)	Large	Broad	No	Alternate
	Grevillea (Spider Flowers)	Small	Linear	Yes	Alternate
	Grevillea lanigera'(Mt Tamboritha')	Small	Linear	Yes	Alternate
	Hebe 'Icing Sugar' (Icing sugar)	Small	Ovate	Yes	Opposite
	Lavandula stoechas (Spanish lavender)	Small	Linear	Yes	Opposite
	Leptospermums (Teatrees)	Small	Linear	Yes	Alternate
	Metrosideros thomasii (NZ Christmas Bush)	Medium	Obovate	No	Opposite
	Pittosporum tenuifolium (Hole in one)	Medium	Obovate	No	Alternate
	Proteaceae (Grevillea superb)	Medium	Linear	Yes	Alternate
	Rosemarinus officinalis (Rosemary)	Small	Linear	Yes	Opposite
	Westringia fruticosa Mundi (Dwarf Coast Rosemary)	Small	Linear	Yes	Opposite
Dicot Herbaceous	*Argyranthemum frutescens* (Marguerite Daisy)	Small	Obovate	No	Alternate
	Dichondra argentea (Dichondra sliver falls)	Small	Round	Yes	Alternate
	Felicia amelloides (Blue Daisy)	Small	Obovate	Yes	Alternate
	Gazania (Gazania Silver Leaf)	Small	Obovate	Yes	Alternate
	Pratia pedunculata (White Star Creeper)	Small	Round	Yes	Alternate
	Senecio cineraria 'Silver Dust' (Dusty Miller)	Small	Obovate	Yes	Alternate
	Viola hederacea (Native Violet)	Small	Round	Yes	Alternate
	Viola odorata (Purple Violet)	Small	Ovate	Yes	Alternate
Ferns	*Blechnum gibbum* (Silver Lady)	Medium	Pinnate	No	Alternate
	Nephrolepis exaltata (Boston Fern)	Medium	Pinnate	No	Alternate
Dicot Succulent	*Carpobrotus glaucescens* (Pigface)	Medium	Succulent	Yes	Alternate
	Limonium perezii (Statice, Sea Lavender)	Small	Obovate	No	Basal

[a] Leaf size were determined as follows: Small <30cm^2, medium 30–60 cm^2, large >60cm^2.

Fig. 1. NAI Experimental design and set-up.

and an open petri dish (diameter = 240 mm) containing 1 L of water to provide 100 % relative humidity (RH). Changes in ambient NAI levels were recorded under each condition. Soil moisture was monitored using a soil hygrometer (Procheck Teros 11, METER Group, Inc., USA), with three readings taken at different locations for each group. Both plant-containing and plant-free pots were irrigated with 1 L of water and allowed to drain for one hour before testing. For humidity NAI generation, potted *S. wallisi* (LAI = 4.23) under controlled sealed laboratory conditions were compared to those recorded within the high-humidity environment within the research glasshouse.

Lastly to investigate the influence of changing ambient temperature, potted *S. wallisii* (LAI = 4.23) were heated within the experimental chamber using a JBH405 Radiant Patio Heater (1800–2000 W, 50 Hz) to a maximum target temperature of 35 °C. Based on preliminary trials, each heating session lasted 2 h. Following the heating phase, the chamber was left to cool naturally to room temperature. NAI were recorded both during heating and cool down, and temperature and relative humidity were monitored with a TSI 9545 Velocicalc Air Velocity and Humidity Meter and Data Logger (TSI Inc., USA) at 60-s intervals. The experimental design includes two components: the first involves completing three consecutive heat exposure trials within the same day, while the second separates the three trials over three days to minimize the influence of repeated exposure effects.

For NAI testing, plants were placed within the chamber and allowed to acclimate for 5 min before NAI monitoring began, NAI was recorded at 15-s intervals over the course of 20 min (except for the temperature test, as stated).

2.4. Data processing and analysis

To assess the effect of the different plant species and variables, the NAI Net Change (*NAI* NC_t), NAI Max Change Rate (*NAI* CR_t), and NAI Average Change ($\overline{\Delta\ NAI}$) were calculated at each time point *t*. These indices are defined as follows:

$$NAI\ NC_i = NAI_i - NAI_0,$$

$$NAI\ CR_i = NAI_i - NAI_{i-1},$$

$$dNAI_i/dt = \Delta NAI/\Delta t = (NAI_i - NAI_{i-1})/(t_i - t_{i-1})$$

$$\overline{\Delta\ NAI} = \left(\sum_{i=1}^{n} NAI_i - NAI_0\right) \Big/ n'$$

where NAI_i= the i^{th} NAI concentration at time t_i; $NAI_0$is the initial NAI concentration. i = corresponding value at time t; and n = total number of data points- in the experiment. The overbar notation $\overline{\Delta\ NAI}$ denotes the mean value of NAI change throughout the measurement period.

To compare the relative impact of different factors on plant NAI production, *Z*-score normalisation was applied to standardise the data. The normalisation was performed using the following formula:

$$X' = (X - \mu)/\sigma$$

where X' represents the standardized value, X is the original value, μ is the mean of the original dataset, and σ is the standard deviation of the original dataset.

The homogeneity of variances was tested using Levene's test, and data normality was evaluated with the Kolmogorov-Smirnov test. Differences in NAI production between plant species and under varying environmental factors were analysed using one-way ANOVA followed by Tukey's or Dunn's post hoc test as appropriate. Regression analysis was conducted for each trial to compare NAI production rates among plant species. Spearman's rank correlation coefficient was used to evaluate the relationship between environmental factors and the NAI production ability of plants. Data analysis was mainly performed using IBM SPSS Statistics Version 21 (IBM Corp., Armonk, NY, USA), with parts of the statistical analyses and graphical visualisations conducted using the OriginPRO software package (Origin Lab, 2022).

3. Results and discussion

3.1. Comparison of NAI generation across plant species

NAI net change was seen to be significantly influenced by plant species ($p < 0.01$), using the empty chamber as a baseline (Table 3), 34 plant species exhibited a net positive contribution to NAI production. In addition, 42 % of the species demonstrated NAI production rates exceeding those of plant-free pots, while 15 species had net NAI changes comparable to the substrate only. Among the tested plants, *S. wallisii* exhibited the highest net NAI production, generating approximately 2.92×10^3 ions/cm^3, and also exhibited the highest NAI variation rate, releasing 0.70×10^3 ions/cm^3 per second. In contrast, 12 species (Table 3) showed negligible NAI production. Notably, *Grevillea* sp. appeared to reduce NAI levels, with a net change of -0.28×10^3 ions/cm^3 per second. A correlation analysis between LAI and net NAI change across the different plant species revealed no significant relationship ($r = 0.156$, $p = 0.283$). This suggests that NAI values may require further classification, such as categorisation based on plant physiological structure or taxonomic grouping. This discussion will be addressed in the subsequent section.

