Green Climate Control

Analysing the impact of (active) Plant-based Systems on Indoor Air Quality

Armijos Moya, T.E.

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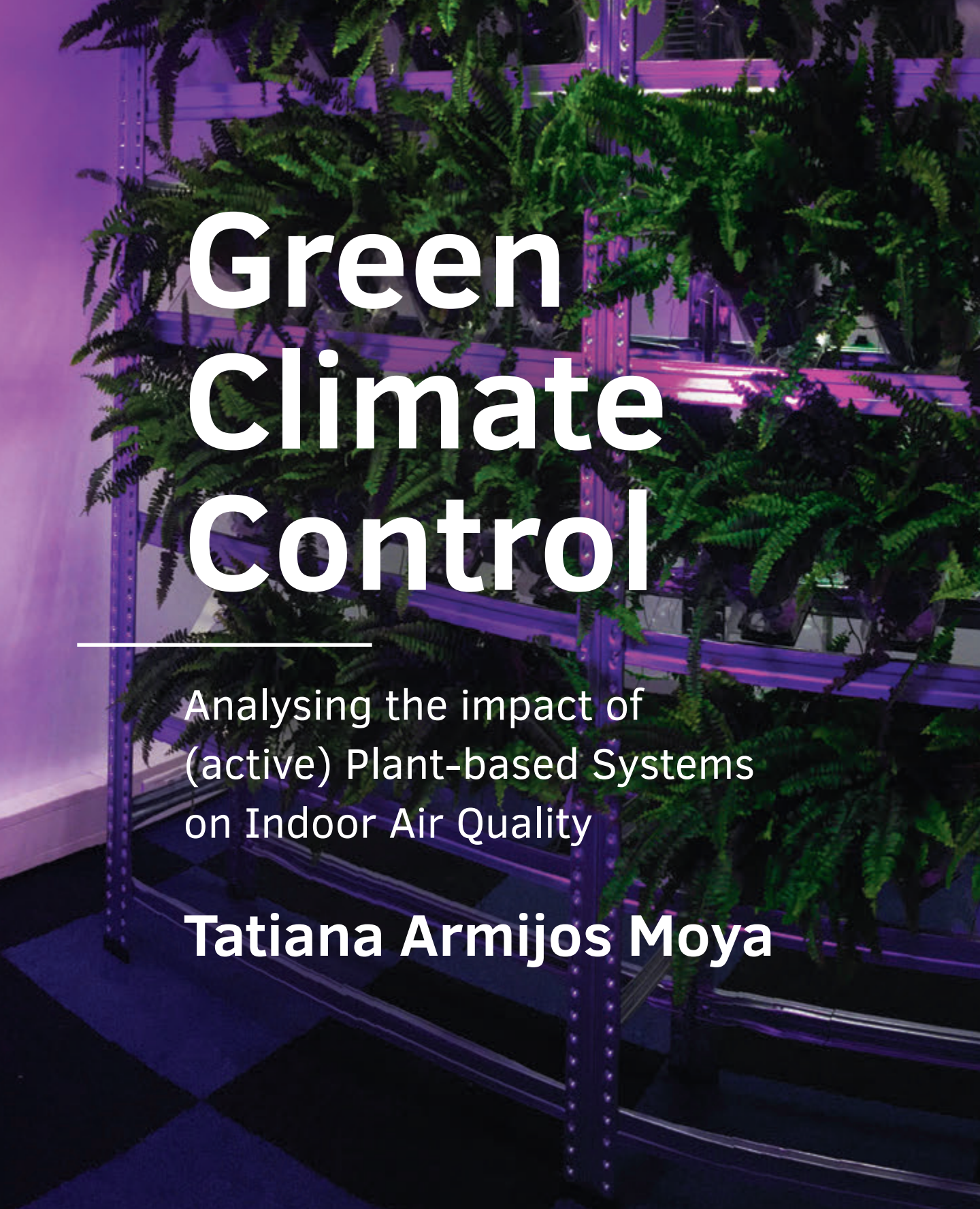

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Green Climate Control

Analysing the impact of (active) Plant-based Systems on Indoor Air Quality

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
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chair of the Board for Doctorates
to be defended publicly on
Monday 13, December 2021 at 12:30 o'clock

by

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Master of Science in Architecture, Urbanism and Building Sciences,
Delft University of Technology, the Netherlands
born in Quito, Ecuador

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This dissertation has been approved by the promotors.

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To my parents

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Thank you.

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List of Abbreviations, Units and Symbols

List of Abbreviations	
AC_D	Dry Activated Carbon
AC_W	Wet Activated Carbon
ANOVA	Analysis Of Variance
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BRI	Building-Related-Illness
CADR	Clean Air Delivery Rate
CH_2O	Formaldehyde
CO_2	Carbon Dioxide
EC	Expanded Clay
EC_D	Dry Expanded Clay
EC_W	Wet Expanded Clay
H_2O	dihydrogen monoxide, water
HVAC	Heating, ventilation, and air conditioning
IEQ	Indoor Environmental Quality
IAQ	Indoor Air Quality
LWSs	Living Wall Systems
MDF	Medium Density Fibreboard
N(0)	Initial amount of pollutant at t = 0h
N(t)	Amount of pollutant after time t
NEPH	Boston fern, plant
NEN-EN	European standards (EN) adopted in the Netherlands
O_3	Ozone
PID	Photoionization Detector
PM	Particulate Matter
POM	Particulate Organic Matter
PPB	Parts Per Billion

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List of Abbreviations	
PPM	Parts Per Million
RH	Relative Humidity
SBS	Sick Building Syndrome
SD	Dry soil
S.D.	Standard Deviation
S.E.	Standard Error
SW	Wet soil
SO_2	Sulphur Dioxide
SPA	Peace Lily, plant
Std. Deviation	Standard Deviation
SVOCs	Semi Volatile Organic Compounds
T	Temperature
UV	Ultraviolet
V	Volume
VOC	Volatile Organic Compound
VOCs	Volatile Organic Compounds
VVOCs	Very Volatile Organic Compounds
WHO	World Health Organization
ZM	Zero Measurement
ZM_P	Zero Measurement with the Plastic pot

List of Units and Symbols	
°C	Celsius
g/mol	Grams per mol
m^2	Square Metre
m^3	Cubic Metre
m^3/h	Cubic metre per hour
m/s	Metre per second
mg/m^3	Milligram per cubic metre
$\mu g/m^3$	Microgram per cubic metre
µl	Microlitre
λ	Decay rate
λn	Natural decay rate
λp	Decay rate including the plastic pot
η	Efficiency

Summary

The thesis ‘Green Climate Control: Analysing the impact of (active) Plant-based Systems on Indoor Air Quality’ aims to explore and evaluate the efficacy of an active plant-based system in terms of Indoor Air Quality (IAQ). Several studies have demonstrated the potential of botanical biofiltration and phytoremediation to remove indoor pollutants and improve overall comfort. However, there is a lack of evidence on how indoor greenery affects the Indoor Environmental Quality (IEQ), particularly on Indoor Air Quality (IAQ). To be able to answer the main research question: “Can an active plant-based system improve the Indoor Air Quality (IAQ)?”, several key (sub)research questions were explored, further elaborated and divided into three sections consisting of six chapters.

PART 1: Theoretical Framework and State of the Art

First, Chapter 1: ‘Introduction’ describes the overall goals of this research project. Then, Chapter 2 “Literature Review: A review of green systems within the indoor environment” presents an extensive literature review, including scientific articles and book sections from the last 30 years. This state-of-the-art analysis is meant to help to evaluate and validate facts and information in further steps. During this exploration it was found that evapotranspiration from plants helps lowering the temperature around the planting environment and this can be utilised for air cooling and humidity control. Indoor greenery can be used to reduce sound levels as a passive acoustic insulation system. Moreover, several studies have indicated that green systems may improve indoor air quality and that they have different pathways for pollutant removal: the plant root zone, the leaves of the plant and the growth medium. It was found that the removal can differ for different plants and different growth media.

PART 2: Methods for IAQ assessment

In part 2, the aim was to test the efficacy of plant-based systems in terms of IAQ. There are different methods available to assess IAQ, such as chemical monitoring, physical monitoring and sensory assessment. Specific protocols were developed for each case and the assessments were executed in laboratory chambers specifically designed for this purpose. In this context, Chapter 3 “Assessment of Perceived Indoor Air Quality: Appraisal and identification of different sources of smell by primary school children in the air quality test chamber of the SenseLab”, addresses

different assessments of (perceived) indoor air quality (IAQ), including physical monitoring and sensory evaluation. In this study 335 primary children were exposed to different sources of smell, and were asked to evaluate and identify those sources at individual level with their noses. Moreover, the possible effect of plants on the reduction and/or production of air pollutants was tested. The results of this study confirmed the need to include sensory assessments in the evaluation of IAQ together with physical monitoring, as well as the need of an active system (that includes a ventilator that sucks the air through the plant-medium system).

Then, Chapter 4 "Optimal plant-medium combination: Air cleaning performance of two species of potted plant and different substrates" describes an experimental study on the removal of indoor air pollutants by common indoor plant species (Peace Lily and Boston Fern) and growth media (expanded clay, soil and activated carbon), using formaldehyde and CO_2 as indicators to evaluate the bio-filtration efficacy of 28 different test conditions. Overall, soil had the best performance in removing formaldehyde (~0.07-0.16 m^3/h), while plants, in particular, were more effective in reducing CO_2 concentrations (Peace lily 0.01 m^3/h) (Boston fern 0.02-0.03 m^3/h). On average, plants (~0.03 m^3/h) were as effective as dry expanded clay (0.02-0.04 m^3/h) in depleting formaldehyde from the chamber. Regarding air cleaning performance, Boston ferns presented the best performance among the plant species, and the best performing substrate was the soil. These experimental results provided insight into the selection of growth media and plant species to be used in the plant-based system prototype.

PART 3: Experimentation, design and integration

In this final part an active plant-based system prototype was developed and evaluated considering the outcomes of the previous experiments. Chapter 5 "Active Plant-based System: The effect of an active plant-based system on perceived air pollution", describes the system in detail including its components and the factors that were analysed. For this evaluation the prototype was placed in a semi-controlled environment and different methods were used to assess its impact on the (perceived) IAQ, including sensory assessments and physical/chemical monitoring. In this study the odour coming out of two test chambers in the SenseLab, both furnished with the same 'new' flooring material was assessed blindly by test subjects over time. The subjects were asked to evaluate the level of acceptability, intensity, odour recognition, and preference at individual level with their noses. The results showed that in general, the level of odour intensity was lower in the chamber without plants, the level of acceptability was lower in the chamber with plants, while the participants identified similar sources in both test chambers. Finally, the preference was slightly higher for the test chamber without the active plant-based system.

Finally, Chapter 6 “Conclusions and Recommendations” explains the impact of this research within a larger context and specific needs for further investigation. A reflection is included regarding the future of plant-based systems in the built environment.

Samenvatting

Het proefschrift ‘Green Climate Control: Analyzing the impact of (active) Plant-based Systems on Indoor Air Quality’, heeft als doel het effect van een actief planten systeem op de binnenluchtkwaliteit te onderzoeken en te evalueren. Uit verschillende onderzoeken blijkt dat botanische biofiltratie en fytoremediatie de potentie hebben om verontreinigende stoffen in binnenruimtes te verwijderen en het algehele comfort te verbeteren. Er is echter een gebrek aan bewijs over de invloed van planten op de kwaliteit van het binnenmilieu, en dan met name op de binnenluchtkwaliteit. Om de hoofdvraag: “Kan een actief plantaardig systeem de luchtkwaliteit binnenshuis verbeteren?” te kunnen beantwoorden, zijn verschillende (deel)onderzoeksvragen onderzocht. Deze vragen zijn uitgewerkt en onderverdeeld in drie delen en totaal zes hoofdstukken.

DEEL 1: Theoretisch kader en state-of-the-art

In deel 1 wordt in hoofdstuk 1 “Inleiding” de doelstellingen van dit onderzoeks-project beschreven. Vervolgens wordt in hoofdstuk 2 “Literatuuroverzicht: een overzicht van planten systemen in het binnenmilieu” een uitgebreid literatuur-overzicht gepresenteerd, van wetenschappelijke artikelen en boeksecties van de afgelopen 30 jaar. Deze state-of-the-art analyse is bedoeld ter ondersteuning bij het evalueren en valideren van feiten en informatie in verdere stappen. Tijdens deze verkenning werd ontdekt dat verdamping van planten helpt om de temperatuur rond de plantomgeving te verlagen en dat dit kan worden gebruikt voor luchtkoeling en het regelen van de vochtigheids. Vegetatie kan binnen worden gebruikt om het geluidsniveau te verlagen als passief akoestisch isolatiesysteem. Bovendien is in verschillende studies aangetoond dat plantsystemen de luchtkwaliteit binnenshuis kunnen verbeteren en daarvoor verschillende manieren ter beschikking hebben: de plant wortel zone, de bladeren van de plant en het groei medium.

DEEL 2: Methoden voor de beoordeling van binnenluchtkwaliteit

In deel 2 was het bedoeling de werkzaamheid van op planten gebaseerde systemen te testen in termen van binnenluchtkwaliteit. Er zijn verschillende methoden beschikbaar om de binnenluchtkwaliteit te beoordelen, zoals chemische monitoring, fysieke monitoring en sensorische beoordeling. Voor elke testcasus werden specifieke protocollen ontwikkeld en de beoordelingen werden

uitgevoerd in speciaal daarvoor ontworpen testruimtes. In deze context behandelt Hoofdstuk 3 “Beoordeling van de waargenomen binnenluchtkwaliteit: beoordeling en identificatie van verschillende geurbronnen door basisschoolkinderen in de luchtkwaliteitstestkamer van het SenseLab”, verschillende beoordelingen van de (waargenomen) binnenluchtkwaliteit, inclusief fysische monitoring en sensorische evaluatie. In deze studie werden 335 primaire kinderen blootgesteld aan verschillende bronnen van geur, en werd hen gevraagd die bronnen individueel met hun neus te evalueren en te identificeren. Daarnaast werd het mogelijke effect van planten op het verminderen en/of produceren van geuren getest. De resultaten van deze studie bevestigden de noodzaak om naast fysische monitoring, sensorische beoordelingen mee te nemen in de evaluatie van de binnenluchtkwaliteit, en de noodzaak voor een actief systeem (met een ventilator die lucht door het plant-medium systeem kan halen).

Dan beschrijft Hoofdstuk 4 “Optimaal plant-mediumcombinatie: luchtzuiverende prestatie van twee soorten potplanten met verschillende substraten”, een experimenteel onderzoek naar de verwijdering van binnenluchtverontreinigingen door gewone kamerplanten (Peace Lily en Boston Fern) en groeimedia (geëxpandeerde klei, potgrond en actief kool), met behulp van formaldehyde en CO_2 als indicatoren om de biofiltratie-efficiëntie van 28 verschillende testomstandigheden te evalueren. In het algemeen verwijderde potgrond het beste formaldehyde (~0,07-0,16 m^3/h), terwijl de planten effectiever waren in het verlagen van de CO_2-concentraties (Peace lily 0,01 m^3/h) (Boston fern 0,02-0,03 m^3/h). Gemiddeld waren de planten (~0,03 m^3/h) even effectief als droge geëxpandeerde klei (0,02-0,04 m^3/h) in het verwijderen van formaldehyde uit de testkamer. Wat betreft de luchtzuiverende werking, presteerden de Boston-varens het beste onder de plantensoorten, en het best presterende substraat was de potgrond. De uitkomsten van deze studie gaven inzicht in de selectie van het groeimedium en de plant die kon worden gebruikt in het prototype van het planten-systeem.

DEEL 3: Experimenteren, ontwerp en integratie

In dit laatste deel werd een prototype van een actief planten systeem ontwikkeld en geëvalueerd, waarbij rekening werd gehouden met de uitkomsten van de voorgaande studies. Hoofdstuk 5 “Actief planten systeem: het effect van een actief op planten gebaseerd systeem op de waargenomen luchtverontreiniging”, beschrijft het systeem in detail, inclusief de componenten en de factoren die werden geanalyseerd. Voor deze evaluatie werd het prototype in een semi-gecontroleerde omgeving geplaatst en werden verschillende methoden gebruikt om het effect ervan op de (waargenomen) binnenluchtkwaliteit te beoordelen, waaronder sensorische beoordelingen en fysische/chemische metingen. In deze studie was werd de geur afkomstig uit

twee verschillende testkamers van het SenseLab beiden met dezelfde ‘nieuwe’ vloerbedekking, door verschillende proefpersonen blindelings in de tijd beoordeeld. Zij werden gevraagd het niveau van aanvaardbaarheid en de intensiteit met hun neus te beoordelen, welke geuren ze herkenden en hun voorkeur voor 1 van de twee testkamers te geven. De uitkomsten lieten zien dat de geurintensiteit over het algemeen lager was in de kamer zonder planten, het niveau van aanvaardbaarheid lager was in de kamer met planten, en dat de deelnemers in beide testkamers dezelfde geurbronnen herkenden. Ten slotte was de voorkeur iets hoger voor de testkamer zonder het actief op planten gebaseerde systeem.

Tenslotte, wordt in Hoofdstuk 6 “Conclusies en aanbevelingen”, het effect van dit onderzoek in een grotere context uitgelegd, en worden specifieke behoeften voor verder onderzoek aangegeven. Er wordt gereflecteerd op de toekomst van op planten gebaseerde systemen in de gebouwde omgeving.

Resumen

La tesis ‘Green Climate Control: Analysing the impact of (active) Plant-based Systems on Indoor Air Quality’ tiene como objetivo explorar y evaluar la eficacia de un sistema vegetal activo en la calidad del aire interior. Varios estudios han demostrado el potencial de la biofiltración botánica y la fitorremediación para eliminar los contaminantes en espacios interiores y mejorar así la comodidad en general. Sin embargo, hay una falta de evidencia sobre cómo la vegetación afecta la Calidad Ambiental Interior, particularmente en la Calidad del Aire Interior. Para poder responder a la pregunta principal de la investigación: “¿Puede un sistema activo basado en plantas mejorar la calidad del aire interior?”, se exploraron varias (sub) preguntas claves relacionadas con el tema, las cuales se desarrollaron y dividieron en tres secciones que se presentan a continuación de seis capítulos.

SECCIÓN 1: Marco teórico y Estado del arte

Primero, el Capítulo 1: “Introducción” describe los objetivos generales de este proyecto de investigación. A continuación, el Capítulo 2 “Revisión de la literatura: Una revisión de los sistemas basados en plantas dentro de espacios interiores” presenta una extensa revisión de literature científica, que incluye artículos científicos y secciones de libros de los últimos 30 años. Este análisis tiene como objetivo ayudar a evaluar y validar información y hallazgos en pasos posteriores. Durante esta exploración se descubrió que la evapotranspiración de las plantas ayuda a reducir la temperatura alrededor de los sistemas vegetales y esto se puede utilizar para enfriar el aire y controlar la humedad. La vegetación interior se puede utilizar para reducir los niveles de sonido como un sistema de aislamiento acústico pasivo. Además, varios estudios han indicado que los sistemas verdes pueden mejorar la calidad del aire interior y que tienen diferentes vías para la eliminación de contaminantes: la zona de la raíz de la planta, las hojas de la planta y el sustrato. Se encontró que la eliminación puede diferir para diferentes plantas y diferentes medios de crecimiento.

SECCIÓN 2: Métodos para la evaluación de la calidad del aire interior

En esta sección, el objetivo es evaluar la eficacia de los sistemas vegetales en la mejora de la calidad del aire interior. Hay diferentes métodos disponibles para ejecutar dicha evaluación, como por ejemplo el análisis químico, el análisis l físico y la evaluación sensorial. Se desarrollaron protocolos específicos para cada caso y las

evaluaciones se ejecutaron en cámaras de laboratorio diseñadas específicamente para este propósito. En este contexto, el Capítulo 3 “Evaluación de la calidad del aire interior percibida: evaluación e identificación de diferentes fuentes de olor por parte de niños de escuela primaria en la cámara de prueba de calidad del aire del SenseLab”, aborda diferentes evaluaciones de la calidad del aire interior (percibida), incluidas diferentes evaluaciones sensorial. En este estudio, 335 niños de primaria fueron expuestos a diferentes fuentes de olor, y se les pidió que evaluaran e identificaran esas fuentes a nivel individual con sus narices. Además, se probó el posible efecto de las plantas en la reducción y / o producción de contaminantes atmosféricos. Los resultados de este estudio confirmaron la necesidad de incluir evaluaciones sensoriales en la evaluación de la calidad del aire interior junto con el monitoreo físico, así como la necesidad de un sistema vegetal activo (que incluya un ventilador que succione el aire a través del sistema planta-medio).

Luego, el Capítulo 4 “Óptima Combinación de sustrato y tipo de planta: evaluación de limpieza del aire de dos especies de plantas y diferentes sustratos” describe un estudio experimental sobre la eliminación de contaminantes del aire en espacios interiores por especies comunes de plantas (Lirios de la paz y helechos comunes) y diferentes sustratos (arcilla expandida, tierra de cultivo y carbón activado), utilizando formaldehído y CO_2 como indicadores para evaluar la eficacia de la biofiltración de 28 condiciones diferentes. En general, la tierra de cultivo tuvo el mejor desempeño en la eliminación de formaldehído (~ 0.07-0.16 m^3 / h), mientras que las plantas, en particular, fueron más efectivas para reducir las concentraciones de CO_2 (lirios de la paz: 0.01 m^3 / h) (helechos: 0.02-0.03 m^3 / h). En promedio, las plantas (~ 0.03 m^3 / h) fueron tan efectivas como la arcilla expandida seca (0.02-0.04 m^3 / h) para eliminar el formaldehído de la cámara. En cuanto al desempeño de la limpieza del aire, los helechos presentaron el mejor desempeño entre las especies de plantas, y el sustrato de mejor desempeño fue la tierra de cultivo. Estos resultados experimentales proporcionaron información sobre la selección de medios de crecimiento y especies de plantas que se utilizarán en la construcción de un prototipo de sistema vegetal active.