Previous studies have hypothesised that leaf morphology and trichome structure may contribute to variations in plant-derived NAI (Wang and Li, 2009; Jiang et al., 2018; Tikhonov et al., 2004; Siņicina and Martinovs, 2017). As a result of this, analysis comparing the possible effects of individual leaf area, leaf morphology, presence of leaf hair, leaf growth sequence and plant species classification on NAI generation were performed in the current study (Table 1). The study found no significant effects for any of these variables among the current plant species (Table 2). Interestingly, while individual leaf area and morphology did not significantly affect NAI net change within the current work.

Tikhonov et al. (Tikhonov et al., 2004) assessed NAI generation of several plant species, findings revealed *Aloe arborescens* to highest NAI generator ($120 \pm 15 \times 10^3$ ion/cm^3) hypothesising pointed parts of

Table 2
Results of plant NAI analysis based on plant physiological structure.

Variable	p-value	Significance
By Leaf Size	0.790	Not significant
By Leaf Shape	0.232	Not significant
By Leaf Hair	0.745	Not significant
By Leaf Arrangement	0.086	Not significant
By Plant Type	0.096	Not significant
By Plant Species	< 0.001	Highly significant

leaves attribute to higher NAI generation. In the current work, *Elaeocarpus* '*Prima Donna*' (broad leaved) exhibited relatively high NAI production capacity, whereas *Grevillea lanigera* (characterized by narrow, linear leaves) demonstrated lower NAI output (Table 3). These observations may lend some support to the hypothesis that leaf shape influences NAI production. However, the data shown in Table 3 indicates that high-NAI-emitting species have a range of leaf shapes besides blade-shaped, providing evidence that leaf shape alone is not the sole decisive factor in determining NAI production (Jiang et al., 2018). Furthermore, some research found that plant trichome density was significantly correlated with NAI generation under plant electrical pulse treatments (Jiang et al., 2021; Tikhonov et al., 2004). In contrast, within the present study trichome density did not enhance NAI production, as both high-performing and low-performing species contained trichomes, suggesting they do not play a significant role in influencing plant-derived NAI emissions in the absence of the electrical stimuli. According to Table 2, the *p*-values for leaf arrangement and plant type displayed a near-significant trend. Future research should incorporate a broader range of plant species to validate these findings and consider additional physiological and metabolic factors that might influence NAI production.

3.2. Plant density and LAI effects on NAI production

For potted *S. wallisii*, increasing the chamber plant density significantly influenced both NAI concentration and net change rates (Table 4). As plant density increased, the maximum net NAI change rate also increased, reaching up to $1.05 \pm 0.03 \times 10^3$ ions/cm^3 per 15 s. Pearson correlation indicated that LAI, as influenced by plant density, had a significant effect on NAI production ($r = 0.614$, $p < 0.001$). However, the rate of NAI change remained fairly constant at approximately 0.01×10^3 ions/cm^3 per 15 s with each additional plant apart from the setup with two plants versus a single plant, where the net NAI change value anomalously decreased. One-way ANOVA indicated significant differences in NAI levels across the varying plant densities ($F = 313.691$, $p < 0.001$; Fig. 2b). Linear regression analysis of LAI indices (Fig. 2a) indicated a positive correlation between increasing LAI and enhanced NAI generation. It should be noted that increasing chamber RH was strongly correlated with increasing plant density ($r = 0.935$, $p = 0.020$), so changes in LAI cannot be attributed to plant associated factors independently from humidity.

These results correspond with the majority of previous studies which have identified that higher planting densities results in higher numbers of stomata and facilitate a strong positive correlation between stomatal conductance and plant-derived, surpassing the influence of environmental parameters such as ambient humidity and temperature (Wang and Li, 2009; Jiang et al., 2018; Shi et al., 2022; Jovanić and Jovanić, 2001). Whilst the existing literature has focused on the relationship of NAI release and plant density using simple potted plant arrangements, within the indoor environment the maximum feasible potted plant density is limited by the amount of floor space available for the plants. With the ongoing development of new green infrastructure technologies, vertical green walls have emerged as an effective addition to the indoor environment as plants and substrate are aligned vertically greatly increasing the planting density per unit of indoor volume, while

Table 3
Release of NAI from different plants species ranked by maximum recorded net NAI change.

Scientific Name	LAI	Max. NAI 15mins net change (x10^3 ions/cm^3)	NAI rate change (x10^3 ions/cm^3/s^1)	Average NAI change (x10^3 ions/cm^3/s^1)	NAI net change /LAI
Spathiphyllum wallisii	1.13	2.92 ± 0.76	0.70 ± 0.31	1.03 ± 0.18	2.58
Anigozanthos	0.24	1.87 ± 0.57	0.41 ± 0.33	0.89 ± 0.26	7.70
Argyranthemum frutescens	0.85	1.67 ± 1.63	0.15 ± 0.01	0.72 ± 0.70	1.96
Rosemarinus officinalis	0.10	1.49 ± 0.44	0.27 ± 0.44	0.47 ± 0.08	14.90
Viola odorata	0.16	1.18 ± 0.18	0.19 ± 0.10	0.52 ± 0.11	7.45
Gazania	0.90	0.96 ± 0.25	0.19 ± 0.07	0.45 ± 0.11	1.06
Blechnum gibbum	1.08	0.84 ± 0.21	0.28 ± 0.12	0.43 ± 0.08	0.78
Leptospermum sp.	0.19	0.58 ± 0.16	0.08 ± 0.01	0.30 ± 0.08	2.96
Elaeocarpus Prima Donna	0.51	0.47 ± 0.27	0.10 ± 0.02	0.22 ± 0.13	0.92
Aloe marlothii arborescens Sea Urchin PBR	0.30	0.42 ± 0.08	0.11 ± 0.05	0.20 ± 0.05	1.40
Pratia pedunculata	0.10	0.41 ± 0.03	0.10 ± 0.01	0.20 ± 0.01	4.16
Zamioculcas zamiifolia	0.58	0.39 ± 0.10	0.17 ± 0.09	0.14 ± 0.04	0.68
Agapanthus orientalis 'Blue'	0.68	0.35 ± 0.06	0.10 ± 0.03	0.19 ± 0.10	0.52
Phormium tenax	0.09	0.33 ± 0.03	0.11 ± 0.02	0.18 ± 0.01	3.55
Grevillea banksii	1.08	0.33 ± 0.15	0.21 ± 0.10	0.14 ± 0.19	0.30
Dietes grandiflora	0.25	0.32 ± 0.06	0.10 ± 0.01	0.14 ± 0.01	1.31
Lavandula stoechas	0.54	0.32 ± 0.07	0.25 ± 0.18	0.09 ± 0.04	0.58
Veronica Hebe 'Icing Sugar'	0.46	0.30 ± 0.12	0.28 ± 0.14	0.04 ± 0.01	0.65
Substrate (14 cm pot)	–	0.28 ± 0.02	0.29 ± 0.03	−0.03 ± 0.01	–
Lomandra longifolia x *confertifolia* spp. *pallida* 'Lime Tuff'	1.09	0.24 ± 0.09	0.11 ± 0.04	0.15 ± 0.02	0.22
Coprosma repens	0.87	0.24 ± 0.06	0.17 ± 0.06	0.04 ± 0.07	0.28
Chlorophytum comosum	0.50	0.21 ± 0.04	0.11 ± 0.03	0.08 ± 0.01	0.42
Ficus insipida	0.14	0.19 ± 0.06	0.12 ± 0.02	0.05 ± 0.02	1.41
Felicia amelloides 'Mauve Cloud'	0.12	0.18 ± 0.05	0.19 ± 0.06	0.04 ± 0.01	1.50
Dichondra argentea	0.03	0.17 ± 0.02	0.16 ± 0.04	0.04 ± 0.03	5.07
Nephrolepis exaltata	1.05	0.17 ± 0.06	0.15 ± 0.02	0.03 ± 0.03	0.16
Carpobrotus glaucescens	0.05	0.17 ± 0.02	0.13 ± 0.03	0.05 ± 0.00	3.22
Metrosideros thomasii	0.65	0.17 ± 0.06	0.19 ± 0.08	0.05 ± 0.02	0.25
Substrate (30 cm pot)	–	0.16 ± 0.06	0.06 ± 0.01	0.10 ± 0.04	–
Pittosporum tenuifolum	0.39	0.16 ± 0.04	0.11 ± 0.01	0.05 ± 0.02	0.41
Substrate (20 cm pot)	–	0.16 ± 0.02	0.18 ± 0.05	−0.01 ± 0.04	–
Festuca glauca	0.04	0.15 ± 0.06	0.09 ± 0.01	0.04 ± 0.00	3.75
Acmena smithii	0.40	0.14 ± 0.03	0.10 ± 0.03	0.06 ± 0.04	0.35

(*continued on next page*)

Table 3 (*continued*)

Scientific Name	LAI	Max. NAI 15mins net change ($x10^3$ ions/cm^3)	NAI rate change ($x10^3$ ions/cm^3/s^1)	Average NAI change ($x10^3$ ions/cm^3/s^1)	NAI net change /LAI
Epipremnum aureum	0.24	0.13 ± 0.07	0.10 ± 0.04	0.04 ± 0.06	0.55
Acacia stricta	0.12	0.12 ± 0.02	0.13 ± 0.02	0.05 ± 0.02	1.03
Dracaena fragrans	0.27	0.12 ± 0.05	0.11 ± 0.07	0.01 ± 0.04	0.44
Control (empty chamber)	–	**0.11 ± 0.23**	**0.51 ± 0.04**	**−0.23 ± 0.20**	–
Dracaena trifasciata	0.59	0.10 ± 0.01	0.09 ± 0.02	0.02 ± 0.01	0.16
Dianella congesta	0.17	0.10 ± 0.08	0.13 ± 0.00	0.00 ± 0.08	0.58
Viola hederacea	0.21	0.09 ± 0.04	0.07 ± 0.02	0.01 ± 0.05	0.42
Dianella caerulea	0.15	0.07 ± 0.08	0.24 ± 0.21	0.00 ± 0.06	0.47
Neomarica northiana	0.15	0.06 ± 0.06	0.07 ± 0.01	−0.05 ± 0.07	0.40
Senecio cineraria 'Silver Dust'	0.12	0.04 ± 0.06	0.10 ± 0.02	−0.03 ± 0.07	0.34
Dianella tasmanica	0.80	0.04 ± 0.01	0.08 ± 0.05	−0.01 ± 0.00	0.05
Carex brunnea	0.29	0.04 ± 0.01	0.08 ± 0.04	−0.07 ± 0.03	0.12
Limonium perezii	0.52	0.02 ± 0.02	0.14 ± 0.03	−0.08 ± 0.00	0.03
Westringia fruticosa Mundi	0.08	0.01 ± 0.01	0.12 ± 0.01	−0.06 ± 0.00	0.06
Grevillea lanigera	0.35	0.00 ± 0.01	0.14 ± 0.04	−0.28 ± 0.05	0.01
Grevillea Juniperina	0.10	0.00 ± 0.05	0.08 ± 0.05	−0.13 ± 0.04	0.00

reducing the required floor space (Douglas et al., 2021; Darlington et al., 2001). Future research should investigate vertical green walls as a more practical and space-efficient alternative to potted plants for the enhancement of NAI production, particularly within spatially constrained indoor environments.

3.3. Relationship between light intensity and NAI

One-way ANOVA demonstrated that net NAI change varied significantly across different light intensities, showing an increasing trend with higher light exposure ($F = 50.430$, $p < 0.001$, Fig. 2d). Correlation analysis confirmed that variations in light intensity had a substantial impact on net NAI emissions ($r = 0.472$, $p < 0.001$). Linear regression analysis (Fig. 2c) identified a positive monotonic relationship between light intensity and NAI net change. Moreover, the rate of NAI change increased significantly with increasing light intensity (Table 5). At a light intensity of 276.13 lx, the maximum NAI production reached 3.21 ± 0.27 × 10^3 ions/cm^3 per second. Post-hoc Tukey's testing identified a threshold light level of around 122.0 lx, beyond which NAI net change values were significantly different from those observed under lower light intensities ($p < 0.004$). The most substantial difference in NAI emission rates occurred between 276.13 lx and 30.77 lx, whereas under low light conditions (30.77 and 75.00 lx), NAI net changes remained fairly low (Fig. 2d). When comparing one-light and no-light conditions, NAI change rates were similar (~0.02 × 10^3 ions/cm^3 per second), and the net NAI changes were 0.46 ± 0.03 × 10^3 ions/cm^3 and 0.55 ± 0.03 × 10^3 ions/cm^3, respectively.

Previous research on chlorophyll fluorescence in plant canopies has demonstrated a strong positive correlation between solar intensity and NAI levels, supporting the existence of a relationship between light exposure and NAI release (Shi et al., 2022). Comparisons with other related studies consistently confirm that higher light exposure stimulates NAI production (Wang and Li, 2009; Jiang et al., 2018; Wu, 2017). Shi et al. (Shi et al., 2021) investigated spatial changes of NAI across different forest communities, findings indicated sites with higher chlorophyll fluorescence intensity produced higher daily mean NAI concentrations of up to 910 ion/cm^3, concluding stronger photosynthetic capacity resulted in stronger NAI generation (Wang and Li, 2009; Shi et al., 2022; Jovanić and Jovanić, 2001).