SECCIÓN 3: Experimentación, diseño e integración

En esta parte final se desarrolló y evaluó un prototipo de un Sistema vegetal activo considerando los resultados de los experimentos anteriores. El Capítulo 5 “Sistema activo basado en plantas: el efecto de un sistema vegetal activo sobre la contaminación del aire percibido”, describe el sistema en detalle, incluidos sus componentes y los factores que se analizaron. Para esta evaluación, el prototipo se colocó en un entorno semicontrolado y se utilizaron diferentes métodos para evaluar su impacto en la calidad del aire (percibido), incluidas evaluaciones

sensoriales y monitoreo físico / químico. En este estudio, los participantes del estudio evaluaron ciegamente el olor que sale de dos cámaras de prueba en el SenseLab, ambas equipadas con el mismo material de piso “nuevo”. Se pidió a los sujetos que evaluaran el nivel de aceptabilidad, intensidad, reconocimiento de olores y preferencia con la nariz. Los resultados mostraron que, en general, el nivel de intensidad del olor fue menor en la cámara sin plantas, el nivel de aceptabilidad fue menor en la cámara con plantas, mientras que los participantes identificaron fuentes similares en ambas cámaras de prueba. Finalmente, la preferencia fue ligeramente mayor por la cámara de prueba sin el sistema vegetal activo.

Finalmente, el Capítulo 6 “Conclusiones y recomendaciones” explica el impacto de esta investigación dentro de un contexto más amplio y la necesidad de futuras investigaciones en el tema. Se incluye una reflexión sobre el futuro de los sistemas de purificación del aire basados en plantas en el entorno construido.

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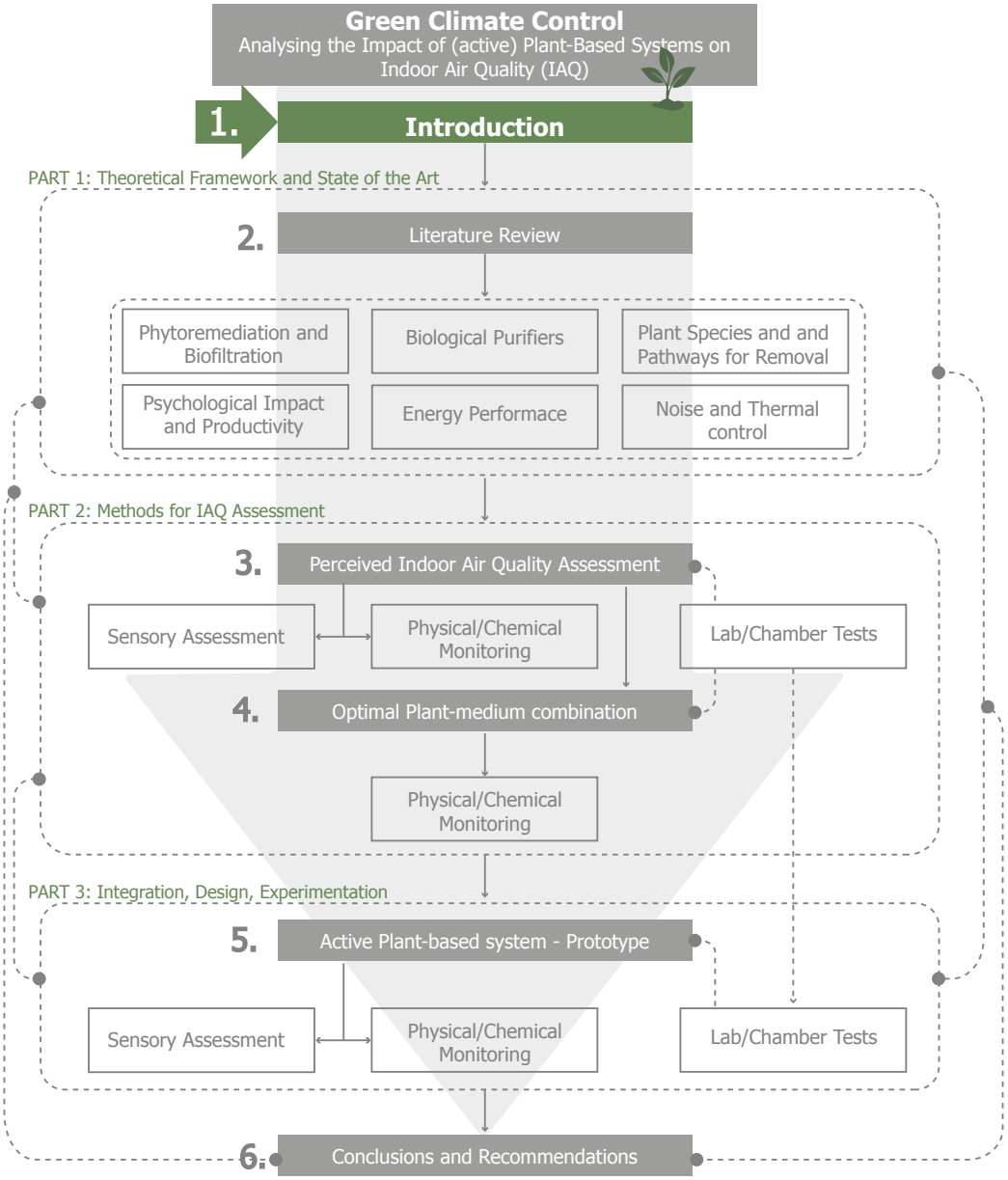
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1 Introduction

1.1 Background and Problem Statement

Humans possess a natural instinct to connect with nature and other forms of life.[1–3] The positive psychological effect of being in contact with nature has been well documented through different studies,[4–10] showing that workplaces that include environmental features such as natural lighting, natural ventilation and/or plants result in improved worker performance, lower stress and greater motivation.[3] However, there is a lack of evidence on how indoor greenery affects the Indoor Environmental Quality (IEQ) positively and/or negatively, particularly regarding Indoor Air Quality (IAQ).[10] Consequently, the motivation of this dissertation is to analyse and evaluate the positive and/or negative effects of plant-based systems in the built environment in terms of IAQ.

Most people spend more than 80% of their time indoors; therefore, the risks of having health problems may be greater due to indoor air pollution than to outdoor air pollution.[11,12] Several studies have demonstrated the potential of botanical biofiltration and phytoremediation to remove indoor pollutants and improve overall comfort.[13–24] Therefore, common indoor plants may provide a valuable strategy to avoid rising levels of indoor air pollution. However, there is still a lack of solid and relevant data available to understand the true pollutant-removal mechanisms and factors in these systems, their cooling effect within indoor environments, and the effect of these systems within the energy performance of the building. Although the plant's ability to remove pollutants from the air is well documented in laboratory studies,[15,19] the effect of plants on indoor air in complex environments requires further investigations to clarify the full capacity of plants in real-life settings.

Since plants have been shown to uptake gaseous pollutants via their stomata during normal gas exchange, it is recommended to use plant species with high stomatal conductance and lower sensitivities to the pollutants.[25–29] Besides, some bacteria growing on plant leaves could also contribute to the bio-degradation of Volatile

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Organic Compounds (VOCs).[30] In addition to the stomata, the root zone, including its microbial environment has been shown to be an important contributor to the removal of gaseous pollutants.[18,21,24,26,31,32] Therefore, to assess the role of vegetation as a sink of gaseous pollutants it is important to evaluate different plants and the efficacy by which their leaves and root zone absorb these pollutants.

It is important to establish the process for a botanical biofiltration to develop a proper climate design and prototype. A botanical biofiltration process involves five main mechanisms:

1. rhizosphere bio-degradation (by microorganisms),
2. phytoextraction (plant-liquid extraction),
3. stomatal uptake (plant-gas extraction),
4. phytodegradation (via enzymatic catalysis inside tissues),
5. phytovolatilisation (directly by evaporation from leaves or indirectly by plant transpiration).[27]

At the end, the performance of these processes depends on the interactions among pollutants–plants–microorganisms.[19] Careful selection of the species of plants and of the operating parameters, and a combination with other technologies could improve botanical biofiltration and thermal performance.[13,14] This system could have significant effects on the amount of energy used by the standard air condition systems, in the sense that recirculating the air through the system will omit the process of warming/cooling outdoor air because the indoor air will already be at the desired temperature and humidity level.[33]

On the other hand, using plants as design elements in indoor environments brings nature inside and provides many positive outcomes in the overall Indoor Environmental Quality (IEQ). The use of plants indoors creates warm and inviting spaces that reduce stress and increase the overall well-being, resulting in healthier working and living areas that decrease absenteeism and that increase overall satisfaction and happiness in people's lives and hence provides a natural way of helping combat Sick Building Syndrome (SBS).[6–9,34] They can be used as thermal and humidity control systems due to the evapotranspiration of the plants, the selected growth medium or substrates.[35–38] Furthermore, plants can be used as biomonitors, since plants can indicate directly whether the ambient concentration of a pollutant is harmful.[39]

The aim of the research is to develop an active plant-based system that could have the potential to improve the indoor environment. The research on using green walls as climate control systems is relatively new; therefore, there are many uncertainties

and gaps to fill. For these reasons, it is proposed to conduct more studies into the possibilities of plant-based systems as potential eco-friendly design tool to achieve overall comfort. In order to assess the plant-based system, specific tests and experiments will be conducted and analysed to further design a prototype. Besides, this research project was conducted as a multidisciplinary research where many fields, such as building technology, biology, mechanical engineering and chemistry, were integrated to develop a solid product.

1.2 Aim of the study

The aim of this research project is to explore and evaluate the efficacy of an active plant-based system in terms of indoor air quality (IAQ).

1.3 Research Questions

This dissertation aims to answer the following main research question, that is going to be the main driver of this research project:

— **Can an active plant-based system improve the Indoor Air Quality (IAQ)?**

To be able to answer the main research question, several key (sub)research questions were explored and further elaborated in different chapters of this dissertation.

PART 1: A theoretical framework and State of the art analysis (Chapter 2).

— What is the available knowledge regarding indoor greenery in the built environment? (Chapter 2)

PART 2: Evaluating different methods for assessing perceived IAQ; this section includes laboratory and chamber experiments (Chapters 3 and 4).

- How to properly assess plant-based systems in the indoor environment in terms of perceived IAQ? (Chapter 3)
- Which (plant-based) systems or combinations are suited as a solution for improving IAQ? (Chapter 4)

PART 3: Integration of the design principles in a final prototype and its evaluation (Chapter 5)

- Does an active plant-based system prototype have the potential to improve IAQ in a semi-lab environment? (Chapter 5)

1.4 Methodology

PART 1: Theoretical Framework and State of the Art

To establish the best methodology to develop scientific research it is important to analyse and establish some principles, concepts and/or theories. Figure 1.1 illustrates the general scheme of the methodological structure used during this research project. First of all, an extensive literature review was developed, including scientific articles and book sections from the last 30 years. This state-of-the-art analysis is going to help to evaluate and validate facts and information in further steps.

Publications:

Armijos Moya T, van den Dobbelsteen A, Ottelé M, Bluyssen PM. A review of green systems within the indoor environment. *Indoor Built Environ.* 2019;28(3):298-309.

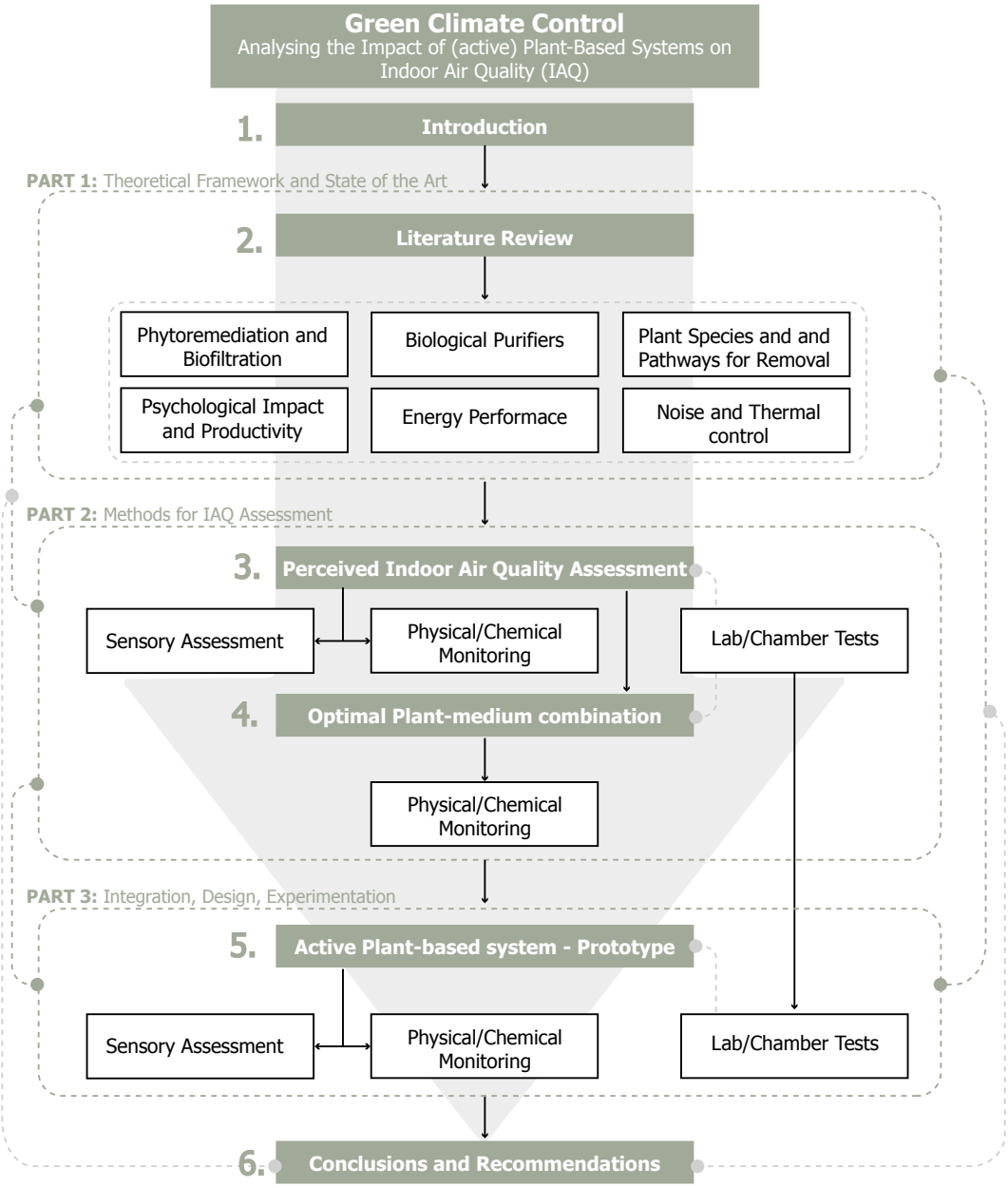

FIG. 1.1 Methodology scheme.

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PART 2: Methods for IAQ assessment

In this part different methods for assessing IAQ were performed and tested, such as chemical measurements and sensory evaluations. Specific protocols were developed for each case and the assessments were executed in laboratory chambers specifically designed for this purpose. Figure 1.2 presents the experimental process followed to assess the selected methods.

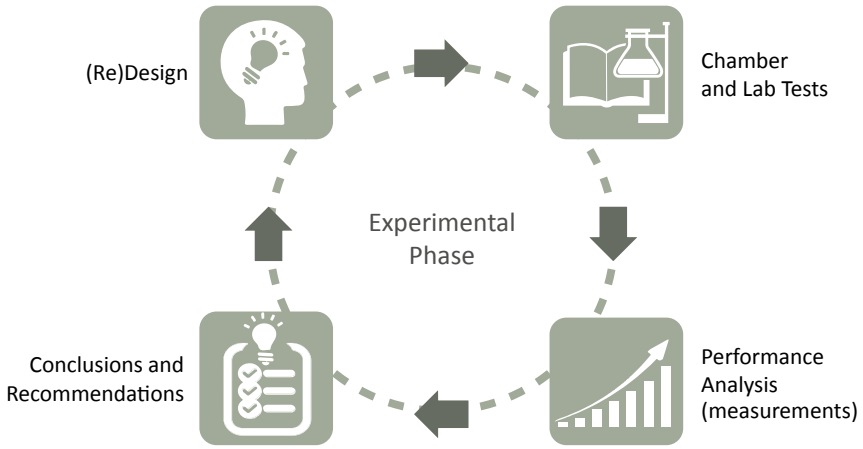

FIG. 1.2 Experimental process diagram.

In this part, the aim was to test the efficacy of plant-based systems in terms of IAQ. There are different methods available to assess IAQ, such as chemical monitoring, physical monitoring and sensory assessment. Most guidelines and regulations regarding the effect of gaseous pollutants in the indoor environment are focused on the evaluation and analysis of indoor concentrations of air pollutants regarding its toxicities.[40,41] Additionally, guidelines are available for assessing the odour intensity of volatile organic compounds emitted by different indoor materials.[42,43] Therefore, experimental setups were created to test both the chemical and the sensory effect on IAQ of a plant-based system.

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Publications:

Armijos Moya T and Bluyssen PM. Appraisal and identification of different sources of smell by primary school children in the air quality test chamber of the SenseLab. *Intelligent Buildings International* 2019, 13:2, 142–155.

Armijos Moya T, Zhang D, Bluyssen PM. Perceived Air Quality of different sources of smell evaluated by primary school children. *E3S Web of Conferences*,2019, 111,[06043].https://doi.org/10.1051/e3sconf/201911106043

Armijos Moya T, van den Dobbelsteen A, Ottelé M, Bluyssen PM. Botanical Biofiltration: Experimental Protocol and Method. Abstract from Indoor Air 2018: *15th Conference of the International Society for Indoor Air Quality and Climate (ISIAQ)*, Philadelphia, United States. 2018

Armijos Moya T, de Visser P, van den Dobbelsteen A, Ottelé M, Bluyssen PM. Air cleaning performance of two species of potted plants and different substrates. *(Under review).* 2021, doi: 10.21203/rs.3.rs-314387/v1

PART 3: Experimentation, design and integration

In this final part an active plant-based system prototype was developed and evaluated considering the outcomes of the previous experiments. The prototype is described in detailed including its components and the factors that were analysed. For this evaluation the prototype was placed in a semi-controlled environment and different methods were used to assess its impact on the perceived IAQ, including sensory assessments and physical/chemical evaluations. Subsequently, the conclusions and recommendations for future research regarding the impact of these systems in the indoor environment are presented.

Publications:

Armijos Moya T, Ottelé M, van den Dobbelsteen A, Bluyssen PM. The Effect of an Active Plant-Based System on Perceived Air Pollution. *Int. J. Environ. Res. Public Health* 2021,18, 8233. https:// doi.org/10.3390/ijerph18158233

1.5 Research impact and contribution

This research project aims to expand the current knowledge regarding the effect of greenery in the indoor built environment, focusing on the impact of plant-based systems on IAQ. The evaluation of the state of the art of green systems within the indoor environment is considered as a significant contribution to the field as a guide to identify research gaps guiding future research related with the effect of using plants in the indoor built environment. Moreover, the methodology proposed is regarded as an important contribution to understanding how the real effect of indoor greenery in the built environment can be assessed in terms of IAQ, evaluating different ways of assessing the impact of plants on IAQ, considering not only physical measurements as a means of evaluation but also including sensory evaluations that have not been considered yet as an assessment in this field. Finally, this research project not only references and analyses previous studies, but aims to complement this data with new information to fill scientific gaps and to define future steps for a better integration of plant-based systems in the built environment.

1.6 Outline of the dissertation

This dissertation is divided into three sections consisting of six chapters, which are going to be described below:

- **Chapter 1**, “Introduction”, presents the overall goals of the research. It provides a statement of the problem, and the approach of this work.

- **Chapter 2**, “Literature Review: A review of green systems within the indoor environment”, presents a general overview and state-of-the-art findings regarding passive and active vegetation systems and their effect on the indoor environment, drawn from studies from the past 30 years, from different scientific fields, such as biology, chemistry, engineering, and architecture. The review aims to identify the potentials, challenges and knowledge gaps and to define current paths and trends for further exploration. The general goal behind this review is to support the design of an (active) plant-based system to evaluate its impact on the indoor environmental quality (IEQ) through examination of past experiences and challenges.

- **Chapter 3**, “Assessment of Perceived Indoor Air Quality: Appraisal and identification of different sources of smell by primary school children in the air quality test chamber of the SenseLab”, addresses different assessments of perceived indoor air quality (IAQ), including physical measures and sensory evaluation.

- **Chapter 4**, “Optimal plant-medium combination: Air cleaning performance of two species of potted plant and different substrates”, describes an experimental study regarding the removal of volatile organic compounds (VOCs) by common indoor plant species and growth media, using formaldehyde as a reference. These experimental results provide insight into the selection of growth media and plant species to be used in the plant-based system prototype.

- **Chapter 5**, “Active Plant-based System: The effect of an active plant-based system on perceived air pollution”, describes the system in detail, together with its design parameters and system components. Furthermore, it describes the effect of the system on the perceived IAQ.

- **In Chapter 6**, “Conclusions and Recommendations” explains the impact of this research within a larger context and specific needs for further investigation. A reflection is included regarding the future of plant-based systems in the built environment.

References

1 Kellert S, Heerwagen J and M M. *Biophilic Design: The Theory, Science and Practice of Bringing Buildings to Life*. New Jersey: John Wiley & Sons, 2011.