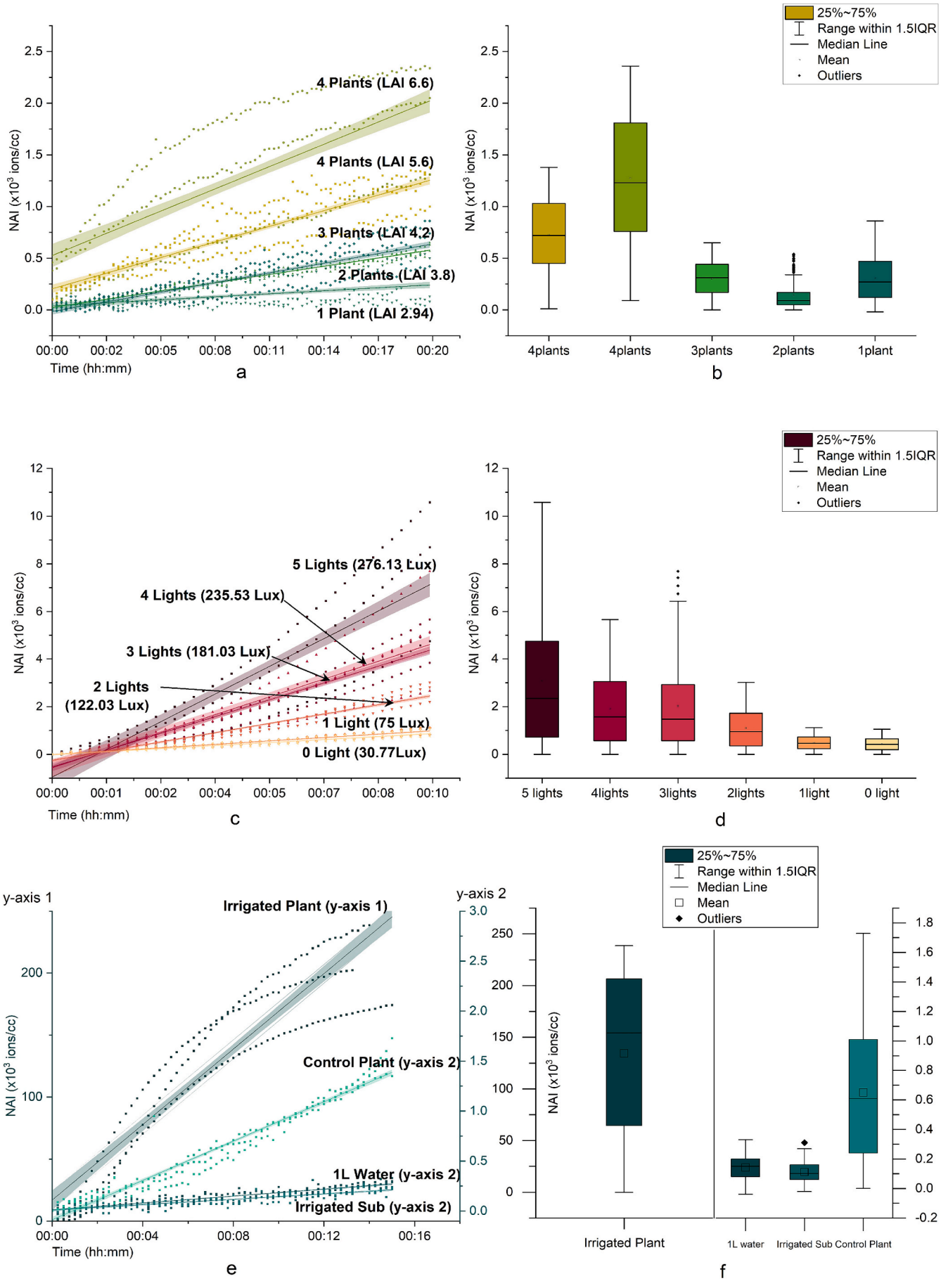
The Australian and New Zealand standard for indoor workplace illumination (AS/NZS 1680.1:2006), recommendeds that indoor light intensity levels should fall within the range of 320 to 400 lx. Our work indicates that peak NAI concentrations are achieved at light levels >276 lx, and thus indoor plants maintained under standard workplace illumination conditions will be at optimal levels for NAI production. It should be noted that only *S.wallisii* was investigated for its behaviour related to light intensity and it is known that species-dependent variability exists, and certain plants do not appear to exhibit significant responses to increased light exposure (Wang and Li, 2009; Jiang et al., 2018). It would be of value if future research incorporated similar methodologies to this present work, with the inclusion of varied species of plants with differing preferences to light intensity. This would provide valuable insights into finding high performing species — light intensity combinations for natural NAI generation.

3.4. Association of irrigation with NAI

Irrigation was found to significantly influence NAI production for *S. wallisii* ($r = 0.923$, $p < 0.001$; Fig. 2e). After sprinkler irrigation (~50 mL), the net NAI change increased to 125.91 ± 5.15 × 10^3 ions/cm^3, which were peak concentrations compared to all other irrigation conditions. Pure water, non-irrigated soil, and irrigated soil demonstrated similar NAI change and rate of increase (Table 6, Fig. 2f). This suggests that NAI production from soil might be primarily driven by water evaporation processes. Furthermore, when assessing the non-irrigated plant group, plants still significantly contributed to NAI production ($p < 0.001$), with net NAI changes reaching 0.84 ± 0.05 × 10^3 ions/cm^3, confirming the contribution of plants to NAI production. Although the effect of sprinkler irrigation on NAI warrants further study and comparison with alternative irrigation techniques, previous studies have already demonstrated that sprinkler irrigation efficiently enhances NAI production through water shearing forces (the Lenard effect) (Wu and Lin, 2012). Moreover, any form of water movement including sprinkler systems influence additional environmental variables, including increasing ambient humidity and providing evaporative cooling effects,

Table 4
NAI results under different LAI and ambient data.

Number of plants	LAI (m^2/m^2)	NAI ($x10^3$ ions/cm^3/s)			Temperature (°C)	Humidity (%)
		Max. net change	Rate change	Average NAI change		
1 Plant	2.94	0.33 ± 0.02	0.01 ± 0.00	0.52 ± 0.02	22.9 ± 0.03	75.0 ± 0.27
2 Plants	3.78	0.12 ± 0.01	0.00 ± 0.00	0.26 ± 0.01	21.5 ± 0.03	71.9 ± 0.35
3 Plants	4.23	0.32 ± 0.01	0.01 ± 0.00	0.61 ± 0.01	21.0 ± 0.00	73.1 ± 0.29
4 Plants	6.60	1.05 ± 0.03	0.02 ± 0.00	1.45 ± 0.03	22.0 ± 0.04	78.6 ± 0.21
4 Plants	5.64	0.73 ± 0.02	0.01 ± 0.00	1.10 ± 0.02	22.5 ± 0.03	78.2 ± 0.22



(caption on next page)

Fig. 2. Comparisons of NAI net change for different characteristics using *S. wallisii* potted plants. a, Scatterplot showing the relationship between NAI and LAI in *S. wallisii.* The solid line indicates the regression trend line with a 95 % confidence band. b, Box plot showing the relationship between NAI and LAI in *S. wallisii,* showing the mean and the interquartile range, and bars showing minimum and maximum values. c, Scatterplot illustrating the relationship between NAI net change and different chamber light intensities for *S. wallisii.* The solid line represents the regression trend with a 95 % confidence interval. d, Comparison of NAI net changes across different light intensities, with box plot as above. e, f, Scatterplot and box plot showing the correlation between NAI net change and different irrigation application rates.

Table 5
NAI results under different light intensities and ambient data for *S. wallisii.*

	Light intensity (lux)	NAI (x10^3 ions/cm^3/s)			Temperature (°C)	RH (%)
Amount of Lamps		Max net change	Rate change	Average NAI change		
No Light	30.77	0.46 ± 0.03	0.02 ± 0.00	0.69 ± 0.03	22.0 ± 0.00	57.5 ± 0.23
1 light	75.00	0.55 ± 0.03	0.02 ± 0.00	1.02 ± 0.04	21.5 ± 0.04	60.7 ± 0.24
2 light	122.03	1.27 ± 0.08	0.07 ± 0.00	1.53 ± 0.08	22.0 ± 0.00	60.9 ± 0.30
3 light	181.03	2.34 ± 0.19	0.13 ± 0.01	2.58 ± 0.19	22.0 ± 0.00	62.6 ± 0.39
4 light	235.53	2.22 ± 0.15	0.12 ± 0.01	2.55 ± 0.16	21.7 ± 0.04	63.9 ± 0.38
5 light	276.13	3.21 ± 0.27	0.19 ± 0.01	3.65 ± 0.29	21.0 ± 0.07	66.7 ± 0.34

Table 6
NAI results under different Irrigation situations for *S. wallisii.*

Treatment	Irrigation	NAI (x10^3 ions/cc per second)			Temperature (°C)	Humidity (%)
		Max. net change	Rate change	Average NAI change		
1 L Water	–	0.16 ± 0.01	0.03 ± 0.00	0.72 ± 0.01	24.0 ± 0.01	72.5 ± 0.20
Pot Plant	NO	0.84 ± 0.05	0.05 ± 0.01	1.10 ± 0.04	20.9 ± 0.03	64.8 ± 0.50
Pot Plant	YES	125.91 ± 5.15	3.49 ± 0.18	128.19 ± 5.16	20.0 ± 0.00	79.0 ± 0.48
Substrate only	NO	−0.01 ± 0.00	0.03 ± 0.00	0.36 ± 0.00	24.4 ± 0.04	64.8 ± 0.16
Substrate only	YES	0.14 ± 0.01	0.03 ± 0.00	0.65 ± 0.01	25.2 ± 0.03	70.7 ± 0.19

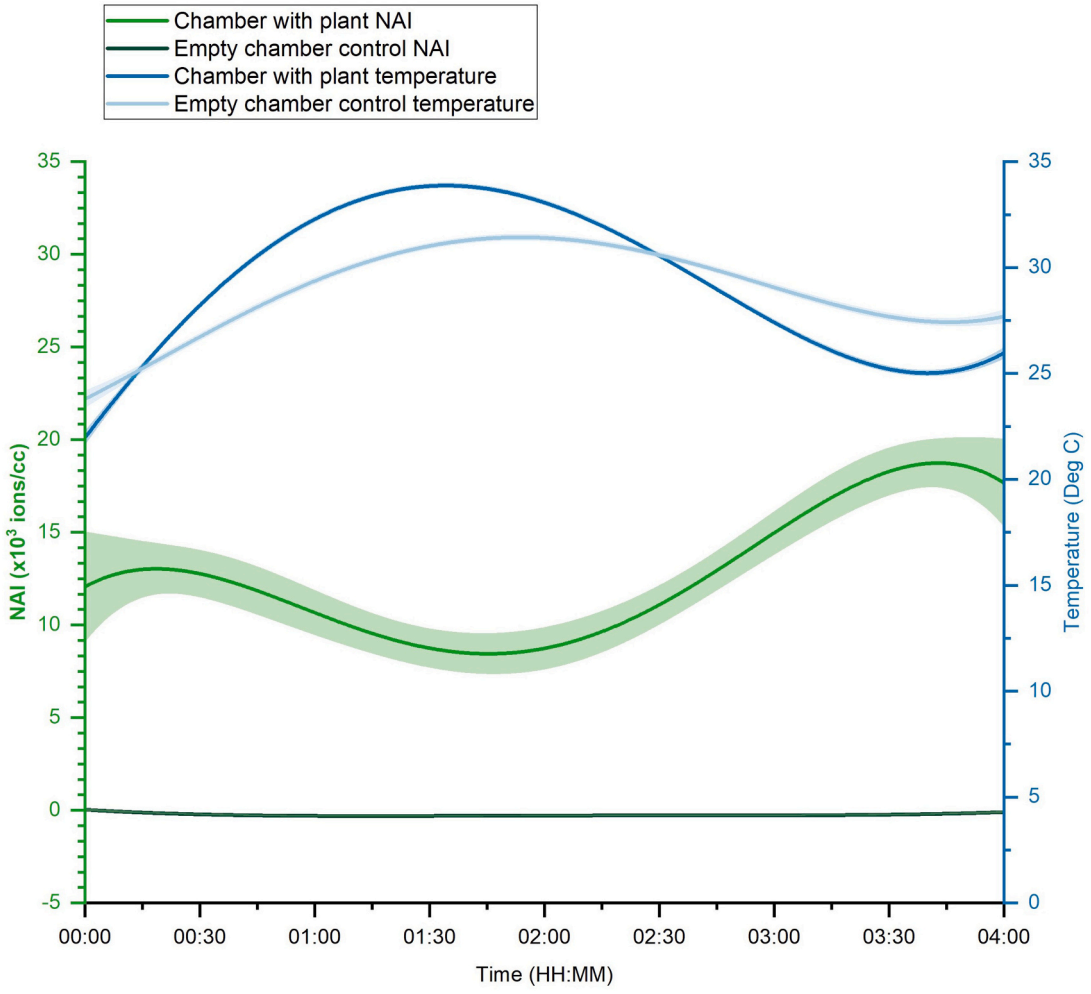


Fig. 3. Scatter plots of *S.wallisii* NAI production and ambient temperature over time (n = 3, shaded area represents 95 % confidence band).

thus making its role in plant NAI production multi contributive (Wu and Lin, 2012).