2 Wilson E. *Biophilia*. Cambridge, MA: Harvard University Press, 1984.

3 Kellert S. *Building for Life: Understanding and Designing the Human-Nature Connection*. Washington DC: Island Press. Washington. Covelo. London, 2005.

4 Mangone G and van der Linden K. Forest microclimates: Investigating the performance potential of vegetation at the building space scale. *Build Environ* 2014; 73: 12-23.

5 Qin J, Sun CJ, Zhou X, et al. The effect of indoor plants on human comfort. *Indoor Built Environ* 2014; 23: 709-723.

6 Relf PD. Psychological and Sociological Response to Plants - Implications for Horticulture. *Hortscience* 1990; 25: 11-13.

7 Shoemaker CA, Randall K, Relf PD, et al. Relationships between Plants, Behavior, and Attitudes in an Office Environment. *HortTechnology* 1992: 205-206.

8 Lohr VI, Pearson-Mims CH and Goodwin GK. Interior plants may improve worker productivity and reduce stress in a windowless environment. *Journal of Environmental Horticulture* 1996; 14: 97-100.

9 Gray T and Birrell C. Are Biophilic-Designed Site Office Buildings Linked to Health Benefits and High Performing Occupants? *Int J Env Res Pub He* 2014; 11: 12204-12222.

10 Armijos Moya T, van den Dobbelsteen A, Ottelé M, Bluyssen PM. A review of green systems within the indoor environment. *Indoor Built Environ*. 2019;28(3):298-309.

11 WHO. Organic pollutants. *Air Quality Guidelines for Europe*. Second Edition ed.: World Health Organization, 2000, pp.58-121.

12 WHO. *WHO guidelines for indoor air quality: selected pollutants*. World Health Organization, 2010.

13 Darlington A, Chan M, Malloch D, et al. The biofiltration of indoor air: Implications for air quality. *Indoor Air-International Journal of Indoor Air Quality and Climate* 2000; 10: 39-46.

14 Darlington AB, Dat JF and Dixon MA. The biofiltration of indoor air: Air flux and temperature influences the removal of toluene, ethylbenzene, and xylene. *Environ Sci Technol* 2001; 35: 240-246.

15 Dela Cruz M, Christensen JH, Thomsen JD, et al. Can ornamental potted plants remove volatile organic compounds from indoor air? - a review. *Environ Sci Pollut R* 2014; 21: 13909-13928.

16 Irga PJ, Pettit TJ and Torpy FR. The phytoremediation of indoor air pollution: a review on the technology development from the potted plant through to functional green wall biofilters. *Rev Environ Sci Bio* 2018; 17: 395-415.

17 Orwell RL, Wood RA, Burchett MD, et al. The potted-plant microcosm substantially reduces indoor air VOC pollution: II. Laboratory study. *Water Air Soil Poll* 2006; 177: 59-80.

18 Orwell RL, Wood RL, Tarran J, et al. Removal of benzene by the indoor plant/substrate microcosm and implications for air quality. *Water Air Soil Poll* 2004; 157: 193-207.

19 Soreanu G, Dixon M and Darlington A. Botanical biofiltration of indoor gaseous pollutants - A mini-review. *Chem Eng J* 2013; 229: 585-594.

20 Torpy F, Clements, N., Pollinger, M., Dengel, A., Mulvihill, I., He, C., & Irga, P. . Testing the single-pass VOC removal efficiency of an active green wall using methyl ethyl ketone (MEK). *Air Quality, Atmosphere & Health* 2017: 1-8.

21 Wolverton BC and Wolverton JD. Plants and soil microorganisms: removal of formaldehyde, xylene, and ammonia from the indoor environment. *Journal of the Mississippi Academy of Sciences* 1993; 38: 11-15.

22 Wolverton BC, Johnson A and Bounds K. Interior Landscape Plants for Indoor Air Pollution Abatement, Final Report NASA (NASA-TM-101766, NAS 1.15:101766). *National Aeronautics and Space Administration* 1989: 1-22. Technical Report.

23 Wood RA, Burchett MD, Alquezar R, et al. The potted-plant microcosm substantially reduces indoor air VOC pollution: I. Office field-study. *Water Air Soil Poll* 2006; 175: 163-180.

24 Wood RA, Orwell RL, Tarran J, et al. Potted-plant/growth media interactions and capacities for removal of volatiles from indoor air. *J Hortic Sci Biotech* 2002; 77: 120-129.

25 Fujii S, Cha H, Kagi N, et al. Effects on air pollutant removal by plant absorption and adsorption. *Build Environ* 2005; 40: 105-112. DOI: 10.1016/j.buildenv.2004.04.015.

26 Omasa KS, H.;Youssefian, S.; Kondo, N. . *Air Pollution and Plant Biotechnology*. Japan: Springer-Verlag Tokyo 2002, 2002.
27 Pilon-Smits E. Phytoremediation. *Annu Rev Plant Biol* 2005; 56: 15-39.
28 Schaffner A, Messner B, Langebartels C, et al. Genes and enzymes for in-planta phytoremediation of air, water and soil. *Acta Biotechnol* 2002; 22: 141-151.
29 Schmitz H, Hilgers U and Weidner M. Assimilation and metabolism of formaldehyde by leaves appear unlikely to be of value for indoor air purification. *New Phytol* 2000; 147: 307-315.
30 Sandhu A, Halverson LJ and Beattie GA. Bacterial degradation of airborne phenol in the phyllosphere. *Environ Microbiol* 2007; 9: 383-392.
31 Kim KJ, Kil MJ, Il Jeong M, et al. Determination of the Efficiency of Formaldehyde Removal According to the Percentage Volume of Pot Plants Occupying a Room. *Korean J Hortic Sci* 2009; 27: 305-311.
32 Yoo MH, Kwon YJ, Son KC, et al. Efficacy of indoor plants for the removal of single and mixed volatile organic pollutants and physiological effects of the volatiles on the plants. *J Am Soc Hortic Sci* 2006; 131: 452-458.
33 Rodgers K, Handy R and Hutzel W. Indoor Air Quality (Iaq) Improvements Using Biofiltration in a Highly Efficient Residential Home. *J Green Build* 2013; 8: 22-27.
34 Fjeld T, Veiersted B, Sandvik L, et al. The effect of indoor foliage plants on health and discomfort symptoms among office workers. *Indoor Built Environ* 1998; 7: 204-209.
35 Davis MJM, Ramirez F and Perez ME. More than just a Green Facade: vertical gardens as active air conditioning units. *Procedia Engineer* 2016; 145: 1250-1257.
36 Armijos Moya T, van den Dobbelsteen A, Ottelé M, Bluyssen PM. Green air conditioning: Using indoor living wall systems as a climate control method. *Rehva Journal* 2017: 3, 27-31.
37 Armijos Moya T, van den Dobbelsteen A, Ottelé M, Bluyssen PM. Using indoor living wall systems as a climate control method in hot humid climates. In *Proceedings of the international scientific conference Healthy Buildings 2017 Europe*, Lublin, Poland, 2017. *[0066]*.
38 Davis MM and Hirmer S. The potential for vertical gardens as evaporative coolers: An adaptation of the 'Penman Monteith Equation'. *Build Environ* 2015; 92: 135-141.
39 Van der Wat L and Forbes PBC. Lichens as biomonitors for organic air pollutants. *Trac-Trend Anal Chem* 2015; 64: 165-172.
40 Bluyssen PM. *All you need to know about indoor air – A simple guide for educating yourself to improve your indoor environment*. Delft, The Netherlands: Delft Academic Press, 2015.
41 Kotzias D. Indoor air and human exposure assessment - needs and approaches. *Exp Toxicol Pathol* 2005; 57: 5-7.
42 Bluyssen PM. *The Indoor Environment Handbook: How to make buildings healthy and comfor*table. London, UK: Taylor&Francis, 2009.
43 Nicell JA. Assessment and regulation of odour impacts. *Atmos Environ* 2009; 43: 196-206.

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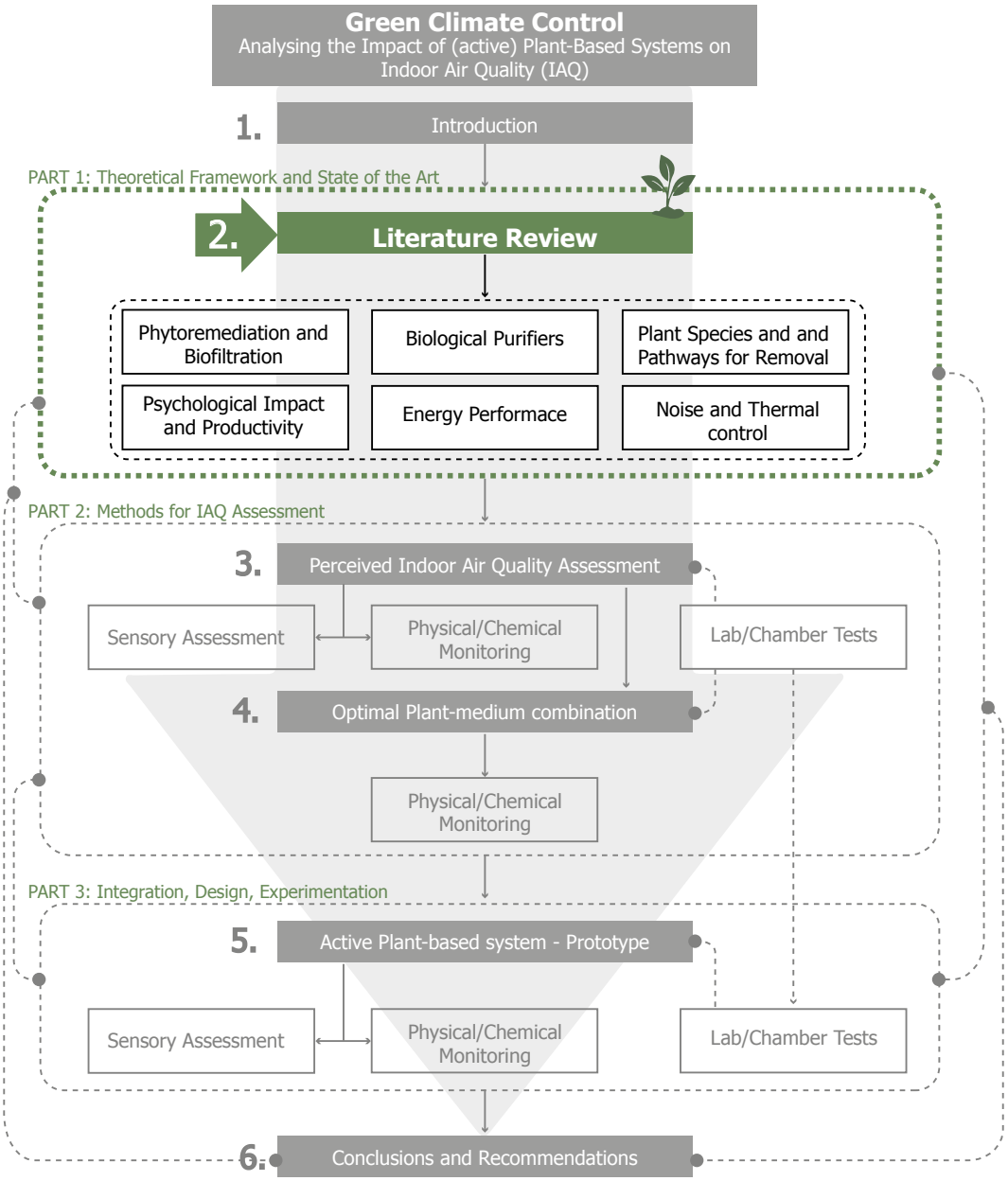
Green Climate Control
Analysing the Impact of (active) Plant-Based Systems on Indoor Air Quality (IAQ)
1.
Introduction
PART 1: Theoretical Framework and State of the Art
2.
Literature Review
Phytoremediation and Biofiltration
Biological Purifiers
Plant Species and and Pathways for Removal
Psychological Impact and Productivity
Energy Performace
Noise and Thermal control
PART 2: Methods for IAQ Assessment
3.
Perceived Indoor Air Quality Assessment
Sensory Assessment
Physical/Chemical Monitoring
Lab/Chamber Tests
4.
Optimal Plant-medium combination
Physical/Chemical Monitoring
PART 3: Integration, Design, Experimentation
5.
Active Plant-based system - Prototype
Sensory Assessment
Physical/Chemical Monitoring
Lab/Chamber Tests
6.
Conclusions and Recommendations

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2 Literature Review

A review of green systems within the indoor environment

Published in: Indoor and Built Environment
This chapter is based upon the following article: Armijos Moya T, van den Dobbelsteen A, Ottelé M, Bluyssen PM. A review of green systems within the indoor environment. *Indoor Built Environ.* 2019;28(3):298-309.

ABSTRACT The chapter reviews the state of art of vegetation systems and their effect on the indoor environmental quality (IEQ), based on scientific studies from the past 30 years. Some studies have shown that biophilic workspaces and interaction with plants may change human attitudes, behaviours, improve productivity and the overall well-being. Evapotranspiration from plants helps lowering the temperature around the planting environment and this can be utilised for air cooling and humidity control. Also, indoor greenery can be used to reduce sound levels as a passive acoustic insulation system. Living wall systems in combination with biofiltration are emerging technologies to provide beneficial effects on improvement of indoor comfort. Several studies have indicated that green systems may improve indoor air quality and that they have different pathways for pollutant removal of volatile organic compounds. The plant root zone in potted plants may be an effective area for removing volatile organic compounds under controlled conditions. In conclusion, the full capacity of plants in real-life settings will need to be clarified to establish the true pollutant-removal mechanisms and the general effect on IEQ. The effects of green systems in combination with mechanical elements such as conventional heating, ventilation and air conditioning would need to be studied.

KEYWORDS Biofiltration, Indoor air quality, Living wall systems, Plants, Indoor environmental quality, Phytoremediation

2.1 Introduction

People spend on average 80% of their time indoors,[1,2] therefore, the health risks due to indoor air pollution may be greater than outdoor air pollution.[3,4] From past studies, it is clear that indoor environmental quality (IEQ) can play an important role in work performance, productivity and the health of building users.[5–10] Using plants as design elements in working environments brings nature inside to create inviting spaces that may reduce stress and may increase the overall well-being, resulting in healthier work and living areas. Interaction with plants can change human attitudes, behaviours and physiological responses. Furthermore, it may decrease absenteeism, increase productivity and overall satisfaction and happiness in people's lives.[11–14] Even though some studies with potted plants and vegetation systems, such as bio- walls, have shown potential for absorbing potentially

harmful pollutants and improve the overall comfort,[2,15–42] there is still a lack of solid and relevant data available to understand the true pollutant-removal mechanisms and factors in these systems. At present, the use of indoor greenery offers several benefits such as producing oxygen through photosynthesis, generating humidity and providing an aesthetical pleasant environment to work and live as well as visual performance to indoor environment.[8,11,43,44] In active vegetation systems (vegetation systems combined with mechanical systems), air-cleaning rates have proven to be significantly higher than in passive vegetation systems because of the use of active fan-assisted hydroponics technology that draws the air through the root rhizomes of the plants.

This review includes a panorama of vegetation systems, active and passive and their effect on the indoor environment, drawn from studies from past 30 years. Literature from different scientific fields, such as biology, chemistry, engineering and architecture, has been consulted in order to identify the potentials, challenges and knowledge gaps and define current paths and trends for further exploration. The general goal behind this research is to support the design of an Active Building-Integrated Vegetation System to improve IEQ through examination of past experiences.

2.2 Materials and methods

Research experiences from peer-reviewed journal articles were considered as base material for this review. In order to collect relevant articles within the scope of the study, some parameters were defined as input for the search. The constraints served the purpose of limiting the results to the most corresponding articles, and limiting the number to a manageable amount at the same time, which allowed an initial review and categorisation of information. Hence, the search focused on articles published from 1984 onwards considering title, abstract and keywords matching terms as 'biofiltration', 'phytoremediation', 'Indoor Air Quality' and 'Plants and Pollutants'. It was decided to include articles from different back- grounds, including chemistry, engineering and biology, in order to have a complete scope of the topic. Therefore, the search query was performed in online journal article databases related with the topic, such as Indoor and Built Environment, Building and Environment, Environmental Science and Technology, Atmospheric Environment, Chemical Engineering Journal, Horticulture, Environment and Biotechnology. After an initial review of results, filtering outliers and checking references from articles to have a complete overview of the latest papers published, a consolidated database of journal articles was generated. The inquiries were performed during November 2015 and November 2017, resulting in a consolidated database of 104 scientific articles in December 2017, including mostly original research but also reviews from other researchers.

2.3 Results

2.3.1 Indoor air quality (IAQ), phytoremediation and biofiltration

From the review it is clear that air pollution is not confined to outdoor environment in cities, urban areas and industrial sites only. Most office buildings studied were mechanically ventilated, with a minimum required amount of fresh air, often only based on the number of occupants present, ignoring the presence of pollution sources such as printers, building and furnishing materials, and cleaning procedures. Consequently, health professionals, architects, researchers and building industry

undertook actions to improve IAQ through different systems and techniques.[45] In the 1980s, the NASA Clean Air Study presented some studies about the behaviour of plants regarding IAQ. Its results suggested that certain common indoor plants may provide a natural way of removing toxic agents such as benzene, formaldehyde and trichloroethylene from the air.[40,41] The results of these tests suggested that (1) low-light-requiring houseplants with activated carbon filters have potential for improving IAQ and (2) the plant root zone is an effective area for removing volatile organic compounds (VOCs). In fact, a maximum air exposure to plant root–soil (rhizosphere) area was recommended for best filtration, and the use of activated carbon filters was recommended to be part of the houseplant/air-cleaning plan.

Since Wolverton's research, several studies have been conducted regarding the effect of phytoremediation and biofiltration on IAQ. Phytoremediation can be defined as the use of plants to remove pollutants from the air, water and soil. Biofiltration is defined as the process of drawing air in through organic material (such as moss, soil and plants), resulting in the removal of organic gases such as VOCs, and contaminants with a mechanical system involved. Plants have been shown to uptake air pollutants via their stomata during normal gas exchange. Also, plants have frequently been used for cleaning large contaminated areas of soil and water in the outdoor environment, especially with heavy metals, fertilisers, oil spills and solvents.[46] Several studies showed that the performance of botanical biofiltration depends on the interactions between pollutants, plants and microorganisms: the most suit- able plant species seemed to be those with high stomatal conductance and lower sensitivities to the pollutants.[47–52] Additionally, it seemed that careful selection of plants and substrates might improve the phytoremediation process considerably.[53] The techniques used for phytoremediation have been differentiated according to the physical properties of the contaminants (Figure 2.1), the type of plant used and the medium to be remediated. These various techniques can be listed as:[46] (1) Phytoextraction: the use of plants to clean up pollutants via accumulation in harvestable tissues; (2) phyto(rhizo) filtration: the use of plants in hydroponic set-up for filtering polluted water; (3) phytostabilisation: the use of plants to stabilise pollutants in soil by preventing erosion, leaching, or runoff, or by converting pollutants to less bioavailable forms; (4) phytodegradation: the breakdown of pollutants by plant enzymes, usually inside tissues; (5) rhizodegradation: the degradation of pollutants in the rhizosphere due to microbial activity and (6) phytovolatilisation: the release of pollutants by plants in volatile form. In phytoextraction, phyto(rhizo)filtration and phytostabilisation, plants need to be changed. In phytodegradation, rhizodegradation and phytovolatilisation, plants do not need to be harvested. These techniques treat contaminants through their metabolic process or by microorganisms in the rhizosphere, which is the region of soil that is directly influenced by interactions between plant roots, soil constituents and microorganisms.[54]

With regard to carbon dioxide (CO_2) levels and perceived IAQ, some findings have shown a positive effect of indoor greenery in reducing CO_2 levels.[55] CO_2 concentrations change based on human activity in indoor living spaces.[55] In fact, research has shown that in non-industrial indoor environments such as offices, schools and homes, the major source of CO_2 is human metabolism.[56] Nevertheless, CO_2 has not been considered to be a pollutant but rather an indicator of the presence of pollutants that are related to the presence of people indoors.[56] Plants use energy caught in leaf pigments during the photosynthetic process, for the conversion of CO_2 and water to cellulose, while producing oxygen.[47] Some aquatic plants have shown to release oxygen through their roots, stimulating the growth of rhizosphere microorganisms improving the botanical biofiltration process.[46,47]

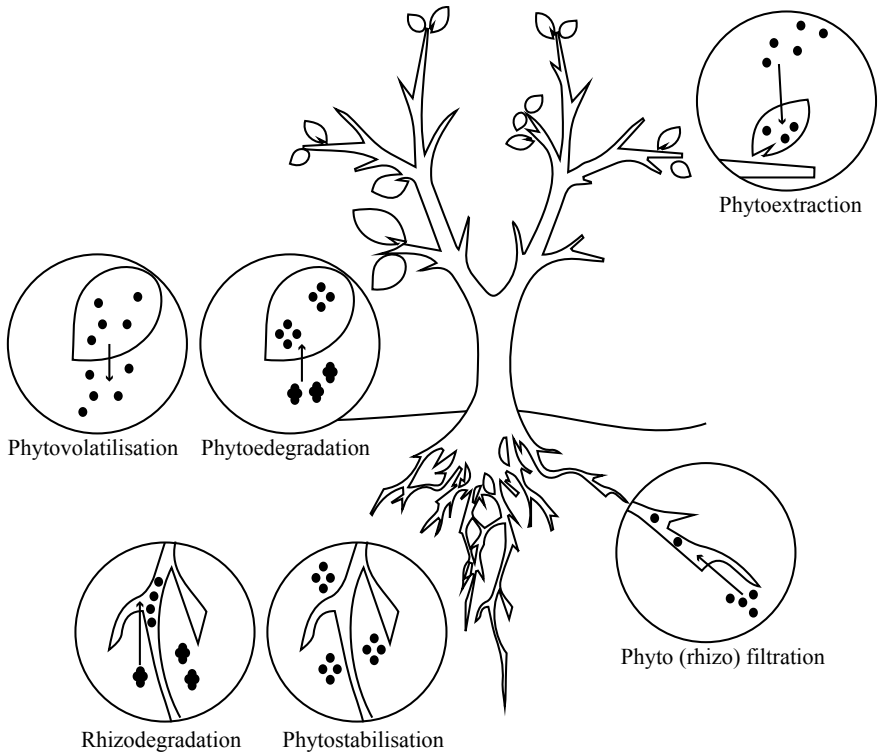

FIG. 2.1 Phytoremediation techniques.