3.5. Temperature effects on S. wallisii NAI generation

As shown in Fig. 3, high temperatures exerted a negative effect on NAI generation. Spearman's correlation analysis confirmed a statistically negative association between temperature and NAI production ($r = -0.351$, $p < 0.001$). With increasing temperatures, NAI concentrations around the plants rapidly declined. However, once heating ceased and the ambient temperature dropped, NAI levels rebounded significantly, reaching asymptotic levels within two hours. In contrast, results from the empty control chamber demonstrated a slight increase in NAI concentration, which promptly returned to baseline levels once heating was discontinued. The observed temperature-NAI relationship in plants appears to be linked to the plant's physiological response to heat stress. One hypothesis is that stomata serve as a key pathway for NAI release (Jiang et al., 2018; Aubrecht et al., 2000). When exposed to high temperatures, plants close their stomata or reduce stomatal conductance to mitigate water loss through transpiration. At the same time, photosynthetic and other metabolic activity decline under heat stress (Jiang et al., 2018; Shi et al., 2022). The results within this work suggest under high temperatures, *S.wallisii* undergoes stomatal closure and reduced photosynthetic rates which limits the release of NAI's into the surrounding air. However, while high temperatures are expected to reduce plant-released NAIs, ambient NAI concentrations should remain stable or show a gradual increase following a temperature rise. Instead, a decline in NAI concentration was observed under high-temperature conditions. This effect may be attributed to the instability of NAIs at high concentrations, as electrically charged particles tend to neutralize over time due to natural recombination processes (Jiang et al., 2018; Iwama et al., 2002; Wu et al., 2006). Additionally, molecular kinetic theory suggests that increased thermal motion at higher temperatures enhances ion activity, thereby accelerating the rate of neutralization reactions. A comparison with the blank control experiment, NAI concentrations remained consistently low and exhibited minimal response to temperature variations, further supporting the role of plant-derived NAI production and environmental interactions in this process. This observation may also contribute to the lower NAI levels observed at night in natural environments, which could result from reduced photosynthetic activity and ion neutralization processes (Li et al., 2021).

Interestingly, during the cooling phase after heat exposure, NAI concentrations recovered rapidly and even exceeded their initial levels. This may suggest that, despite stomatal closure preventing NAI release under high temperatures, internal NAI production within the plant remains active (Li et al., 2021; Shi et al., 2022; Wu, 2017). The repeated heating experiment results shown in Fig. 4, reveal gradual changes in NAI release from the plant. As heating cycles continued, the peak NAI data steadily increased, suggesting that plants may enhance their NAI production capacity as an adaptive response to high-temperature exposure. As shown in Table 7, following the final heating cycle, plants reached a maximum NAI release of $24.9 \pm 0.23 \times 10^3$ ions/cm^3, and the rate of NAI change increased with each heating treatment. Furthermore, when comparing temperature fluctuations and NAI levels,

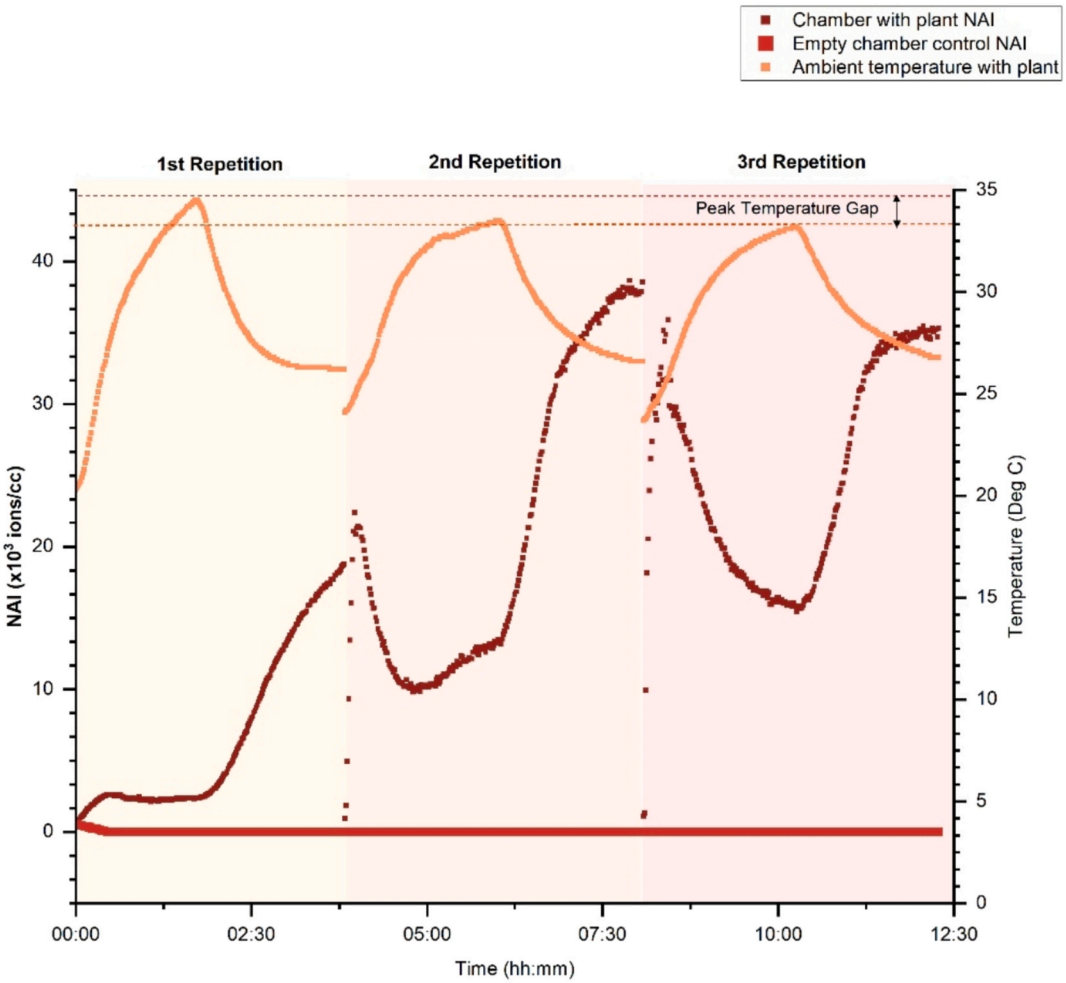


Fig. 4. Under repeated high-temperature experiments, Scatter plots of plant NAI and ambient temperature over time and fitted curves plot.

Table 7
Results of NAI data under repeated heating experiments.

Type Of Chamber	Repetitions	Heating Duration	NAI (X10^3 Ions/cm^3/s)			Temperature (Deg C)	Humidity (%)
			MAX Net Change	Rate Change	Averange NAI Change		
Empty	0	2 h	−0.22	0.00	0.06	28.7 ± 2.38	57.4 ± 0.08
Pot Plants	1	2 h	6.18	0.02	6.80	28.8 ± 3.46	80.4 ± 0.08
Pot Plants	2	2 h	20.18	0.04	21.13	29.7 ± 2.00	80.2 ± 0.07
Pot Plants	3	2 h	23.74	0.03	24.86	29.5 ± 1.98	80.1 ± 0.07

the increase in NAI release was significantly greater than the temperature variation, suggesting that temperature may act as a secondary factor, with plant physiological responses playing a more critical role (Borra et al., 1997; Wang and Li, 2009). Moreover, with repeated heating cycles, the fluctuations in NAI concentration became more pronounced, suggesting the involvement of additional influencing factors, potentially related to plant metabolic activity (Borra et al., 1997; Wang and Li, 2009).