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2.3.2 Health symptoms, psychological impact and productivity

In a recent study named OFFICAIR, performed in 167 office buildings in eight European countries, the most prevailing building-related health symptoms of the 7441 office workers included in the survey were dry eyes (31%), headache (29%) and dry irritated throat (20%).[5] Although the prevalence of most of these symptoms was most likely multifactorial (individual, occupational and environmental risk factors were involved), several indoor air pollution sources were pointed out as important risk factors, in particular for dry eyes complaints, showing the potential for green systems.[57]

In 1996, Lohr et al.[12] performed a study on productivity in a working environment and concluded that interior plants may improve worker productivity and reduce stress in a windowless environment. The outcome suggested that the reaction time of workers in the presence of plants was 12% faster than in the absence of plants, indicating that plants contributed to an increased productivity. Lohr et al.[12] also reported that the presence of foliage plants in interior spaces change particulate matter (PM) accumulation: accumulation was lower in both rooms where plants were pre- sent than where plants were absent.[12] Other studies showed that vegetation with rough surfaces and fine hairs or raised veins seem more effective in intercepting PM than smooth vegetation, and plant roots may absorb some pollutants and render them harmless in the soil.[22,45] While some researchers found that vegetation may improve worker productivity and creativity[4,12,58] other researchers found that vegetation may improve occupant comfort and their overall perception of the quality of their environment creating a more desirable place to work.[13,59,60] Some benefits perceived by workers using vegetation within the working environment that have been put forward are enhanced collaboration amongst staff, including across teams, improved morale, reduced stress and decreased absenteeism.[11,14]

Additionally, Mangone and van der Linden[61] stated that the use of vegetation can have both a positive psychological and economic impact within office environments, because improving worker performance is more effective than improving energy performance.

2.3.3 Plant species and pathways for removal of VOCs

According to Dela Cruz et al.,[62] the pathways for removal of VOCs by plants can be divided into the following (Figure 2.2):

1. Removal by the above-ground plant zone,
2. removal by the microorganisms living in the soil,
3. removal by the roots and
4. removal by the growing media (substrate).

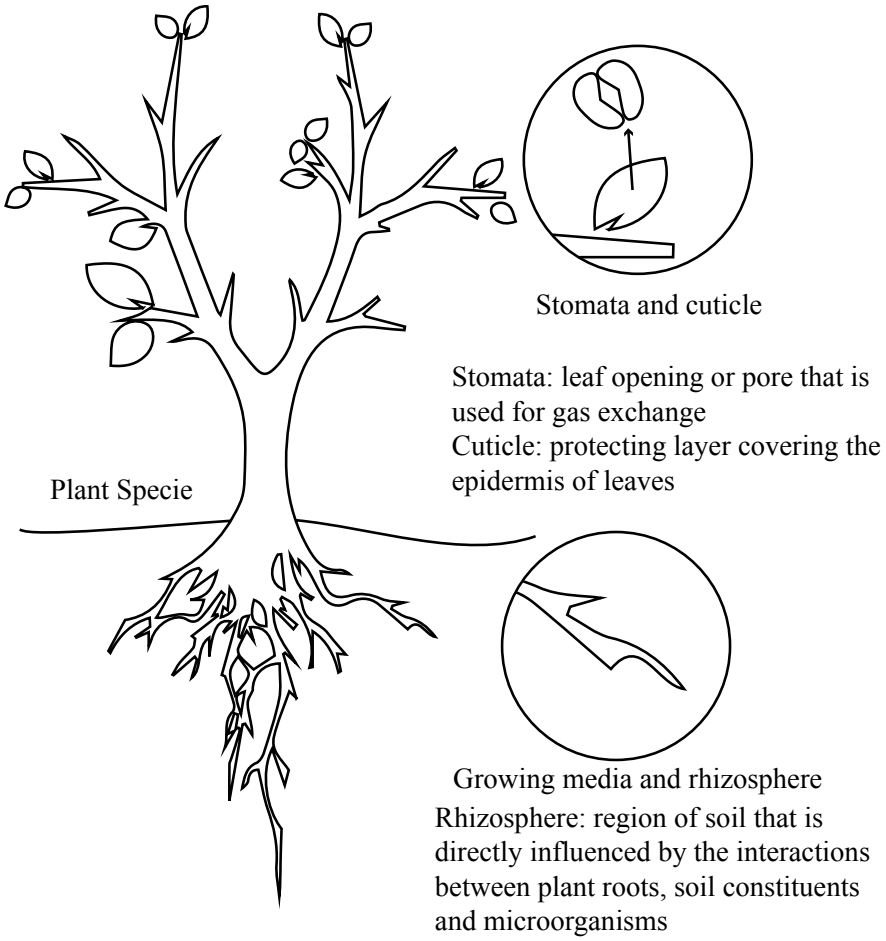

FIG. 2.2 Pathways for removal of VOCs by potted plants.

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Plants have been observed to take in air pollutants via their stomata during normal gas exchange. Therefore, to use plants for the remediation of atmospheric pollutants, it was concluded in several studies that the most suitable plant species will be those with high stomatal conductance and lower sensitivities to the pollutants.[49–51,63] Additionally, it was found that some bacteria growing on plant leaves also contribute to VOC biodegradation.[48] Wetzel and Doucette[16] stated that the waxy cuticle coating on leaves may provide a simple, cost-effective means to sample indoor air for VOCs and to help improve IAQ. Certain plants such as lichens were found to be excellent biomonitors to establish the type of pollutants present in the area.[64] Next to the stomata, the root zone has been shown to be an important contributor to the removal of VOCs.[22] In addition to the photosynthesis-induced gas exchange through the leaves, the root microbial matrix was found to be an important element in assisting the removal of indoor air pollutants. In some studies, rhizosphere microorganisms, found in the growing media, were identified as significant direct agents of VOCs removal, which also has implications for biofiltration.[2,39,63,65–68]

Therefore, in order to assess the role of vegetation as a sink of air pollutants it is important to evaluate a wide range of species, the efficacy by which the leaves absorb these pollutants and the extent to which the leaves are adversely affected by the exposure. Gas diffusion models can be used to analyse the exchange of water vapour, CO_2 and other pollutants between the atmosphere and the plant leaves.[63]

According to Soreanu et al.,[47] about 120 individual plants species have been analysed by different researchers in several pot-based studies for VOC removal and the following was concluded: (1) the common tropical house plants Janet Craig and Peace Lily were the most studied but not the best performing potted plants[69,70] and (2) the best performing plants seem to be Purple waffle, Purple heart, English Ivy, Asparagus fern, Variegated wax[69] and Crassula portulacea.[62] Upadhyay and Kobayashi[45] pointed out that plants with a large leaf surface area are more suitable for removing pollutants. Clausen et al.[71] recommended to use a large leaf surface area in combination with an appropriate ventilation rate to obtain an appropriate performance with potted plants. It has also been stated that rhizosphere degradation (rhizoremediation) could play a major role in VOC removal by botanical biofiltration.[30] Some studies have shown that most plants have limited pollutant removal capacity in the absence of rhizosphere microorganisms.[72] Guieysse et al.[29] found that the diversity of microbial species in the rhizosphere microcosm appeared to be a key parameter in the reduction of VOCs. Most of the houseplants described are commonly found in tropical and subtropical forests, where they received light filtered through the branches of taller trees. Hence, their leaf performed photosynthesis efficiently under relatively low light conditions.

It is also important to consider that air pollution has both direct and indirect impacts on the life of the plant. Some plants are very sensitive to air pollution. The early recognition of pollutant damage to plants, notably characteristic visible foliar symptoms, acts as an alarm for toxic dangers to humans and their environment.[45] Many air pollutants reduce plant growth, partly through their negative effects on photosynthesis. For instance, pollutants such as sulphur dioxide (SO_2) and ozone (O_3), which enter the leaf through stomata, directly damaged the photosynthetic cells of the leaf.[73] Both the stomata and cuticle (Figure 2.2) have been suggested to be pathways for VOC removal by the aboveground plant parts: studies conducted on only the above-ground plant parts showed higher removal of formaldehyde, benzene and toluene in light than in darkness. It was therefore concluded that these com- pounds were taken up through the stomata, as stomata open in light and close in darkness.[28,67,74,75] The pathway for VOC uptake by the above-ground plant parts seems likely to dependent on the properties of VOCs. A hydrophilic VOC such as formaldehyde has been found to diffuse easily through the cuticle that consists of lipids, whereas a lipophilic VOC such as benzene was found to more likely penetrate through the cuticle. The relative importance of the stomatal uptake, compared to the cuticular uptake, seemed therefore to be dependent on the VOC in question.[76,77]

After entering the leaf, a compound can suffer degradation, storage or excretion, either at site of uptake or after translocation to other parts of the plant. Degradation to harmless constituents is the optimal goal, but storage or excretion will be necessary if degradation cannot occur. Storage by the plant will remove VOCs from the air, but excessive storage may lead to damaging effects on the plant due to pollutants building up to lethal concentrations. If the VOC is excreted after uptake, the effect on the indoor VOC concentration is limited. However, the pollutant may be excreted by the roots and subsequently degraded by microorganisms in the soil or adsorbed to the soil particles.[62]

Microorganisms existing in the soil of potted plants have appeared to be essential in removal of VOCs from indoor air.[2,40,68,78] It has been shown that roots can absorb pollutants by themselves,[79] but can also increase the availability of pollutants for the microorganisms.[80] Increased bioavailability has been achieved through the excretion of root exudates.[80–82] Uptake by roots has been found to depend on the root morphology where the lipid content and specific surface area are significant parameters.[83] Once absorbed by the root, the pollutant could therefore undergo the same processes as in the leaf (e.g., degradation, storage or excretion). Consequently, the uptake around the above-ground area affects the root region, both through the lack of root exudation and through the lack of a driving force for the transpiration stream.[62] On the other hand, it has been shown that the growth

medium represents an essential component for cleaning the air; but it may require a regular replacement of the filtration medium to remain effective, and to prevent the re-emission of absorbed gases.[40,84] Some studies have shown that activated carbon is the most effective microbial biofilter.[84,85]

2.3.4 Vegetation system and biological purifiers

Common biological processes for VOC reduction include bioscrubbers, biotrickling filters and biofilters.[86–88] In bioscrubbers, the air is cleaned with an aqueous phase into which the pollutants transfer, and the aqueous phase is transferred into a bioreactor where the pollutants are biodegraded. In biotrickling filters, microorganisms are grown on an inert material (plastics resins, ceramics, etc.). In biofilters, air is passed through a moist porous material which supports microbial growth. Water remains within the packing material and is added intermittently to maintain humidity and microbial viability. The growth media is generally a natural material, which is biodegradable and provides nutrients to the microorganisms, although intensive research has been done on using synthetic materials.[29,89] There are different green systems and strategies that can be used within the indoor environment, such as living wall systems (LWSs) that are vertical hydroponical systems pictured as ecological cores that can be also used as a biofilter (biowall).[37] An LWS supports vegetation that is either rooted on the walls or in substrate attached to the wall itself, rather than being rooted at the base of the wall.[43] Moreover, it is possible to use the evapotranspiration of plants for air cooling and humidity control.[90] LWSs can work as biofilters when they work as an active vegetation system. In an active vegetation system air-cleaning rates may be significantly higher than in passive vegetation systems using active fan-assisted hydroponics technology, which draws the air through the root rhizomes of the plants.

On the other hand, building-integrated vegetation systems combining phytoremediation technology with conventional heating, ventilation and air conditioning (HVAC) systems helped increase the air-cleaning capacity and have been shown to decrease energy consumption of buildings, for example for the biowall.[91] Air passing through the plant wall is cleaned and recirculated within the area instead of introducing outdoor air to replace stale indoor air. Moreover, the air does not have to be conditioned (heated or cooled). Therefore, there is a potential to save energy. As air moves through the wall, impurities are removed and clean air is distributed throughout the building via the HVAC system.[91]

In the mini-review by Soreanu et al.[47] who pointed out that many industrial biofilters pass contaminated air through a substrate that has limited life expectancy because of the exhaustion of its organic content, which acts as a supplemental or alternative food source for the beneficial microorganisms. Therefore, the media must be replaced in a regular interval, depending on the selected media it may be once per year. Root systems of plants growing in the rooting material of botanical biofilters constantly release organics into the media partly through exudation of materials from living roots and partly from turnover of the entire root mass. Consequently, the rooting zone of the botanical biofiltration system is a packing material with a constantly rejuvenated organic content.[47] Biological indoor air treatment can potentially release dust, microorganisms and water. These problems can be simultaneously solved; for instance, by using membrane bioreactors which physically disconnect the sorption step (air–water exchange) from the biodegradation step. According to Ergas et al.,[92] membrane bioreactors for VOC removal have only been used at high pollutant concentrations. Furthermore, since biological purifiers have been typically saturated with water and since indoor air treatment requires high flows, indoor biological purification might increase the moisture content in the room or building where it is used. This beneficial effect when indoor air is too dry (moisture contents of 30–70% are generally recommended for comfort) could also cause an excessive growth of fungi with negative impact on IAQ,[93] although these effects are still uncertain.[94,95] Darlington et al.[37,96] described that the use of an indoor biological purifier could significantly increase the concentrations of total suspended spores, although these values were similar to concentrations found in flats containing house plants. However, there are limited data available and the potential release of microorganisms from indoor biological purifiers should be better studied and prevented if necessary.

2.3.5 Energy performance

Some studies have been conducted to analyse the energy performance of some living systems, including potted biowalls and potted plants which have shown some positive outcomes. For instance, in INHome, a Solar Decathlon project developed by Purdue University in 2011, a biowall was integrated as an air filtration system that utilises plants placed in a vertical wall. It was claimed that this biowall saves energy and provides a calming ambiance by bringing nature inside the home. This green vertical system is connected to the HVAC system in the home serving as a natural air purifier.[91] The Biowall concept could become a competitor against the energy recovery system that is more commonly used with HVAC systems. An energy recovery system uses a heat exchanger to transfer energy between the

exhaust air and the supply air intake. This saves energy and reduces the cost to condition outside air by reducing the need for preheating and precooling.[91] Logan et al.[97] created a plant microbial fuel cell, which is based on the following principle: with the aid of sunlight, plants convert CO_2 into organic compounds (photosynthesis).

The plant uses some of the compounds for its own growth, while the remainder is eliminated through the roots. Microorganisms that are naturally found in the ground around the roots of plants break down these organic compounds. This process causes electrons to be released. It is possible to gather these electrons with an electrode and use them to generate electricity.

2.3.6 Noise control and biological purifiers

An LWS can also be used as a passive acoustical insulation system.[98] Some studies show that vegetation can reduce sound levels in three ways. First, sound can be reflected and dispersed by plant elements, such as trunks, branches, twigs and leaves. A second mechanism is absorption by vegetation. This effect can be attributed to mechanical vibrations of plant elements caused by sound waves. Finally, sound levels can be reduced by the destructive interference of sound waves due to the growth media.[99,100] Thus, there are several factors that influence noise reduction in an LWS, such as the depth of the growing medium, the materials used as structural components and the overall coverage.

2.3.7 Thermal control and biological purifiers

The evapotranspiration from plants is said to lower temperatures around the planting environment. It is shown to be possible to use the evapotranspiration of plants for air cooling and humidity control.[90,101,102] In 2011, a study of indoor living systems performed in warm climates tested different substrates, and the following was concluded:[103]

1. In the room the overall humidity level increased.
2. All substrates tested were suitable for plant growth and their behaviour was similar.
3. Geotextile showed the best cooling capacity but higher water consumption; coconut fibre presented degradation problems.
4. Epiweb performance was the poorest.

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These systems have been proven to be very useful and interesting for warm indoor environments due to the cooling effect observed in addition to their biofiltration capacity and the aesthetic component.

Some studies on thermal control have been conducted and it was concluded that air passing behind the substrate is most effective to generate an evaporative cooling effect since the air is protected from radiation and the greenhouse effect. Therefore, it was concluded that the cooling process should take place behind the substrate.[90,104] Previous studies stated that LWSs can be used as thermal and humidity control systems due to evapotranspiration of plants, the selected growth medium or substrates. However, a ventilation system still is additionally required to optimise the optimal performance of the total system.

2.3.8 General summary

The known and unknown effects of using vegetation indoors are summarised in Figure 2.3.

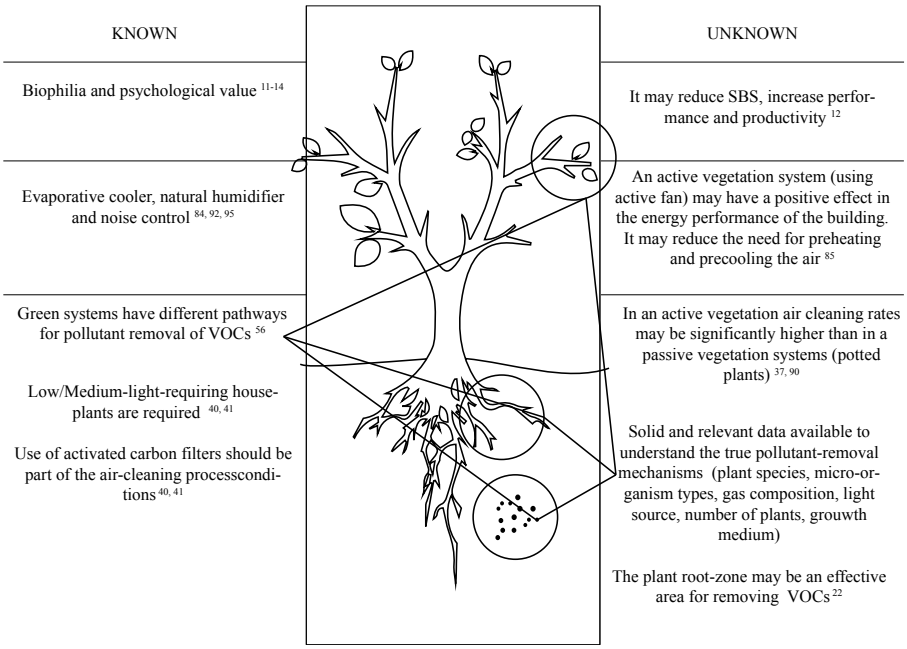

FIG. 2.3 Known and unknown effects of green systems, review.

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2.4 Conclusions and recommendations

This chapter describes the effects of using vegetation indoors and the general conclusions found are the following:

- Biophilic design and vegetation has a positive impact on people within office environments. It increases the overall satisfaction and happiness of people's lives.[4,11–14,58–61] However, there is no solid data that prove that it has a strong impact on the performance, productivity and overall reduction of the Sick Building Syndrome.

- Vegetation has been found to improve occupant comfort, as well as their perception of the quality of their environment, including thermal comfort and acoustics.[59,98,104]

- Several research studies indicate the possible effect of vegetation on IAQ.[40,41,62] However, there is still a lack of solid and relevant data available to understand the true pollutant-removal mechanisms and factors in these systems (plant species, microorganism types, gas composition, light source, number of plants), its cooling effect within indoor environments and the effect of these systems on the energy performance of the building.

- Finally, existing research suggests that in an active vegetation system (green systems in combination with mechanical fans), air-cleaning rates may be significantly higher than in a passive vegetation system (potted plants).[37,96]

  In fact, while the plant's ability to take up pollutants is well documented in laboratory studies, the effect of plants on indoor air in complex environments like offices requires further investigations to clarify the full capacity of plants in real-life settings. Although the role of plants has been speculated and phytoremediation studies have clearly demonstrated improved pollutant removal by rhizodegradation and phytostimulation, a more accurate picture of the involvement of plants in the biological air purifiers needs to be validated.

  This chapter underlines the implications of botanical biofiltration and its implications in the indoor environment. Botanical biofilters in many respects have the appearance of typical interior plantscapes. Greening the indoor space with this sort of botanical elements can improve the occupants' well-being by improving their psychological disposition, which may affect performance and productivity. Because of similar visual content, the integration of botanical biofilters into the built environment could be

expected to have all the psychological impacts of 'greening' the indoor space with green plants. However, for improving IAQ in real life, although predicted from some laboratory studies[2,29,30,32,37,39,40,42,47] still some steps have to be taken (Figure 2.3). The design of biological air purifiers requires the development of new technologies for highly efficient pollutant removal to allow high volumetric treatment flows while preserving high treatment efficiencies. Current biological purifiers have shown some potential but are all limited by their low treatment capacity. This opens interesting possibilities for multi–cross-disciplinary research initiatives.