The minimum NAI levels recorded at peak temperatures also showed a gradual upward trend, potentially indicating progressive metabolic adaptation to heat stress. These findings indicate a proof of concept for *S.wallisii*, suggesting thermal fluctuations may enhance NAI production, further targeted research is warranted with larger samples sizes and experimental designs focused on this phenomenon to validate and expand upon these preliminary observations.

Another intriguing finding concerns the plant-mediated temperature regulation mechanism under continuous heat stress conditions. Despite each experimental group undergoing the same heating treatment (i.e. 2 h of heating), a comparison of peak environmental temperatures revealed that plants subjected to repeated heat stress modulated their surrounding temperature more effectively, resulting in lower peak temperatures and a more gradual return to room temperature. Conversely, in the blank control group (empty chamber), post-heating cooling exhibited a substantially longer cooling duration, requiring over 6 h to return to room temperature. In comparison, plants accelerated environmental cooling, bringing ambient temperature close to room conditions within just 2 h. This is likely due to heat-induced transcription factors activating the production of heat shock proteins (HSPs) in plants (Kotak et al., 2007). HSPs protect cellular structures and help maintain proper protein function under elevated temperatures (Kotak et al., 2007). Under repeated heat stress, HSPs can accumulate, enabling plants to return to normal metabolic function more rapidly—a process known as acquired thermotolerance (Kotak et al., 2007; Prerostova and Vankova, 2023). This faster metabolic recovery may indirectly enhance ambient cooling times via faster returns to plant evapotranspiration. This discovery further supports the role of plants in climate regulation, demonstrating their potential contribution to modulating indoor thermal conditions.

3.6. Environmental humidity on plant generated NAI

As depicted in Fig. 5, within the *S. wallisi* samples higher humidity conditions (RH = 79.2 ± 2.88 %) saw a peak NAI net change of 0.9 ± 0.39× 10^3 ions/cm^3, significantly outperforming the lower humidity samples (73.1 ± 5.02 %), which saw a NAI net change of 0.3 ± 0.19× 10^3 ions/cm^3($p < 0.001$). A Pearson correlation analysis demonstrated a strong association between humidity and NAI production ($R = 0.827$, $p < 0.001$). This effect may be explained by the role of water molecules in facilitating NAI formation, as well as higher humidity levels enhancing plant metabolic activity, thereby increasing NAI production (Jiang et al., 2018; Lambert and Brand, 2004). Additionally, some studies propose that NAIs in humid environments tend to form hydrated ion clusters,

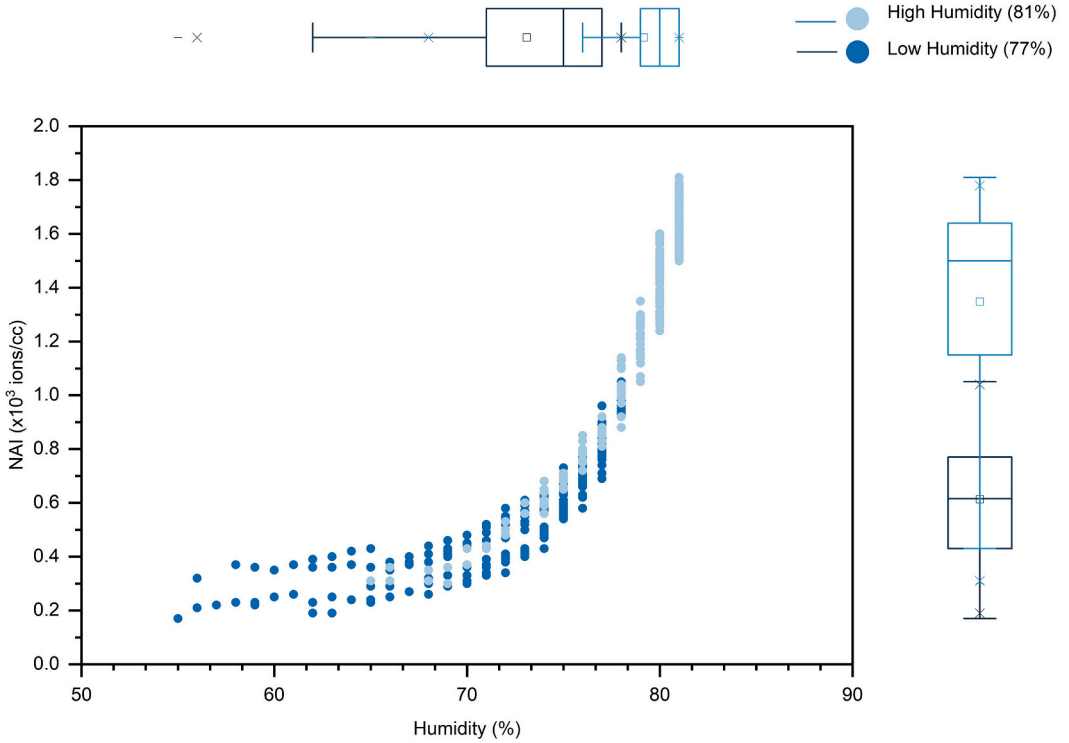


Fig. 5. Scatterplot and box plot composites of changes in *S.wallisi* NAI generation across different humidity environments.

improving their stability and longevity (Jiang et al., 2021; Tammet, 1995; Ortéga et al., 2007).

Some studies have argued that at very high humidity levels (> 70 %), NAIs are more easily neutralised by water molecules, and airborne aerosols may further inhibit their diffusion (Jiang et al., 2018; Lambert and Brand, 2004; Tammet, 1995; Ortéga et al., 2007). However, this was not seemingly present within this work, with *S.wallisi* present within maximum humidity levels of 81 % maintaining strong NAI concentrations ($1.4 \pm 0.17 \times 10^3$ ions/cm^3). The influence of humidity on NAI concentrations has also been observed in forest environments, where rainfall and high humidity are strongly correlated with increased ambient NAI levels (Li et al., 2021). Future investigations should aim to precisely regulate humidity conditions to better understand their impact on plant NAI production.