There are some selection requirements for the type of plants that can be used indoors, such as light settings, climate conditions and growth medium. Therefore, it is recommended to use medium- and low-light plants, and an inorganic growth medium because it is easier to control, regarding nutrients and modularity. Regarding the possible concerns about phytoremediation systems, biofiltration and indoor plants, it is recommended to use non-pollinating plants, regular maintenance and humidity control. The increase of relative air humidity in the rooms with plants is one of the major issues of the phytoremediation process, mainly in summer.[99] Therefore, to avoid mould development and the deterioration of buildings, the RH should be maintained below 70%. Periodical cleaning of leaves is recommended to maintain proper leaf gas exchange. Careful selection of plants and of the operating parameters, and a combination with other technologies could improve botanical biofiltration and thermal performances. It is clear that the process performance depends on the interactions between pollutant, plant and microorganisms, a complex key aspect that is not elucidated yet for indoor air treatment scenarios and is still under evaluation for many other ecosystems. Recommended future studies are therefore (a) to evaluate pollutant-removal mechanisms, (b) to select appropriate plant species and (c) to design active LWSs with the integration of mechanical ventilation. Both lab tests and tests in real office environments, under different thermal and air quality conditions, are required to establish the possibilities of the selected plants, the growth medium and finally the overall system.

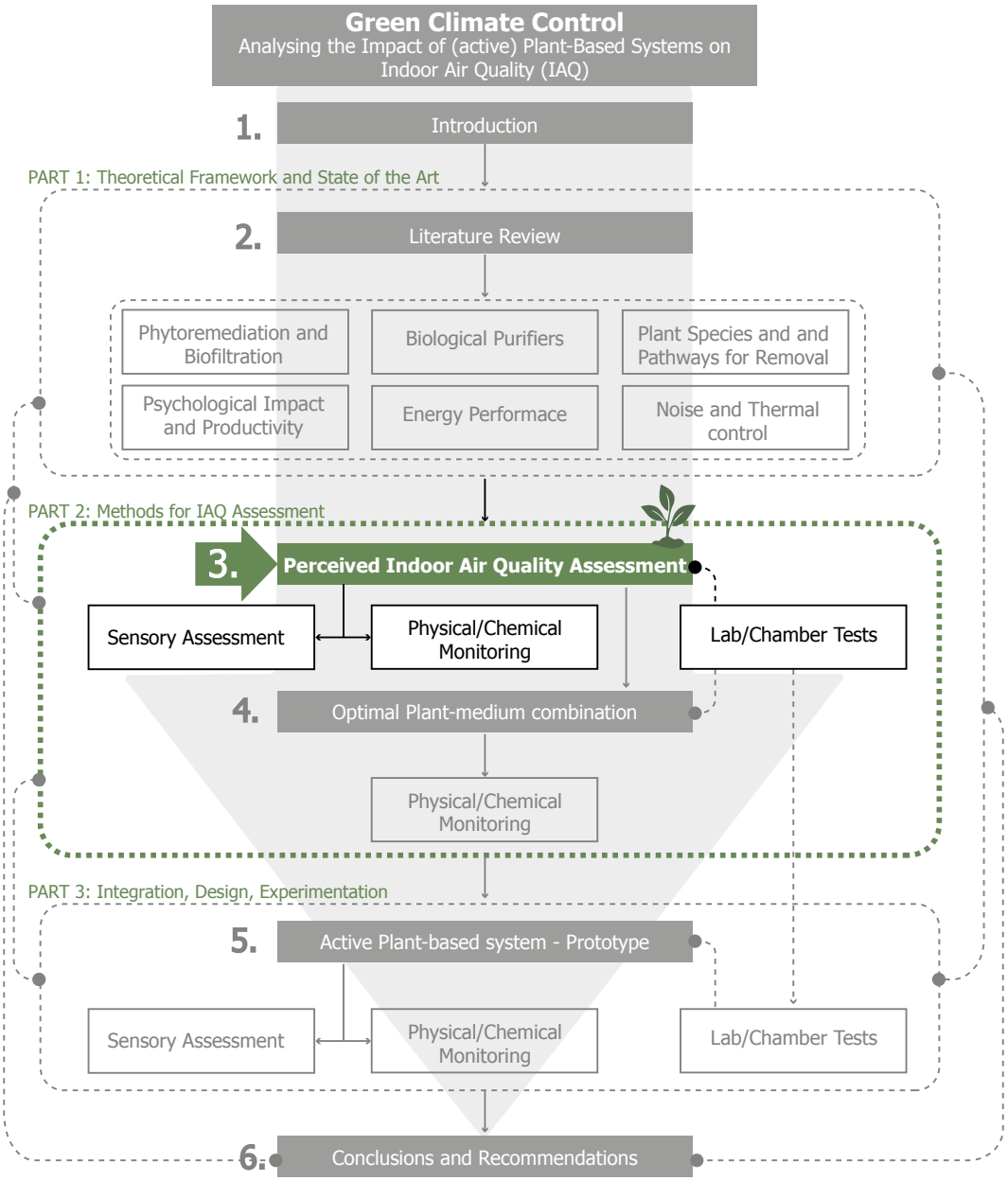
References

1 World Health Organization. WHO guidelines for indoor air quality: selected pollutants. Geneva: WHO,2010.
2 Orwell RL, Wood RL, Tarran J, Torpy F and Burchett MD. Removal of benzene by the indoor plant/substrate microcosm and implications for air quality. Water Air Soil Poll 2004; 157: 193–207.
3 Fjeld T. The effect of interior planting on health and discomfort among workers and school children. HortTechnology2000;10:46–52.
4 Fjeld T, Veiersted B, Sandvik L, Riise G and Levy F. The effect of indoor foliage plants on health and discomfort symptoms among office workers. Indoor Built Environ 1998; 7: 204–209.
5 Bluyssen PM, Roda C, Mandin C, Fossati S, Carrer P, de Kluizenaar Y, Mihucz VG, de Oliveira Fernandes E and Bartzis J. Self-reported health and comfort in 'modern' office buildings: first results from the European OFFICAIR study. Indoor Air 2016; 26: 298–317.
6 Al Horr Y, Arif M, Kaushik A, Mazroei A, Katafygiotou M and Elsarrag E. Occupant productivity and office indoor environment quality: a review of the literature. Build Environ 2016; 105: 369–389.
7 Frontczak M, Schiavon S, Goins J, Arens E, Zhang H and Wargocki P. Quantitative relationships between occupant satisfaction and satisfaction aspects of indoor environmental quality and building design. Indoor Air 2012; 22: 119–131.
8 Raanaas RK, Evensen KH, Rich D, Sjostrom G and Patil C. Benefits of indoor plants on attention capacity in an office setting. J Environ Psychol 2011; 31: 99–105.
9 Wyon DP. The effects of indoor air quality on perfor- mance and productivity. Indoor Air 2004; 14: 92–101.
10 Kosonen R and Tan F. The effect of perceived indoor air quality on productivity loss. Energy Build 2004; 36: 981–986.
11 Gray T and Birrell C. Are biophilic-designed site office buildings linked to health benefits and high performing occupants? IJERPH 2014; 11: 12204–12222.
12 Lohr VI, Pearson-Mims CH and Goodwin GK. Interior plants may improve worker productivity and reduce stress in a windowless environment. J Environ Horticult 1996; 14: 97–100.
13 Shoemaker CA, Randall K, Relf PD and Geller ES. Relationships between plants, behavior, and attitudes in an office environment. HortTechnology 1992; 2: 205–206.
14 Relf PD. Psychological and sociological response to plants – implications for horticulture. HortScience 1990; 25: 11–13.
15 Irga PJ, Paull NJ, Abdo P and Torpy FR. An assessment of the atmospheric particle removal efficiency of an in room botanical biofilter system. Build Environ 2017; 115: 281–290.
16 Wetzel TA and Doucette WJ. Plant leaves as indoor air passive samplers for volatile organic compounds (VOCs). Chemosphere 2015; 122: 32–37.
17 Gawronska H and Bakera B. Phytoremediation of particulate matter from indoor air by Chlorophytum comosum L. plants. Air Qual Atmos Health 2015; 8: 265–272.
18 Wang ZQ, Pei JJ and Zhang JS. Experimental investigation of the formaldehyde removal mechanisms in a dynamic botanical filtration system for indoor air purification. J Hazard Mater 2014; 280: 235–243.
19 Dela Cruz M, Muller R, Svensmark B, Pedersen JS and Christensen JH. Assessment of volatile organic compound removal by indoor plants-a novel experimental setup. Environ Sci Pollut Res 2014; 21: 7838–7846.
20 Kim KJ, Yoo EH and Kays SJ. Decay kinetics of tolu- ene phytoremediation stimulation. HortScience 2012; 47: 1195–1198.
21 Zhou J, Qin F, Su J, Liao J and Xu H. Purification of formaldehyde-polluted air by indoor plants of Araceae, Agavaceae and Liliaceae. J Food Agric Environ 2011; 9: 1012–1018.
22 Xu ZJ, Wang L and Hou HP. Formaldehyde removal by potted plant-soil systems. J Hazard Mater 2011; 192: 314–318.
23 Kim KJ, Yoo EH, Jeong MI, Song JS, Lee SY and Kays SJ. Changes in the phytoremediation potential of indoor plants with exposure to toluene. HortScience 2011; 46: 1646–1649.
24 Xu ZJ, Qin N, Wang JG and Tong H. Formaldehyde biofiltration as affected by spider plant. Bioresour Technol 2010; 101: 6930–6934.
25 Kim KJ, Il Jeong M, Lee DW, Song JS, Kim HD, Yoo EH, Jeong SJ and Han SW. Variation in formaldehyde removal efficiency among indoor plant species. HortScience 2010; 45: 1489–1495.
26 Tani A and Hewitt CN. Uptake of aldehydes and ketones at typical indoor concentrations by houseplants. Environ Sci Technol 2009; 43: 8338–8343.

27 Lim YW, Kim HH, Yang JY, Kim KJ, Lee JY and Shin DC. Improvement of indoor air quality by houseplants in new-built apartment buildings. J Jpn Soc Hort Sci 2009; 78: 456–462.
28 Kim KJ and Kim HD. Development of model and calculating equation for rate of volatile formaldehyde removal of indoor plants. Horticult Environ Biotechnol 2008; 49: 155–161.
29 Guieysse B, Hort C, Platel V, Munoz R, Ondarts M and Revah S. Biological treatment of indoor air for VOC removal: potential and challenges. Biotechnol Adv 2008; 26: 398–410.
30 Wood RA, Burchett MD, Alquezar R, Orwell RL, Tarran J and Torpy F. The potted-plant microcosm substantially reduces indoor air VOC pollution: I. Office field-study. Water Air Soil Pollut 2006; 175: 163–180.
31 Orwell RL, Wood RA, Burchett MD, Tarran J and Torpy F. The potted-plant microcosm substantially reduces indoor air VOC pollution: II. Laboratory study. Water Air Soil Pollut 2006; 177: 59–80.
32 Chen WH, Zhang JSS and Zhang ZB. Performance of air cleaners for removing multiple volatile organic compounds in indoor air. ASHRAE Trans 2005; 111: 1101–1114.
33 Oyabu T, Takenaka K, Wolverton B, Onodera T and Nanto H. Purification characteristics of golden pothos for atmospheric gasoline. Int J Phytoremediat 2003; 5: 267–276.
34 Oyabu T, Sawada A, Onodera T, Takenaka K and Wolverton B. Characteristics of potted plants for removing offensive odors. Sensor Actuat B Chem 2003; 89: 131–136.
35 Oyabu T, Onodera T, Sawada A and Takenaka K. Purification capability of potted plants for removing atmospheric formaldehyde. Electrochemistry 2003; 71: 463–467.
36 Oyabu T, Onodera T, Kimura H and Sadaoka Y. Purification ability of interior plant for removing of indoor-air polluting chemicals using a tin oxide gas sensor. J Jpn Soc Atmos Environ/Taiki Kankyo Gakkaishi 2001; 36: 319–325.
37 Darlington A, Chan M, Malloch D, Pilger C and Dixon MA. The biofiltration of indoor air: implications for air quality. Indoor Air 2000; 10: 39–46.
38 Cornejo JJ, Munoz FG, Ma CY and Stewart AJ. Studies on the decontamination of air by plants. Ecotoxicology 1999; 8: 311–320.
39 Wolverton BC and Wolverton JD. Plants and soil microorganisms: removal of formaldehyde, xylene, and ammonia from the indoor environment. J Miss Acad Sci 1993; 38: 11–15.
40 Wolverton BC, Johnson A and Bounds K. Interior land- scape plants for indoor air pollution abatement. Final report NASA (NASA-TM-101766, NAS 1.15:101766). Mississippi: National Aeronautics and Space Administration, 1989, pp.1–22.
41 Wolverton BC, Mcdonald RC and Watkins EA. Foliage plants for removing indoor air-pollutants from energy-efficient homes. Econ Bot 1984; 38: 224–228.
42 Stapleton E and Ruiz-Rudolph P. The potential for indoor ultrafine particle reduction using vegetation under laboratory conditions. Indoor Built Environ 2018; 27: 70–83.
43 Ottelé M. Green building envelopes in city ecology. Delft: The Green Building Envelope: Vertical Greening, 2011, pp.1–6.
44 Bringslimark T, Hartig T and Patil GG. Psychological benefits of indoor plants in workplaces: putting experimental results into context. HortScience 2007; 42: 581–587.
45 Upadhyay J and Kobayashi N. Phytomonitoring of air pollutants for environmental quality management. Environmental bioremediation technologies. Berlin Heidelberg New York: Springer-Verlag, 2007, pp.275–292.
46 Pilon-Smits E. Phytoremediation. Annu Rev Plant Biol 2005; 56: 15–39.
47 Soreanu G, Dixon M and Darlington A. Botanical bio- filtration of indoor gaseous pollutants – a mini-review. Chem Eng J 2013; 229: 585–594.
48 Sandhu A, Halverson LJ and Beattie GA. Bacterial degradation of airborne phenol in the phyllosphere. Environ Microbiol 2007; 9: 383–392.
49 Fujii S, Cha H, Kagi N, Miyamura H and Kim YS. Effects on air pollutant removal by plant absorption and adsorption. Build Environ 2005; 40: 105–112.
50 Schaffner A, Messner B, Langebartels C and Sandermann H. Genes and enzymes for in-planta phytoremediation of air, water and soil. Acta Biotechnol 2002; 22: 141–151.
51 Schmitz H, Hilgers U and Weidner M. Assimilation and metabolism of formaldehyde by leaves appear unlikely to be of value for indoor air purification. New Phytol 2000; 147: 307–315.
52 Macek T, Mackova M and Kas J. Exploitation of plants for the removal of organics in environmental remediation. Biotechnol Adv 2000; 18: 23–34.
53 Salt DE, Smith RD and Raskin I. Phytoremediation. Annu Rev Plant Physiol Plant Mol Biol 1998; 49: 643–668.

54 Kvesitadze G, Khatisashvili G, Sadunishvili T and Ramsden J. The ecological importance of plants for contaminated environments. Biochemical mechanisms of detoxification in higher plants: basis of phytoremediation. Berlin Heidelberg: Springer-Verlag, 2006, pp.167–207.
55 Cetin M and Sevik H. Measuring the impact of selected plants on indoor CO_2 concentrations. Pol J Environ Stud 2016; 25: 973–979.
56 Zhang X, Wargocki P, Lian Z and Thyregod C. Effects of exposure to carbon dioxide and bioeffluents on perceived air quality, self-assessed acute health symp- toms, and cognitive performance. Indoor Air 2017; 27: 47–64.
57 de Kluizenaar Y, Roda C, Dijkstra NE, Fossati S, Mandin C, Mihucz VG, Hanninen O, de Oliviera Fernandez E, Silva GV, Carrer P, Bartzis J and Bluyssen PM. Office characteristics and dry eye complaints in European workers – the OFFICAIR study. Build Environ 2016; 102: 54–63.
58 Hesselink JK, vBS, Cornelissen E, van Duijn B, van Hooff M and Geuskens G. Onderzoek met planten aan het werk. Hoofddorp: TNO, 2008.
59 Mangone G, Kurvers SR and Luscuere PG. Constructing thermal comfort: investigating the effect of vegetation on indoor thermal comfort through a four season thermal comfort quasi-experiment. Build Environ 2014; 81: 410–426.
60 Qin J, Sun CJ, Zhou X, Leng HB and Lian ZW. The effect of indoor plants on human comfort. Indoor Built Environ 2014; 23: 709–723.
61 Mangone G and van der Linden K. Forest microclimates: investigating the performance potential of vegetation at the building space scale. Build Environ 2014; 73: 12–23.
62 Dela Cruz M, Christensen JH, Thomsen JD and Muller R. Can ornamental potted plants remove volatile organic compounds from indoor air? – a review. Environ Sci Pollut Res 2014; 21: 13909–13928.
63 Omasa K, Saji H, Youssefian S and Kondo N. Air pollution and plant biotechnology. Tokyo: Springer-Verlag, 2002.
64 Van der Wat L and Forbes PBC. Lichens as biomonitors for organic air pollutants. TRAC 2015; 64: 165–172.
65 Chun SC, Yoo MH, Moon YS, Shin MH, Son KC, Chung IM and Kays JK. Effect of bacterial population from rhizosphere of various foliage plants on removal of indoor volatile organic compounds. Kor J Hort Sci Technol 2010; 28: 476–483.
66 Kim KJ, Kil MJ, Il Jeong M, Kim HD, Yoo EH, Jeong SJ, Pak CH and Son KC. Determination of the efficiency of formaldehyde removal according to the percentage volume of pot plants occupying a room. Kor J Hort Sci Technol 2009; 27: 305–311.
67 Yoo MH, Kwon YJ, Son KC and Kays SJ. Efficacy of indoor plants for the removal of single and mixed volatile organic pollutants and physiological effects of the volatiles on the plants. J Am Soc Hortic Sci 2006; 131: 452–458.
68 Wood RA, Orwell RL, Tarran J, Torpy F and Burchett M. Potted-plant/growth media interactions and capacities for removal of volatiles from indoor air. J Hortic Sci Biotechnol 2002; 77: 120–129.
69 Yang DS, Pennisi SV, Son KC and Kays SJ. Screening indoor plants for volatile organic pollutant removal efficiency. HortScience 2009; 44: 1377–1381.
70 Liu YJ, Mu YJ, Zhu YG, Ding H and Arens NC. Which ornamental plant species effectively remove benzene from indoor air? Atmos Environ 2007; 41: 650–654.
71 Clausen G, Beko G, Corsi RL, Gunnarsen L, Nazaroff WW, Olesen BW, Sigsgaard T, Sundell J, Toftum J and Weschler CJ. Reflections on the state of research: indoor environmental quality. Indoor Air 2011; 21: 219–230.
72 Chen LM, Yurimoto H, Li KZ, Orita I, Akita M, Kato N, Sakai Y and Izui K. Assimilation of formaldehyde in transgenic plants due to the introduction of the bacterial ribulose monophosphate pathway genes. Biosci Biotechnol Biochem 2010; 74: 627–635.
73 Lambers H, Chapin FS III and Pons TL. Photosynthesis, respiration, and long-distance transport. Plant physiological ecology. 2nd ed. Houten: Springer Science & Business Media, 2008, pp.11–99.
74 Treesubsuntorn C and Thiravetyan P. Removal of benzene from indoor air by Dracaena sanderiana: effect of wax and stomata. Atmos Environ 2012; 57: 317–321.
75 Kim KJ, Kil MJ, Song JS, Yoo EH, Son KC and Kays SJ. Efficiency of volatile formaldehyde removal by indoor plants: contribution of aerial plant parts versus the root zone. J Am Soc Hortic Sci 2008; 133: 521–526.
76 Trapp S. Fruit tree model for uptake of organic compounds from soil and air. SAR QSAR Environ Res 2007; 18: 367–387.
77 Bacci E, Calamari D, Gaggi C and Vighi M. Bioconcentration of organic-chemical vapors in plant- leaves – experimental measurements and correlation. Environ Sci Technol 1990; 24: 885–889.

78 Irga PJ, Torpy FR and Burchett MD. Can hydroculture be used to enhance the performance of indoor plants for the removal of air pollutants? Atmos Environ 2013; 77: 267–271.
79 Wild E, Dent J, Thomas GO and Jones KC. Direct observation of organic contaminant uptake, storage, and metabolism within plant roots. Environ Sci Technol 2005; 39: 3695–3702.
80 Wenzel WW. Rhizosphere processes and management in plant-assisted bioremediation (phytoremediation) of soils. Plant Soil 2009; 321: 385–408.
81 Gao YZ, Cheng ZX, Ling WT and Huang J. Arbuscular mycorrhizal fungal hyphae contribute to the uptake of polycyclic aromatic hydrocarbons by plant roots. Bioresource Technol 2010; 101: 6895–6901.
82 Jones DL, Hodge A and Kuzyakov Y. Plant and mycorrhizal regulation of rhizodeposition. New Phytol 2004; 163: 459–480.
83 Zhan XH, Liang X, Xu GH and Zhou LX. Influence of plant root morphology and tissue composition on phenanthrene uptake: stepwise multiple linear regression analysis. Environ Pollut 2013; 179: 294–300.
84 Wang ZQ and Zhang JS. Characterization and performance evaluation of a full-scale activated carbon-based dynamic botanical air filtration system for improving indoor air quality. Build Environ 2011; 46: 758–768.
85 Aydogan A and Montoya LD. Formaldehyde removal by common indoor plant species and various growing media. Atmos Environ 2011; 45: 2675–2682.
86 Iranpour R, Coxa HHJ, Deshusses MA and Schroeder ED. Literature review of air pollution control biofilters and biotrickling filters for odor and volatile organic compound removal. Environ Prog 2005; 24: 254–267.
87 Delhomenie MC and Heitz M. Biofiltration of air: a review. Crit Rev Biotechnol 2005; 25: 53
88 Burgess JE, Parsons SA and Stuetz RM. Developments in odour control and waste gas treatment biotechnology: a review. Biotechnol Adv 2001; 19: 35–63.
89 Jin Y, Veiga MC and Kennes C. Development of a novel monolith-bioreactor for the treatment of VOC- polluted air. Environ Technol 2006; 27: 1271–1277.
90 Davis MM and Hirmer S. The potential for vertical gardens as evaporative coolers: an adaptation of the 'Penman Monteith equation'. Build Environ 2015; 92: 135–141.
91 Rodgers K, Handy R and Hutzel W. Indoor air quality (IAQ) improvements using biofiltration in a highly efficient residential home. J Green Build 2013; 8: 22–27.
92 Ergas SJ, Shumway L, Fitch MW and Neemann JJ. Membrane process for biological treatment of contaminated gas streams. Biotechnol Bioeng 1999; 63: 431–441.
93 SchleibingerH,KellerRandRu¨denH.Indoorairpol- lution by microorganisms and their metabolites. In: Pluschke P (ed) Indoor Air Pollution: The handbook of environmental chemistry. Vol. 4. Berlin Heidelberg: Springer-Verlag, 2004, pp.149–177.
94 Robbins CA, Swenson LJ, Nealley ML, Kelman BJ and Gots RE. Health effects of mycotoxins in indoor air: a critical review. Appl Occup Environ Hyg 2000; 15: 773–784.
95 Pasanen AL. A review: fungal exposure assessment in indoor environments. Indoor Air 2001; 11: 87–98.
96 Darlington AB, Dat JF and Dixon MA. The biofiltration of indoor air: air flux and temperature influences the removal of toluene, ethylbenzene, and xylene. Environ Sci Technol 2001; 35: 240–246.
97 Logan BE, Hamelers B, Rozendal RA, Schrorder U, Keller J, Freguia S, Aelterman P, Verstraete W and Rabaey K. Microbial fuel cells: methodology and tech- nology. Environ Sci Technol 2006; 40: 5181–5192.
98 Davis MJM, Tenpierik MJ, Ramirez FR and Perez ME. More than just a green facade: the sound absorption properties of a vertical garden with and without plants. Build Environ 2017; 116: 64–72.
99 Van Renterghem T, Botteldooren D and Verheyen K. Road traffic noise shielding by vegetation belts of limited depth. J Sound Vib 2012; 331: 2404–2425.
100 Azkorra Z, Perez G, Coma J, Cabeza LF, Bures S, Alvaro JE Erkoreka A and Urrestarazu M. Evaluation of green walls as a passive acoustic insulation system for buildings. Appl Acoust 2015; 89: 46–56.
101 Perez-Urrestarazu L, Fernandez-Canero R, Franco A and Egea G. Influence of an active living wall on indoor temperature and humidity conditions. Ecol Eng 2016; 90: 120–124.
102 Armijos Moya T, van den Dobbelsteen A, Ottelé M, Bluyssen PM. Using indoor living wall systems as a climate control method in hot humid climates. In *Proceedings of the international scientific conference Healthy Buildings 2017 Europe*, Lublin, Poland, 2017. *[0066]*.
103 Fernandez-Canero R, Urrestarazu LP and Franco-Salas A. Assessment of the cooling potential of an indoor living wall using different substrates in a warm climate. Indoor Built Environ 2012; 21: 642–650.
104 Davis MJM, Ramirez F and Perez ME. More than just a green facade: vertical gardens as active air conditioning units. Procedia Eng 2016; 145: 1250–1257.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3 Perceived Indoor Air Quality Assessment

Appraisal and identification of different sources of smell by primary school children in the air quality test chamber of the SenseLab

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This chapter is based upon the following article: Armijos Moya T and Bluyssen PM. Appraisal and identification of different sources of smell by primary school children in the air quality test chamber of the SenseLab. *Intelligent Buildings International* 2019, 13:2, 142–155.

ABSTRACT Previous studies have shown that next to 'human smell', 'stuffy air' is one of the discomforts that children report in classrooms. Besides, people's olfactory system is able to recognize the perceived odour intensity of various materials relatively well and in many cases the nose seems to be a better perceiver of pollutants than some equipment. In the underlying study, the aim was to expose 335 primary children to different sources of smell, and ask them to evaluate and identify those sources at individual level with their noses. Additionally, the possible effect of plants on the reduction and/or production of smells was tested. Selected sources of odour were placed in different containers and the children were asked how they feel about the smell and to identify their source. The results showed statistically significant differences among children's evaluations of different smells, a link between preference and recognition of odours, and, no statistical difference in the assessment of the smells when the potted plants were placed inside the CLIMPAQ. The results confirm the need to include sensory assessments in the evaluation of IAQ together

with physical evaluations. Future studies on the effect of using active vegetation systems instead of passive systems are recommended.

KEYWORDS Indoor air quality; pollution sources; sensory evaluation; primary school children

3.1 Introduction

Indoor environmental quality (IEQ) is a significant concern in educational buildings, since it is directly related to children's activities and well-being.[1,2] Several studies have documented the indoor environment, occupant comfort, productivity and health in offices[3–7] from the point of view of the occupant. For the main occupants of primary schools, the children, there seems less information available on their point of view for comfort, health and performance. Children represent a risk group and are more susceptible than adults to poor IEQ.

IEQ is determined by thermal, light, acoustical and air quality. Poor indoor air quality (IAQ) is a common problem in classrooms, and it has been reported that it causes health and comfort problems among its occupants.[2,8–13] In a previous study executed in the spring of 2017, 54 classrooms in the Netherlands were visited for a survey on the health and comfort of primary school children in relation to their stay in the classrooms. From the 1145 children that completed the questionnaire, 63% of the children was bothered by smell (girls 67% and boys 59%). The most frequently occurring smells in the classroom according to the children were 'human' (56%) and 'stuffy' (27%).[12] While the term 'human' was often related to farting, the term 'stuffy' could not be specifically related to a source.

IAQ is determined by the exposure to pollution over time and this pollution can originate from different sources: people and their activities, building and furnishing materials, outdoor air and even heating, ventilation and air conditioning systems.[14,15] The European projects: the European Database European Database on Indoor Air Pollution Sources in Buildings[16] and MATHIS[17] resulted in databases of building materials and products with both chemical and sensory information, which are the basis for the current guidelines used in European countries. AIRLESS, another European project, showed that the main sources of pollution in ventilation systems are filters and ducts and it may vary depending on the design, the use and the maintenance of the system.[18–20]

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The main groups of pollutants found in indoor air are chemical pollutants, which includes gases, vapours and particulate matter (PM); and biological pollutants. Building and furnishing materials can emit volatile organic compounds (VOCs), such as for example formaldehyde (a very VOC) and several alcohols, that have the potential to affect health and well-being. Several studies have shown that formaldehyde can affect the health, comfort and performance of school children.[2,21,22] It has been well documented that furnishing and flooring materials represent an important source of pollution in classrooms producing inconvenience among the children.[2,23] High PM concentrations are also known to affect health and wellbeing of children in classrooms. Several studies have shown that physical activities of children inside contribute to rising PM concentrations in classrooms, in particular PM10, and that indoor sources are evidently the main contributors to indoors PM concentrations, specially to PM1 and PM2.5.[24,25]

A source that is often not mentioned in the list of polluters, is the plant: a source that can pollute as well as clean the air. There is increasing recognition of the potential for plants to generate an attractive environment that supports social and emotional well-being, recovery from stress, and cognitive performance, especially in classrooms.[26,27] Several studies have described and evaluated the possible effect of plants on the indoor air quality.[28–33] However, there is still a lack of solid evidence proofing the real effect of green systems in the indoor environment,[33] especially regarding air quality.

Health and comfort problems have been reported and associated with emissions of materials used in buildings where occupants spend most of their time. From annoying smells to symptoms such as dry eyes, irritated skin, upper and lower airway problems, to even carcinogenic effects have been associated with exposure to VOCs.[15,34,35] These problem cases have normally been marked belonging to either Sick Building Syndrome (SBS), which are health problems (biological or psychological) caused by the negative impact of buildings,[36] or Building-Related-Illness (BRI), such as legionnaires disease and asbestosis.[37] Therefore, materials need to be evaluated with respect to their VOC and odour emissions.[37] Odours may cause a variety of undesirable reactions in people, ranging from annoyance to documented health effects. Prolonged exposure to odours can generate undesirable reactions ranging from emotional and psychological stresses, discomfort, headaches, or depression to physical symptoms including sensory irritations, headaches, respiratory problems, nausea, or vomiting.[38–40] They are emitted from several construction, consumer and cleaning products, including air fresheners, plants and flowers, food and beverages.[17,41,42] Odours that result directly or indirectly from human activities and that cause an adverse effect are often classified as contaminants and are subject to regulation.[43]

Currently, different methods are available for assessing IAQ, such as chemical and physical monitoring of certain pollutants in the air or at a surface, and sensory assessment with the human nose.[44] Different instrumentation and technologies are used to monitor and assess air quality, such us chemical sensors and gas chromatography. Overall, these instruments can identify a number of substances and their concentrations; however, one of the main limits of this technique is the complexity of concentrations and mixtures of the pollutants and its odours. In real life, the concentrations of the pollutants are usually lower that the instrument detection limit. Additionally, these instruments are in general expensive and they do not provide any information about human perception.[45,46] Series of guidelines and regulations released in many countries, are focused on the concentration limitation of indoor air pollutants based on toxicities.[15,35] The intensity of an odour or smell emitted by different indoor materials was introduced as a measure to assess the VOCs emitted, as some VOCs that are commonly present indoors have been associated with odour[47] and can also cause a variety of undesirable reactions among people, ranging from annoyances, irritations to documented health issues.[48]

In the last years, scientists have focused on developing devices analogue to human senses, such as electronic noses that once calibrated they can be used to perform odour assessment on a continuous basis at a minimum cost.[49,50] However, the range of odour mixtures, concentrations and intensities that the device can detect is still limited.[51] Due to this limitation the use of these devices is still restricted at the moment to monitor environmental odours.[51] Scientists recommend to combine odour measurement procedures using the human nose as detector together with a scientific method and instruments.[46,52]

Sensory assessment of IAQ with human subjects as measuring instruments has been used to establish the appropriate ventilation rates that bring body odour intensity to acceptable levels. It also has been used to assess various processes to improve IAQ, based on the use of different materials.[41,53–55] The nose can detect very low concentrations (parts-per-trillion range) and interpret all at the same time.[14,56] However, some studies have shown that the indoor pollutants with highest chemical concentrations were not the most odour active odorants.[57]

In the underlying study, the aim was to expose children of some of the same primary schools as that were studied before,[12] to different sources of smell, and ask them to evaluate and identify those sources at individual level with their noses. Additionally, the possible effect of plants on the reduction and/or production of smells was tested.

The aims of the study were to evaluate:

1. the perception and identification of smells from known sources in classrooms by children;
2. the relationship between perception in the field study and the lab study;
3. the level of acceptability in relation to recognition of smells by children;
4. the effect of plants on the perception of smells.

3.2 Materials and methods

3.2.1 Study Design

This study was part of a series of tests performed during 10 days with children from the previous studied Dutch schools, in the SenseLab.[12,58,59] During the winter and spring of 2018, 335 students of seven schools in the Netherlands visited the SenseLab to participate in a series of experiments. The recruitment of these schools was on voluntary basis.[12] When the children arrived in the SenseLab, they completed a one-page questionnaire with personal information and were divided into groups (randomly) of maximum 16 children per group. Per day, a maximum of three groups could perform the tests. One group started in the Experience room, one group was divided over the four test chambers (maximum of 4 children per test chamber) and the third group visited the Science Centre (the location in which the SenseLab is located). After approximately 35 min the groups changed: group 1 went to the test chambers, group 2 visited the Science Centre and group 3 went into the Experience room. In each of the test chambers (light, sound, air and thermal), different tests were performed. Every 7–8 min, after the tests were performed, the children changed to another test chamber.[59–62] This paper presents the results of the tests performed in the air quality test chamber.

3.2.2 The SenseLab and the air quality chamber

The experiments were performed in the SenseLab, located in the Science Centre at Delft University of Technology that was described in detail by Bluyssen et al. (2018)[58]. The SenseLab is a laboratory for testing and experiencing single and combinations of indoor environmental conditions. It comprises of an Experience room, where it is possible to study the effects of different combinations of environmental conditions in different scenarios, and four test chambers for each of the indoor environmental factors: indoor air, light, acoustics and thermal aspects. For this specific study, the experiment was carried out in the air quality chamber which had a volume of 17.4 m^3 (floor area 8.3 m^2 × 2.1 m height) (Figure 3.1), and included a stainless steel 'Sniffing table', including different sources of smell, and a table on which the CLIMPAQ 50L was placed. The CLIMPAQ 50 L (Figure 3.1) is a small test chamber that allows to analyse emissions and pollutants from a wide range of materials. The principal elements of the experimental set-up in the air quality chamber are presented in (Figure 3.2).

FIG. 3.1 Air Quality Chamber: CLIMPAQ 50L and sniffing table.

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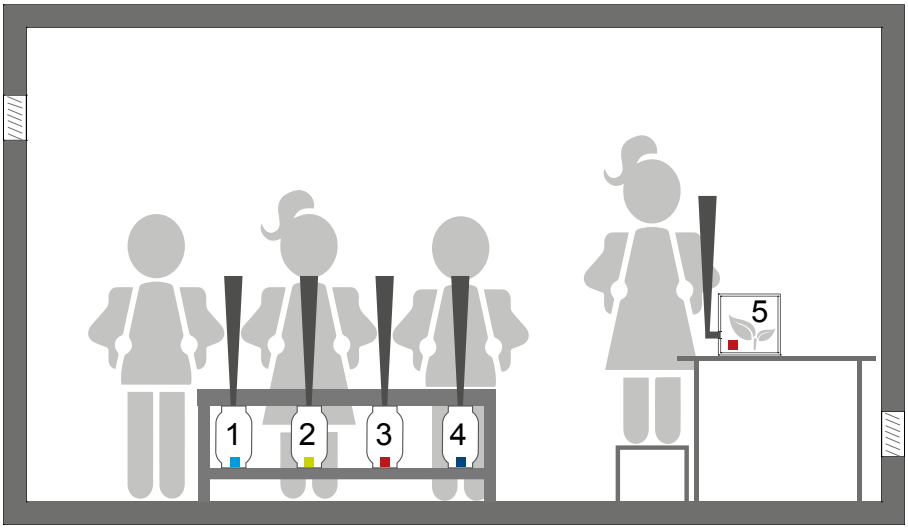

FIG. 3.2 Diagram of the Experimental setup in the Air Quality Chamber.
1. Perfume; 2. Mint leaves; 3. Carpet, MDF (medium density fibreboard), or Vinyl (according to the schedule in Table 3.1); 4. Crayons; 5. Carpet, MDF, or Vinyl (+plant, according to the schedule in Table 3.1).

3.2.3 Ethical aspects

After recruitment of the schools, the parents received an information letter and a consent letter from the school management, which usually happened two weeks before the visit. On the day of the visit, the research team received the consent forms usually from the teachers accompanying the children. For the children without permission to join the experiments, the school management generally decided not to have them join the visit. Furthermore, the children always had the option to opt out if they no longer wanted to participate. The Ethics committee of the TU Delft gave approval for the study.

3.2.4 Experiment

Two similar experiments were conducted to assess the identification of potentially recognizable odours for children. In each session, five odorant sources were used. For the Indoor Air test chamber (Figure 3.1), different olfactory stimuli were selected to be identified for the children (Table 3.1).

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TABLE 3.1 Time schedule and selected sources of smell.

Container No.	Material	Notes and schedule
1	**Perfume**	–
2	**Mint leaves**	New leaves were used for each session. March 15: Liquorice. Mint leaves were used in the rest of the sessions.
3	**Carpet / MDF / Vinyl**	Tuesday, February 13: Carpet Thursday, February 15: Carpet Tuesday, February 20: Carpet Thursday, February 22: Carpet Thursday, March 8: MDF Thursday, March 15: MDF Tuesday, March 20: MDF Tuesday, March 27: MDF Tuesday, April 3: Vinyl Thursday, April 5: Vinyl
4	**Crayons**	Always the same
Climpaq 5	**Carpet / MDF / Vinyl**	Tuesday, February 13: Carpet Thursday, February 15: Carpet Tuesday, February 20: Carpet + Plant Thursday, February 22: Carpet + Plant Thursday, March 8: MDF + Plant Thursday, March 15: MDF + Plant Tuesday, March 20: MDF Tuesday, March 27: MDF Tuesday, April 3: Vinyl Thursday, April 5: Vinyl + Plant

These odorants were selected based on previous studies in Dutch schools.[12] The stimuli were placed in four different covered plastic containers located in the 'sniffing table' with sniffing cones[53] (Figure 3.1). Every session 3–4 children entered the chamber and they were asked to take a sniff of each of the sniffing cones, one at the time, and answer a questionnaire regarding the smell they perceived. At the same time, one of the materials in the plastic containers (container no.3) was also located in the CLIMPAQ 50 L (Figure 3.1; Table 3.1). The children were asked to match the odour with one of the plastic containers. In half of the sessions, three selected potted plants were placed inside of the CLIMPAQ together with the selected material (Figure 3.3) according to the schedule (Table 3.1) to evaluate the effect of the plant on odour depletion/production. The plants selected for these experiments comprised of three Chlorophytum, also known as spider plants, which are common potted plants. Previous studies have stated that this kind of plant may have a positive effect on the reduction of pollutant within the indoor environment.[29,32] Prior to the experiments, a Photoionization Detector (PID), ppbRAE3000 11.7 eV, was used to monitor the VOCs emitted by the selected materials. This VOC-monitoring instrument uses a 11.7 eV lamp that is able to lamp respond to a broad range of compounds, including formaldehyde.

FIG. 3.3 Selected materials + Spider plant inside of the CLIMPAQ 50L.

3.2.5 The questionnaire

The children were asked: ‘How do you like the smell?’ and ‘Can you tell what it is?’. When working with children, who are not always able to clearly communicate and express how they feel, the use of graphic questionnaires could be an alternative option to obtain more information about their experiences. Therefore, the perceived odour was assessed on a five-graphical-grade scale (Figure 3.4). The questionnaire contained special drawings to make it more attractive and interesting for the children. Before administering the questionnaire in the Air Quality Chamber, it was distributed and tested among the staff, in order to improve and adapt it. During the experiment, before the questionnaire was distributed, an explanation was given of the contents and purpose of the questionnaire. In general, it took the children approximately five minutes to perform the test and fill in the questionnaire.

FIG. 3.4 Part of the questionnaire for sniffing test (APPENDIX A).

3.2.6 Data management and analysis

All data from the questionnaires were manually typed in and stored in IBM SPSS Statistics version 25.0. A second person systematically checked the input of the questionnaire data. First, descriptive statistics such as percentages, range or arithmetic mean with standard deviation were used to summarize the data. This descriptive analysis was used to describe children's general information (including age, gender, children with allergies, children with cold, etc.). Additionally, comparisons of mean values were performed with one-way ANOVA tests to evaluate the children's level of acceptability for each of the sources of smell. Finally, independent-Samples T-tests were conducted to evaluate whether statistically significant differences between children's assessment of two same smells (smell 3 and smell 5) occurred.

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3.3 Results

3.3.1 Participants

335 children, including 166 girls and 169 boys from seven primary schools in the Netherlands, that were visited during the field study in the year before this study, participated. The mean age of these children was 10.6 years old. From the 335 children, 254 (76%) children participated in both the field and the lab studies.

3.3.2 VOC-monitoring

A VOC-monitoring instrument was used to measure the emissions coming out from the plastic containers. It was found that the 11.7ev PID monitor measured 0 ppb for almost all the sources with the exception of the perfume and the mint leaves. The measurements were recorded after 3 min after placing the materials inside of the containers. In the case of the mint leaves the instrument measured 0ppb after 5 min of placing the leaves inside of the container (Figure 3.5).

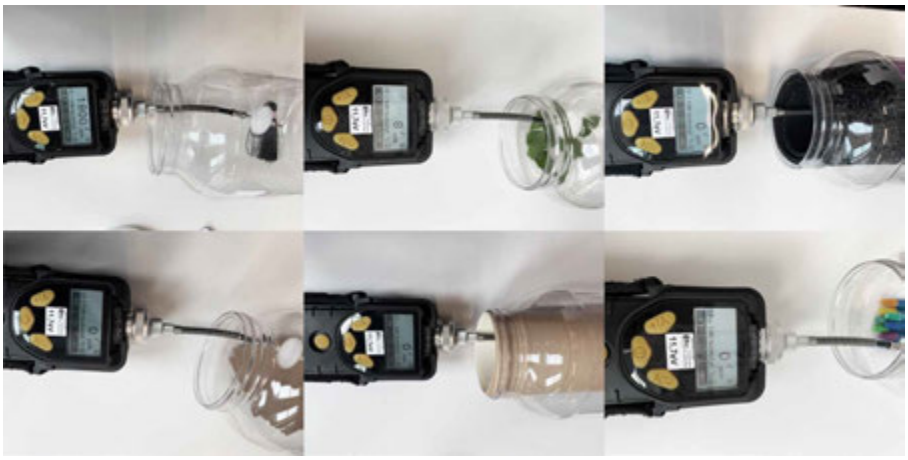

FIG. 3.5 VOCs emitted by the selected materials: (a) perfume; (b) mint leaves; (c) carpet; (d) MDF; (e) vinyl; and (f) crayons.

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3.3.3 Experiment

In the first part of the experiment, children performed a smell identification test with four different smell stimuli. In each session, a perfume stick was placed in container number 1. As shown in Table 3.2, 15% of the children identified the smell as perfume. Most of the children identified the smell as soap or shampoo. Several children identified the smell as similar smells such as fresheners, flowers or perfume. 6% of the children could not give any name to the smell.