3.7. Comprehensive analysis of factors influencing plant-based NAI

A correlation analysis was performed following *Z*-score normalisation of data for plant species, LAI, light intensity, irrigation, temperature, and humidity. The most influential factors were humidity ($r = 0.827$, $p < 0.000$) and irrigation ($r = 0.923$, $p < 0.000$). Since both factors are closely associated with water molecules, this finding further supports the notion that plant NAI production relies not just solely on plant physiology but more so on environmental conditions and water source availability (Wu and Lin, 2012; Li et al., 2022). This is consistent with previous research on outdoor environments, which has demonstrated a strong correlation between humidity, rainfall, and plant NAI levels (Li et al., 2022). Additionally, plant density (calculated by LAI) exhibited a strong correlation with NAI production as well ($r = 0.614$, $p < 0.000$). Surprisingly, temperature and light intensity were found to have limited effects on NAI generation compared to other factors, with correlation values of $r = 0.351$ ($p < 0.001$, temperature) and $r = 0.472$ ($p < 0.001$,light intensity). Since these factors are closely associated with plant metabolism and photosynthetic activity, suggesting that their impact on NAI production is likely indirect (Wang and Li, 2009; Jiang et al., 2018; Tikhonov et al., 2004). Across the 45 plants species tested within this work, multiple individual species exhibited outstanding NAI production capacity (eg. *Spathiphyllum wallisii, Anigozanthos, Argyranthemum frutescens, Rosemarinus officinalis, Viola odorata*) (Fig. 6). However, differences in individual plant LAI did not present itself to have a statistically significant relationship with NAI production ($r = 0.156$, $p = 0.283$) suggesting some other physiological factor not tested within this work separated these species as effective NAI producers compared to the others. Potential areas for further investigation include testing the relationship between NAI emissions and the number of leaves per plant, as well as the use of solvent extraction and microscopy to assess the influence of plant chlorophyll levels, and stomatal density per unit leaf area, as both variables are strongly associated with plant water: gas balance.

4. Future applications and perspectives

To date, research on plant-derived NAI emissions remains in its early stages, with limited exploration into methods for optimising and enhancing plant NAI production. Current artificial NAI generation methods primarily involve corona discharge and pulsed electrical field (PEF) stimulation applied to the plant rhizosphere (Tikhonov et al., 2004; Siņicina and Martinovs, 2017; Manabe and Shimazaki, 2004; Murr, 1963). Artificial NAI production has been linked to unintended ozone pollution, making it less practical for indoor environments in urban buildings (Takahashi et al., 2019). Research incorporating a device for PEF discharge within a plant based system could generate NAIs exceeding 100×10^6 ions/cm^3, and similar applications in turf environments yielded NAI concentrations of approximately 1×10^6 ions/cm^3 (Jiang et al., 2021). Nevertheless, electrical stimulation poses potential risks of plant damage and physiological stress, and energy consumption remains a critical factor requiring further analysis (Jiang et al., 2018; Murr, 1963). When considering indoor residential applications, concerns regarding occupant safety and potential electrical hazards must also be critically assessed. Building upon the findings of this study, future research and innovation should focus on integrating active green walls (AGW) with temperature and humidity regulation (Coma et al., 2017; Baran and Gültekin, 2018). There is evidence that the charged nature of NAIs assists in immediate PM capture, this research is limited to artificially generated NAIs, investigation of PM removal in correlation to plant system NAI generation indoors would provide further valuable insights into the pollution removal mechanisms of botanical biofilters (Jiang et al., 2021). To ensure sustainable implementation and optimisation, efforts should balance environmental impact, energy efficiency, and compliance with indoor environmental standards. While this work was limited to an environmentally isolated chamber set-up to remove confounding variables, it is important for future work investigate the efficacy of planted NAI generation within realistic indoor settings, where factors such as building type, ventilation, occupant density and room volume may impact results. In terms of temperature management, the observed increase in plant NAI production under moderate heat stimulation suggests that active green walls could be enhanced by incorporating heating lamps or warm-air ventilation systems. In real-world applications, integrating active green walls with Heating, Ventilation and Air Conditioning (HVAC) systems could further mitigate thermal energy losses inside the indoor environment (Rahman, 2022). For humidity management, the irrigation system of active green walls can serve a dual function: increasing both NAI production and indoor humidity (Pérez-Urrestarazu et al., 2014; Lyu et al., 2024). Additionally, various irrigation strategies can be systematically compared to evaluate their impact on the overall performance of green walls.

5. Conclusions

Our findings showed that across 45 plant species, *S.wallisii* demonstrated the highest capacity for NAI production within a sealed environment. While NAI generation did vary across plant species, analysis

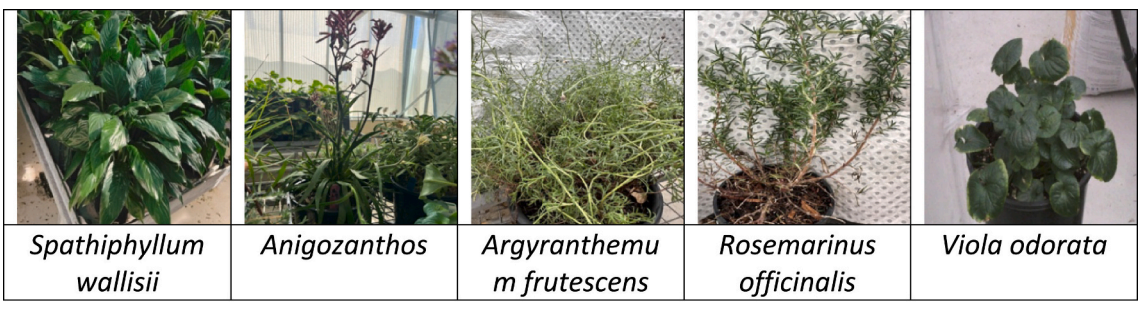


Fig. 6. Top-performing plant species in NAI-releasing capacity.

did not find this effect to be due to species LAI, leaf morphology or presence of leaf hair, it may be that future studies involving a broader range of plant species would be able to find significant correlations. It's recommended these future works incorporate additional plant structural characteristics such as chlorophyll concentration and stomatal density. Humidity and temperature had the strongest correlations with *S.wallisii* NAI production followed by increasing plant density. A proof of concept was also observed for a plant adaptive "rapid NAI surge" following high-temperature exposure, further research is recommended with larger samples sizes and a focused experimental design to expand upon these preliminary observations. This work provides one of the most comprehensive assessments of potted plant-associated NAI release capacity, to date. However, future exploration into methods for optimising and enhancing plant NAI production within the indoor environment need to incorporate technical innovations such as active green walls to provide the most comprehensive understanding of indoor plant NAI generation.

CRediT authorship contribution statement

Luowen Lyu: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Stephen Matheson:** Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Conceptualization. **Nic C. Surawski:** Writing – review & editing, Writing – original draft, Validation, Supervision. **Peter J. Irga:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Conceptualization. **Fraser R. Torpy:** Writing – review & editing, Writing – original draft, Supervision, Resources, Data curation, Conceptualization.

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.

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Data availability

Data will be made available on request.

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