TABLE 3.2 Identification of the smells in containers 1,2 and 4 by the children

Funnel 1: Perfume (n*=335)		Funnel 2: Mint Leaves (n=309)		Funnel 4: Crayons (n=335)	
Fresheners	9.6%	Plants	15.5%	Dust	6.6%
Flowers	10.1%	Tea	6.5%	Wood	5.4%
Soap / Shampoo	49.3%	Flowers	4.9%	Plastic / Rubber/Carpet	8.7%
Perfume / Deo / Cream	15.2%	Mint / Mint tea	38.2%	Spices / Tea / Vinegar	6.9%
Candle	1.5%	Spices	6.1%	Other	42.1%
Other	8.1%	Other	21.0%	Empty / I don't know	30.4%
Empty / I don't know	6.3%	Empty / I don't know	7.8%		

**Number of children that performed the identification test.*

In container 2, some mint leaves where placed. 38% of the children identified the smell of mint. The rest of the children identified the smell as plants, tea, spices, flowers, and other. 8% did not identify the smell. In container 4, several crayon pieces where placed. 30% of the children could not identify the smell. Some kids identified the smell as plastic, rubber, carpet, dust, wood and others (Table 3.2).

During the series of tests, three different materials were placed in container 3. Each material was changed according to the schedule presented in Table 3.1. The children found it difficult to identify the smell when the vinyl and the carpet were placed in container 3, as shown in Table 3.3. When pieces of MDF were placed in container 3, 48% of the children identified the smell as wood.

TABLE 3.3 Identification of the smells in container 3 by the children

Carpet (n*=118)		MDF (n=128)		Vinyl (n=89)	
Carpet	9.3%	Wood	47.7%	Clay	11.2%
Rubber / Plastic	22.9%	Cardboard	12.5%	Rubber / Plastic	16.9%
Dust	5.1%	Other	27.3%	Metal	9.0%
Leather	5.9%	Empty / I don't know	12.5%	Other	43.8%
Gasoline	5.9%			Empty / I don't know	19.1%
Other	33.9%				
Empty / I don't know	16.9%				

n=number of children that performed the test.

TABLE 3.4 Which other funnel has the same smell as this one?

Funnel 3	5. Climpaq	n*	Who identified the smell?
Carpet	**Carpet**	56	66.1%
Carpet	**Carpet + Plant**	62	59.7%
Mdf	**Mdf**	70	79.3%
Mdf	**Mdf + Plant**	58	81.8%
Vinyl	**Vinyl**	46	58.7%
Vinyl	**Vinyl + Plant**	43	81.0%

Number of children who participated in each individual test

The children were also asked: How do you like this smell? The result of the ANOVA test showed that there were statistically significant differences among children's evaluations of different smells (p = 0.00). They liked perfumes most (mean value of 4.2), followed by mint leaves (mean value of 3.4), carpet, MDF and vinyl (mean value of 2.7 and 2.9). They liked crayons the least with a mean value of 2.6 (Table 3.5).

Table 3.4 shows that in general, the children could identify which container emitted the same smell as in the CLIMPAQ 50L. Children in general liked smell 5 more than smell 3 (Tables 3.5 and 3.6). However, the results of the t-tests, comparing the two same smells in funnel 3 and in the CLIMPAQ with the plants inside of the CLIMPAQ, showed no statistically significant difference between these two evaluations (Tables 3.7 and 3.8). Furthermore, the results of the t-tests between the perception of the smells in funnel 3 and in the CLIMPAQ without the plants, showed a statistically significant difference between the two evaluations (Tables 3.7 and 3.8).

In addition, five t-tests were conducted to compare the evaluations of children with a cold and without a cold. The results showed that children who had a cold didn't differ significantly with healthy children regarding their evaluations (Tables 3.5 and 3.6).

TABLE 3.5 Mean evaluations of children when asked "How do you like the smell?": All children

Container N.	Material	n*	Mean	Std. Deviation
1	**Perfume**	332	4.24	0.843
2	**Mint leaves**	328	3.43	1.147
3	**Carpet / MDF / Vinyl**	324	2.73	1.043
4	**Crayons**	326	2.6	1.084
5 Climpaq	**Carpet / MDF / Vinyl**	305	2.97	1.067
	Total	1615	3.2	1.201

**Number of children*
Anova Test between groups (p=0.00)

TABLE 3.6 Mean evaluations of children when asked "How do you like the smell?": without children who had cold

Container N.	Material	n*	Mean	Std. Deviation
1	**Perfume**	153	4.29	0.76
2	**Mint leaves**	152	3.39	1.14
3	**Carpet / MDF / Vinyl**	149	2.78	1.006
4	**Crayons**	149	2.68	1.054
5 Climpaq	**Carpet / MDF / Vinyl**	139	3.12	1.043
	Total	742	3.26	1.163

**Number of children*
ANOVA Test between groups (p=0.00)

TABLE 3.7 "How do you like the smell?": Is there any plant in the chamber: NO

Container N.	Material	n*	Mean	Std. Deviation
1	**Perfume**	157	4.29	0.785
2	**Mint leaves**	156	3.34	1.199
3	**Carpet / MDF / Vinyl**	156	2.82	0.891
4	**Crayons**	158	2.72	1.016
5 Climpaq	**Carpet / MDF / Vinyl**	146	3.16	0.959
	Total	773	3.27	1.128

**Number of children*
Anova Test between groups (p=0.00) / T. Test: Is any plant in the chamber (0.05)

TABLE 3.8 "How do you like the smell?": Is there any plant in the chamber: SI

Container N.	Material	n*	Mean	Std. Deviation
1	**Perfume**	175	4.21	0.892
2	**Mint leaves**	172	3.51	1.095
3	**Carpet / MDF / Vinyl**	168	2.65	1.164
4	**Crayons**	168	2.5	1.137
5 Climpaq	**Carpet / MDF / Vinyl**	159	2.81	1.133
	Total	842	3.15	1.262

**Number of children*
ANOVA Test between groups (p=0.00) / T. Test: Is any plant in the chamber (0.05)

3.4 Discussion

3.4.1 Perception versus chemical measurements

The results of the present study show that even though the chemical measurements didn't show any emission from most of the materials tested (Figure 3.5), the children could perceive a smell with their noses. The outcome confirmed earlier findings and recommendations with regards to performing both sensory evaluations as well as chemical and physical measurements:[37] some pollutants can just not be monitored by the instruments available, while our nose can. Our sensory system (nose) can assess the perceived odour intensity of various materials relatively well, and, in many cases the nose seems to be a better assessor of pollutants than some equipment. The indoor environment comprises thousands of chemical compounds in low concentrations, of which not all can be measured and interpreted by currently available equipment.[14] Sensory evaluation seems therefore a necessary instrument for the measurement of the perceived indoor air quality because chemical and physical analysis alone can in most situations not be used to predict how chemicals will be perceived among users.

3.4.2 Level of acceptability vs. identification of smells

One of the aims of this study was to only include odours that are well known and able to be correctly identified by a majority of children. Previous studies have demonstrated that the ability to identify odours increases with age in children. This is due to an ongoing process of odour learning rather than an actual increase in olfactory function.[63] The evaluation of air quality expressed in acceptability reflects perceptual information in combination with psychological and social values.

The present study showed that the level of acceptability given by the children to the different sources of smell increased when they were more familiar with the source of the smell (able to recognize) and when they had visual contact with the source, as shown in Tables 3.5–3.8. In addition, results showed that children who had a cold didn't differ significantly with healthy children in their assessment. This can be explained by a psychological point of view: each stimulation introduced in the indoor environment needs explanation; therefore, smells that are present and which cannot

be recognized will lead to some discomfort.[64] This is shown in Tables 3.5 and 3.6 that indicates that children prefer the smells that they could easily identify, while the smells that were more difficult to identify were less likeable. However, it is important to mention that an unpleasant odour for some children may be perceived as indifferent or even pleasant by others.

3.4.3 Stuffy air

Stuffy air seems to be an important factor to consider to qualify indoor air quality. It has been used as a descriptive for air quality in a large number of studies in offices, schools and other indoor environments. In the previous field study, it was found that most of the children were bothered by smell: 56% used 'human' to describe the smell they were bothered with and 27% used 'stuffy' (Table 3.9).[12] However, they couldn't describe what stuffy air meant or where it came from. We could assume that stuffy air can be caused by bad ventilation within the classrooms or by emissions emitted by building materials. Therefore, in this study some building materials were included to evaluate how children assess these materials.[2,23] As can be seen in Tables 3.5 and 3.6, children, in general did not like the odour emitted by the selected building materials and in most cases, they could not identify the source of the smell (Table 3.3).

TABLE 3.9 Type of smells in classrooms pointed out by children[12]

Type of smells in classrooms pointed out by children	
Flower	9%
Fruit	13%
Vegetables	4%
Stuffy	27%
Human	56%
Paint	14%
Hospital	3%

3.4.4 Effect of plants

One of the objectives of the study was to evaluate the effect of potted plants on the depletion or production of smells. In the present study, it is shown that the presence of a potted plant inside of the CLIMPAQ did not have a big influence on the identification of the same smell within the sniffing table, with the exception of the vinyl for which the smell in general was more difficult to identify for the children (Table 3.4). Previous lab studies have indicated a possible effect of vegetation on IAQ,[29,31,32] but all of these tests were chemical tests. There is still a lack of solid and relevant data available to understand the true pollutant-removal mechanisms and factors in these systems.[33] In fact, existing research suggests that in an active vegetation system (green systems in combination with mechanical fans), air-cleaning rates may be significantly higher than in a passive vegetation system (potted plants),[30] which was applied in the study reported here.

3.4.5 Limitations

With respect to the limitations of this study, three main weaknesses can be identified. One is the limited time provided to execute each test, especially regarding the evaluation of the effect of the potted plant in the depletion or production of smells. Future experiments should analyse the effects of green systems in relation to the mitigation of odours over a longer period of time.

The second limitation is that the equipment applied to monitor the VOCs emitted by the different sources, comprised of a direct reading instrument that monitored total VOCs (including also VVOCs) at ppb level. For identification of the individual components of 'stuffy air', it might be required to perform long-term measurements that collect enough material for identification.

Finally, the children that performed the tests had to undergo also other tests and activities related with other environmental factors, which resulted in some cases that they didn't complete their questionnaire. The aim of these series of experiments in the SenseLab was to generate a general overview on how the children assess different aspects in the indoor environment. In future tests, it is recommended to focus on specific factors that affect the indoor air quality and on how some elements, such as plants or new materials, can affect the perceived indoor air.

3.5 Conclusions and recommendations

One of the aims of the study was to evaluate children's perception and identification of smells from known sources in classrooms. The present study showed that the level of children's acceptability of smells from the different sources, seems to have a relation with their level of recognition of the smell. Children found the smell in general more acceptable, when they recognized the smell, even though the smell might be unhealthy. For the assessment of emissions of sources found in classrooms, combined sensory and chemical measurements, as recommended in several guidelines, is therefore required as well.

Another aim of the study was to identify where the 'stuffy smell', found during the study field, came from. For that reason, some building materials were included in this study. It was found that in general children did not like the smell of those materials and in most of the cases they could not identify the source of the smell. However, whether there is a correlation between the smells from those materials and the 'stuffy air' that children identified in the classrooms, needs to be studied more in depth.

Finally, the effect of (passive) plants on the perception of smells showed no effect. In future studies, it is therefore recommended to perform tests with an active green system, over a longer period of time. It might take time for the plant to 'clean' the air, and an active green system might improve the air quality faster than a passive one.

References

1 Mendell MJ and Heath GA. Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature (vol 15, pg 27, 2005). *Indoor Air* 2005; 15: 67-67.

2 Bluyssen PM. Health, comfort and performance of children in classrooms - New directions for research. *Indoor Built Environ* 2017; 26: 1040-1050.

3 Frontczak M, Schiavon S, Goins J, et al. Quantitative relationships between occupant satisfaction and satisfaction aspects of indoor environmental quality and building design. *Indoor Air* 2012; 22: 119-131.

4 Al Horr Y, Arif M, Kaushik A, et al. Occupant productivity and office indoor environment quality: A review of the literature. *Build Environ* 2016; 105: 369-389.

5 Bluyssen PM, Roda C, Mandin C, et al. Self-reported health and comfort in "modern' office buildings: first results from the European OFFICAIR study. *Indoor Air* 2016; 26: 298-317.

6 Sakellaris IA, Saraga DE, Mandin C, et al. Perceived Indoor Environment and Occupants' Comfort in European "Modern" Office Buildings: The OFFICAIR Study. *Int J Env Res Pub He* 2016; 13.

7 Mandin C, Boerstra A, Le Ponner E, et al. Indoor air quality and comfort in new and retrofitted offices, and their relations with work performance. Analysis of the French data from the OFFICAIR project, Part 2. *Environ Risque Sante* 2017; 16: 565-574.

8 Annesi-Maesano I, Baiz N, Banerjee S, et al. Indoor Air Quality and Sources in Schools and Related Health Effects. *J Toxicol Env Heal B* 2013; 16: 491-550.

9 Ferreira AMD and Cardoso M. Indoor air quality and health in schools. *J Bras Pneumol* 2014; 40: 259-268.

10 Turunen M, Toyinbo O, Putus T, et al. Indoor environmental quality in school buildings, and the health and wellbeing of students. *Int J Hyg Envir Heal* 2014; 217: 733-739.

11 Fisk WJ. The ventilation problem in schools: literature review. *Indoor Air* 2017; 27: 1039-1051.

12 Bluyssen PM, Zhang Dd, Kurvers S, et al. Self-reported health and comfort of school children in 54 classrooms of 21 Dutch school buildings. *Build Environ* 2018; 138: 106-123.

13 Jarvi K, Vornanen-Winqvist C, Mikkola R, et al. Online Questionnaire as a Tool to Assess Symptoms and Perceived Indoor Air Quality in a School Environment. *Atmosphere-Basel* 2018; 9.

14 Bluyssen PM. Sensory evaluation of indoor air pollution sources. In: P P (ed) *Indoor Air Pollution*. Germany: Springer, Berlin, Heidelberg, 2004, pp.179-217.

15 Bluyssen PM. *All you need to know about indoor air – A simple guide for educating yourself to improve your indoor environment*. Delft, The Netherlands: Delft Academic Press, 2015.

16 Molina JL, Clausen GH, Saarela K, et al. European database on indoor air pollution sources in buildings: Current status of database structure and software. *Indoor Air '96*. Nagoya, Japan1996, p. 531-536.

17 Oliveira Fernandes E, Bluyssen PM, Clausen GH, et al. MATHIS - Materials for healthy indoor spaces and more energy efficient buildings. *Indoor Air 99*. Edinburgh, Scotland,: TNO Bouw, 1999, p. 628-633.

18 Björkroth M, Müller B, Küchen V, et al. What is the reason, how to measure it and how to prevent it?. *Healthy Buildings 2000*. 2000, p. 163-168.

19 Bluyssen PM, Cox CWJ, Souto J, et al. Pollution from filters: What is the reason - How to measure and to prevent it? *Healthy Buildings 2000*. 2000, p. 251-256.

20 Bluyssen PM, Cox C, Seppanen O, et al. Why, when and how do HVAC-systems pollute the indoor environment and what to do about it? the European AIRLESS project. *Build Environ* 2003; 38: 209-225.

21 Smedje G and Norback D. Incidence of asthma diagnosis and self-reported allergy in relation to the school environment - a four-year follow-up study in schoolchildren. *Int J Tuberc Lung D* 2001; 5: 1059-1066.

22 Shu H, Jonsson BA, Larsson M, et al. PVC flooring at home and development of asthma among young children in Sweden, a 10-year follow-up. *Indoor Air* 2014; 24: 227-235.

23 Bluyssen PM. The role of flooring materials in health, comfort and performance of children in classrooms. *Cogent Psychol* 2016; 3.

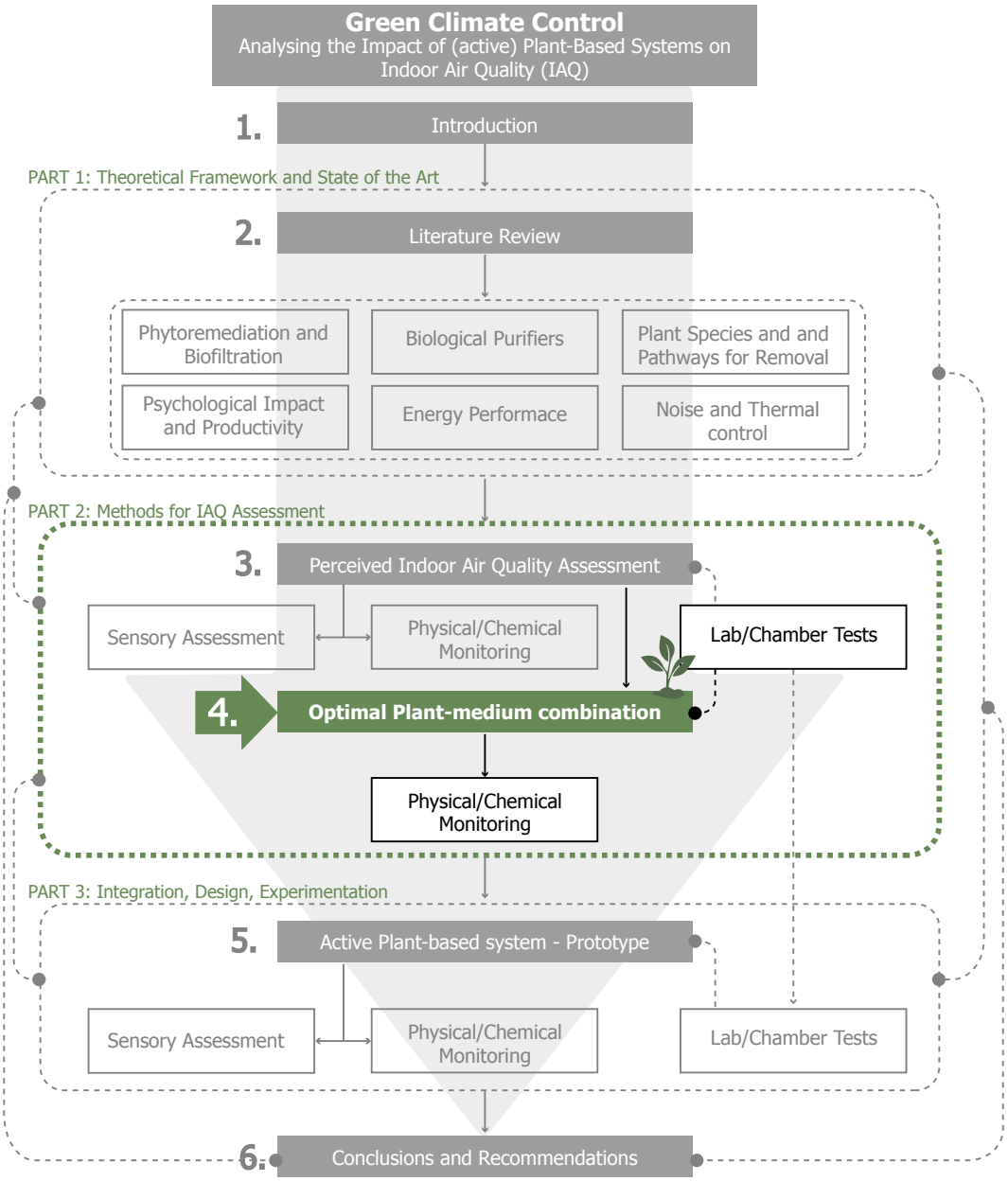
24 Fromme H, Diemer J, Dietrich S, et al. Chemical and morphological properties of particulate matter (PM10, PM2.5) in school classrooms and outdoor air. *Atmos Environ* 2008; 42: 6597-6605.

25 Branco PTBS, Alvim-Ferraz MCM, Martins FG, et al. Indoor air quality in urban nurseries at Porto city: Particulate matter assessment. *Atmos Environ* 2014; 84: 133-143.

26 Kaplan S. The Restorative Benefits of Nature - toward an Integrative Framework. *J Environ Psychol* 1995; 15: 169-182.

27 van den Berg AE, Wesselius JE, Maas J, et al. Green Walls for a Restorative Classroom Environment: A Controlled Evaluation Study. *Environ Behav* 2017; 49: 791-813.
28 Wolverton BC, Mcdonald RC and Watkins EA. Foliage Plants for Removing Indoor Air-Pollutants from Energy-Efficient Homes. *Econ Bot* 1984; 38: 224-228.
29 Wolverton BC, Johnson A and Bounds K. Interior Landscape Plants for Indoor Air Pollution Abatement, Final Report NASA (NASA-TM-101766, NAS 1.15:101766). *National Aeronautics and Space Administration* 1989: 1-22. Technical Report.
30 Darlington AB, Dat JF and Dixon MA. The biofiltration of indoor air: Air flux and temperature influences the removal of toluene, ethylbenzene, and xylene. *Environ Sci Technol* 2001; 35: 240-246.
31 Soreanu G, Dixon M and Darlington A. Botanical biofiltration of indoor gaseous pollutants - A mini-review. *Chem Eng J* 2013; 229: 585-594.
32 Dela Cruz M, Christensen JH, Thomsen JD, et al. Can ornamental potted plants remove volatile organic compounds from indoor air? - a review. *Environ Sci Pollut R* 2014; 21: 13909-13928.
33 Armijos Moya T, van den Dobbelsteen A, Ottelé M, Bluyssen PM. A review of green systems within the indoor environment. *Indoor Built Environ*. 2019;28(3):298-309.
34 Fanger PO. Indoor air quality in the 21st century: Search for excellence. *Indoor Air-International Journal of Indoor Air Quality and Climate* 2000; 10: 68-73.
35 Kotzias D. Indoor air and human exposure assessment - needs and approaches. *Exp Toxicol Pathol* 2005; 57: 5-7.
36 Vural M and Balanlı A. Sick Building Syndrome from an Architectural Perspective. In: Abdul-Wahab SA (ed) *Sick Building Syndrome*. Springer-Verlag Berlin Heidelberg, 2011, pp.371-391.
37 Bluyssen PM, Cochet C, Fischer M, et al. *Evaluation of VOC emissions from building products: Solid flooring materials*. Report no. Report No. 18, 1997. European Collaborative Action.
38 National-Research-Council. *Odors from stationary and mobile sources*. Washington, DC: National Academy of Sciences, 1979.
39 Herz RS. Influences of odors on mood and affective cognition. In: Rouby C, Schaal B, Dubois D, et al. (eds) *Olfaction, taste, and cognition*. Cambridge: Cambridge University Press, 2002.
40 Bluyssen PM. Stress response mechanisms. *The Healthy Indoor Environment: How to assess occupants' wellbeing in buildings*. New York: Routledge, 2014, pp.77-137.
41 Berglund B, Bluyssen PM, Clausen G, et al. *Sensory evaluation of indoor air quality*. Report no. 20, 1999. European Commission Report: European Collaborative Action: Indoor Air Quality and its Impact on Man.
42 Bluyssen PM, de Oliveira Fernandes E and Molina JL. Database for sources of pollution for healthy and comfortable indoor environment (SOPHIE): Status 2000. *Healthy Buildings 2000*. 2000, p. 385-390.
43 Brancher M, Griffiths KD, Franco D, et al. A review of odour impact criteria in selected countries around the world. *Chemosphere* 2017; 168: 1531-1570.
44 Bluyssen P and Fanger P. Addition of Olfs from Different Pollution Sources,determined by a Trained Panel. *Indoor Air* 1991; 4: 414-421.
45 Yuwono A and Lammers P. Odor pollution in the environment and the detection instrumentation. *Agricultural Engineering International: CIGR Journal* 2004; VI: 1-33.
46 Brattoli M, de Gennaro G, de Pinto V, et al. Odour Detection Methods: Olfactometry and Chemical Sensors. *Sensors-Basel* 2011; 11: 5290-5322.
47 Peng CY, Lan CH and Wu TJ. Investigation of indoor chemical pollutants and perceived odor in an area with complaints of unpleasant odors. *Build Environ* 2009; 44: 2106-2113.
48 Nicell JA. Assessment and regulation of odour impacts. *Atmos Environ* 2009; 43: 196-206.
49 Hudon G, Guy C and Hermia J. Measurement of odor intensity by an electronic nose. *J Air Waste Manage* 2000; 50: 1750-1758.
50 Szulczynski B, Arminski K, Namiesnik J, et al. Determination of Odour Interactions in Gaseous Mixtures Using Electronic Nose Methods with Artificial Neural Networks. *Sensors-Basel* 2018; 18.
51 Yan LC, Liu JM, Jiang S, et al. The Regular Interaction Pattern among Odorants of the Same Type and Its Application in Odor Intensity Assessment. *Sensors-Basel* 2017; 17.
52 Walker JC. The performance of the human nose in odour measurement. *Water Sci Technol* 2001; 44: 1-7.
53 Bluyssen PM. *Air quality evaluated by a trained panel*. Doctoral Dissertation, Technical University of Denmark, Lyngby, 1990.
54 Knudsen HN, Clausen G and Fanger PO. Sensory characterization of emissions from materials. *Indoor Air-International Journal of Indoor Air Quality and Climate* 1997; 7: 107-115.

55 Wargocki P. Sensory pollution sources in buildings. *Indoor Air* 2004; 14: 82-91.
56 Meilgaard MC, Civille GV and Carr BT. *Sensory Evaluation Techniques*. 4th ed. Boca Raton: FL: CRC Press, 2006.
57 Yi Q, Liu JM, Wang GH, et al. Evaluation of indoor air quality based on qualitative, quantitative and olfactory analysis. *Chinese Sci Bull* 2013; 58: 986-991.
58 Bluyssen PM, van Zeist F, Kurvers S, et al. The creation of SenseLab: a laboratory for testing and experiencing single and combinations of indoor environmental conditions. *Intell Build Int* 2018; 10: 5-18.
59 Bluyssen PM, Zhang D, Krooneman AJ, et al. The effect of wall and floor colouring on temperature and draught feeling of primary school children. *Clima 2019*. Bucharest, Romania2019.
60 Ortiz M, Zhang D and Bluyssen PM. Table top surface appraisal by school children under different lighting conditions tested in the SenseLab. *Clima 2019*. Bucharest, Romania2019.
61 Zhang D, Tenpierik M and Bluyssen PM. The effect of acoustical treatment on primary school children's performance, sound perception, and influence assessment. *Clima 2019*. Bucharest, Romania2019.
62 Bluyssen PM, Zhang D, Kim DH, et al. First SenseLab studies with primary school children: exposure to different environmental configurations in the experience room. *Intell Build Int* 2019: 1-18.
63 Schriever VA, Agosin E, Altundag A, et al. Development of an International Odor Identification Test for Children: The Universal Sniff Test. *J Pediatr-Us* 2018; 198: 265-+.
64 Vroon PA. *Psychologische aspecten van ziekmakende gebouwen [Psychological Aspects of Building Related Illness]*. Utrecht, The Netherlands: Rijkuniversiteit Utrecht, 1990.


Green Climate Control
Analysing the Impact of (active) Plant-Based Systems on Indoor Air Quality (IAQ)
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Cuvet 2
OUTPUT
POWER

4 Optimal plant-medium combination

Air cleaning performance of two species of potted plants and different substrates

Under review
This chapter is based upon the following article: Armijos Moya T, de Visser P, van den Dobbelsteen A, Ottelé M, Bluyssen PM. Air cleaning performance of two species of potted plants and different substrates. (Under review). 2021, doi: 10.21203/rs.3.rs-314387/v1

ABSTRACT Potted plants have been reported to uptake VOCs and help 'cleaning' the air. This paper presents the results of a laboratory study in which two species of plants (Peace Lily and Boston Fern) and three kinds of substrates (expanded clay, soil and activated carbon) were tested and monitored on their capacity to deplete formaldehyde and CO_2 in a glass chamber. Formaldehyde and CO_2 were selected as indicators to evaluate the bio-filtration efficacy of 28 different test conditions; relative humidity (RH) and temperature (T) were monitored during the experiments. To evaluate the efficacy of every test the Clean Air Delivery Rate (CADR) was calculated. Overall, soil had the best performance in removing formaldehyde (~0.07-0.16 m^3/h), while plants, in particular, were more effective in reducing CO_2 concentrations (Peace lily 0.01 m^3/h) (Boston fern 0.02-0.03 m^3/h). On average, plants (~0.03 m^3/h) were as effective as dry expanded clay (0.02-0.04 m^3/h) in depleting formaldehyde from the chamber. Regarding air cleaning performance, Boston ferns presented the best performance among the plant species, and the best performing substrate was the soil.

KEYWORDS Phytoremediation, Botanical biofiltration, Indoor air quality, Plant monitoring, Clean air delivery rate, Formaldehyde

4.1 Introduction

Studies have shown that poor Indoor Air Quality (IAQ) affects human health in a long-term exposure[1] (WHO, 2010). In the INDEX project[2,3] several chemicals, their concentration levels and their toxicity information were analysed and evaluated in indoor environments. It was concluded that Volatile Organic Compounds (VOCs), such as benzene, toluene and xylene, together with aldehydes should be considered as priority pollutants regarding their health effects. Several studies related with IAQ have indicated that VOCs are emitted by indoor sources such as building materials, furnishings and cleaning products.[4–8] In 1998, Yu and Crump published a review on VOC-emissions from newly built houses.[9] They stated that building material emissions are the sources of VOCs in the indoor environment, especially most during the first six months after construction.[9] Among the indoor pollutants, VOCs are ubiquitous and have harmful effects on human health such as asthma, wheezing, allergic rhinitis, and eczema.

VOCs are frequently classified according to their boiling point:[10] very volatile organic compounds (VVOCs), such as formaldehyde; VOCs, such as solvents and terpenes; Semi VOCs (SVOCs), such as pesticides; and Particulate Organic Matter (POM), such as biocides. Regarding IAQ, VOCs and VVOCs are the pollutants most frequently found indoors.[11] Some of them are toxic and carcinogenic, such as formaldehyde; and in general, exposure to formaldehyde is higher indoors than outdoors.[12–14] Formaldehyde (CH_2O) is a highly reactive aldehyde. It is a ubiquitous pollutant and it is a component of different chemical and industrial products.[14] Because of its occurrence indoors and the evident impact on human health, the study presented focused on the reduction of indoor formaldehyde concentrations.

4.1.1 Sources of formaldehyde

Formaldehyde is released directly into the indoor air from various types of sources. People are exposed to environmental formaldehyde from adhesives, lubricants, wall coverings, rubber, water-based paints, cosmetics, electronic equipment, and glued wood-based products. For instance, formaldehyde is known to be emitted considerably by chipboard, MDF, plywood and other wood-based products containing resins.[5,8] Next to these building materials, formaldehyde is a component of tobacco smoke and of combustion gases from heating stoves and gas appliances. It is used

TOC

as a disinfectant and as a preservative in biological laboratories. It is also used in the fabric and clothing industry.

Major sources of formaldehyde in non-smoking environments are building materials and consumer products. This applies to new materials and products and can last several months, especially in conditions with high relative humidity (RH) and high indoor temperatures.[14–16] Formaldehyde is also one of the main components for resins, which are contained in various products, mainly in wood products. Furthermore, it should be noted that secondary formation of formaldehyde occurs in air through the oxidation of VOCs. However, the influence of these secondary chemical processes to the ambient and indoor concentrations has still not been fully measured.[17]

4.1.2 Health effects of formaldehyde

In general, humans are mainly exposed to formaldehyde through inhalation. Since formaldehyde is soluble in water, it is rapidly absorbed in the respiratory and gastrointestinal tracts and metabolized.[1] Predominant symptoms of formaldehyde exposure in humans are irritation of the eyes, nose and throat, discomfort, sneezing, coughing, nausea, among others.[18] The lowest concentration may cause sensory irritation of the eyes with humans, increasing eye blink frequency and conjunctival redness.[1]

4.1.3 Formaldehyde guidelines and regulations

In the Netherlands, several formaldehyde measurement studies have been executed specially in homes and at schools, where there were complaints which might have been caused by formaldehyde. Several complaints were connected with a concentration above 120 µg/m^3. In Dutch schools the highest concentration measured was 2.5 mg/m^3. In homes, the highest concentrations found were between 0.75 and 1 mg/m^3.[15] In 2011, Van Gemert reported that the odour thresholds for formaldehyde can fluctuate from 0.03 to 2.2 mg/m^3.[19]

WHO 2010 reported that the lowest concentration to cause sensory irritation of the eyes in humans is 0.38 mg/m^3 for four hours.[1] Besides, a formaldehyde concentration of 0.6 mg/m^3 increases eye blink frequency and conjunctival redness. Regarding the perception of odour of formaldehyde, some individuals

reported sensory irritation, and formaldehyde may be perceived at concentrations below 0.1 mg/m^3. However, this is not considered to be an adverse health effect.[1,17,18]

4.1.4 Effects of plants on formaldehyde removal

It has been well established that potted-plants can help to phytoremediate a diverse range of indoor air pollutants. In particular, a substantial body of literature has demonstrated the ability of the potted-plant system to remove VOCs from the indoor air. These findings have largely originated from laboratory-scale chamber experiments, with several studies drawing different conclusions regarding the primary VOC removal mechanism, and removal efficacies.[20–23] The process of VOC depletion found in most studies is through the microbial activity in the substrate and rhizosphere, where bacteria absorb the VOCs and metabolise them as a nutrient source.[22–25]

In 2011, Aydogan and Montoya tested the formaldehyde removal efficiency of the root area and aerial parts independently and found that while the aerial parts of plants were capable of VOC removal, removal by the root area occurred at a substantially faster rate.[25] Other research has identified the potential for the microorganisms existing on and in leaves to remove VOCs.[26,27] However, most recent research has acknowledged that the mechanisms of removal are mainly located in the substrate, rather than the plant itself.[28–30]

Based on the studies mentioned, it is valid to assume that plants together with is substrate can have a positive removal effect on the concentration of formaldehyde in indoor environments. However, the extent to which different plants remove formaldehyde is not well known yet. This paper presents the results of a study on the uptake of formaldehyde and CO_2 from selected potted plants and substrates, with the objective of using the outcome of these experiments to select the best performing plant and substrate for the construction of an indoor plant-based system (biowall).

4.2 Materials and methods

4.2.1 Experimental setup

The setup, schematically presented in Figure 4.1, consisted mainly of a dynamic chamber. The dynamic chamber was made out of glass with an inner diameter of 28 cm, height of 60 cm and volume (V) of 0.033 m^3. The glass chamber had three air entrances that were sealed during the tests. The gas stream of 300 ppb concentration of formaldehyde was released in the chamber by heating the formaldehyde solution.

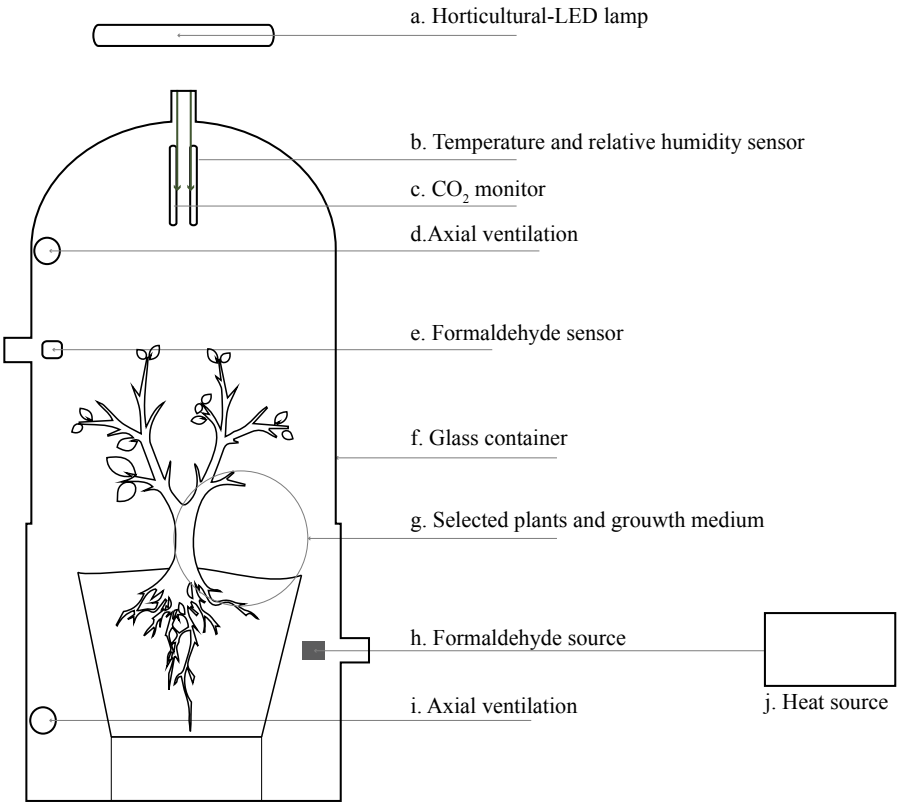

FIG. 4.1 Schematic view of the experimental setup.

TOC

The actual formaldehyde concentration was determined by a formaldehyde sensor (DART-sensor 11 mm, calibrated, ppb-level, lower detection limit of <30 ppb, response time (T90) <30 s, resolution 10 ppb). Two axial fans were placed into the glass chamber to distribute the air evenly within the chamber. The sensor performed a measurement every minute. During the tests a LED growing lamp was activated (1500 $\mu molm^{-2}s^{-1}$ – 1900 $\mu molm^{-2}s^{-1}$), and the temperature, relative humidity and CO_2 levels were also monitored. CO_2 levels were monitored with VAISALA CO_2 probe GMP252 (ppm-level). Furthermore, the glass container was sealed with a solvent free, plastic, self-adhesive sealant, kneading material, based on synthetic rubber during the tests.

4.2.2 Chemicals

The formaldehyde solution used for these experiments was: Solution Sigma F8775, 25 ml (36.5 - 38% formaldehyde in H_2O). The formaldehyde solution was mixed with demi-water in order to generate 300 ppb within the chamber. The mixture was executed by technicians in the laboratories of the University of Wageningen, as follows:

- 10 µl formaldehyde + 90 µl demi-water = 100 µl (final mixture)
- 10 µl of the final mixture generated 300 ppb of formaldehyde, within the chamber.

It is important to report that the formaldehyde solution contained 10-15% of methanol, as stabiliser to prevent polymerisation. The DART-sensor is also sensitive to methanol. So, by introducing formaldehyde, a small amount of methanol was introduced as well. The response of the DART-sensor to this amount of methanol therefore also needed to be tested.

4.2.3 Preparation of the substrates

Three different growth media were chosen for the test: soil, activated carbon and expanded clay. The selected potting soil was composed by peat, green compost, lime and fertilizers. The selection of the substrates was based on previous studies and because they are common substrates available on the market.[24,25] For every type of substrate six tests were executed, three with a dry substrate and three with a wet substrate. The substrates were placed each in a plastic container with a capacity of 1.1 litres (0.0011 m^3) with 0.14 m diameter in the upper part, which was the exposed area of the substrate.

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4.2.4 Preparation of the plant samples

Two different plant species were tested: Spathiphyllum Wallisii Regel (Common name: Peace Lily) and Nephrolepis exaltata L. (Common name: Boston Fern) (Figure 4.2*)*. Three plants of every species were chosen for the tests and they were selected with similar characteristics of age and size (Peace lily: 0.35 m height; Boston fern: 0.30 m height).

FIG. 4.2 Selected plants: a. Spathiphyllum Wallisii Regel (Common name: Peace Lily); and b. Nephrolepis exaltata L. (Common name: Boston Fern) in the glass container.

The plants were selected based on information gathered by previous studies, which demonstrated that the capability of these species in uptake of some VOCs was good.[28,31,32] And they were also chosen because they can be used in Living Wall Systems (LWSs) and/or green walls, besides, they are commonly used for indoor decoration. The plants were bought in a house-plant shop in the Netherlands and were re-potted 25 days prior the experiments, to minimize the stress of the plant, in a 14 cm diameter plastic pot of 1.1 litre (0.0011 m^3) of expanded clay growth medium. The expanded clay was selected as a growth medium for the tests because it is the most common substrate used indoors and it is most suitable to be used in indoor living wall systems. All the plants went through a 30 min acclimatization and adaptation process in the laboratory where they were exposed to similar conditions, in order to minimize the stress of the plants prior the execution of the tests.

4.2.5 Procedure

Two zero-measurement evaluations were performed to establish the conditions of the set-up in the glass container in which the depletion of the formaldehyde took place: one at the beginning of the test series and one at the end. Similarly, two extra zero-measurement evaluations were performed with a plastic container that had the same characteristics of the containers that were used during every test.

The measurements were executed for 1-1.5 hours until the formaldehyde was depleted or stabilized in the chamber. Gas concentrations were measured in ppb in the case of formaldehyde and in ppm in the case of $CO_{2.}$ For further analysis the concentrations of these gases were expressed as micrograms per cubic meter ($\mu g/m^3$) and milligrams per cubic meter, respectively. For each test, ~368.48 $\mu g/m^3$ (~300 ppb) of formaldehyde was released in the chamber to generate every time exactly the same condition.

Each set of experiments was conducted three times, in order to evaluate consistently each condition tested (Tables 4.1 and 4.2). For each test, the glass container was wiped with a wet paper towel after each measurement. The plastic container with the substrate or plant sample was placed in the centre of the glass chamber. Depending on the height of the plant a stainless-steel base was placed at the bottom (stainless steel is an inert material).

A small plate connected to a heat source was placed in the lower hole and 10 µl of formaldehyde solution was placed on the plate with a pipette. After a drop of formaldehyde solution was placed on the plate, the hole was closed, and the heat source was activated in order to realise the solution in the air. This was the beginning of the test. During the tests with the Boston ferns, it was necessary to inject some CO_2 when the level was lower than ~410 ppm (~738 mg/m^3) which is the global atmospheric CO_2 concentration (average outdoor concentration)[33,34] and is sufficient for the plants to grow although some studies have shown that the optimal CO_2 concentration is around 900 ppm.[35]

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To calculate the amount of formaldehyde depleted inside of the chamber the following formula was used:[36]

$$-\lambda = \frac{\ln\left(\frac{N(t)}{N(0)}\right)}{t} \quad [1]$$

With:
λ= Decay rate [h^{-1}]
N(t) = Amount of pollutant after time t [$\mu g/m^3$] or [mg/m^3]
N(0) = Initial amount of pollutant at t = 0h [$\mu g/m^3$] or [mg/m^3]

To calculate the rates of contaminant reduction in the test chamber the Clean Air Delivery Rate (CADR) was calculated:[37,38]

$$CADR = (\lambda e - \lambda n - \lambda p)V \quad [2]$$

With:
λe = Total decay rate [h^{-1}]
λn = Natural decay rate which is the reduction of the contaminant due to natural phenomena in the test chamber [h^{-1}]
λp = Decay rate when the plastic pot was placed in the chamber[h^{-1}]
V = Volume of the chamber [m^3], 0.033 [m^3]

To calculate the removal efficiency of the different test conditions the following formula was used:[36]

$$\eta = \left(\frac{N(0) - N(t)}{N(0)}\right) * 100 \quad [3]$$

With:
η = Efficiency [%]
N(t) = Amount of pollutant after time t [$\mu g/m^3$] or [mg/m^3]
N(0) = Initial amount of pollutant at t = 0h [$\mu g/m^3$] or [mg/m^3]

A portable leaf area meter was used to scan and calculate the leave area of the plant species. Since the three plants of every species had similar characteristics, one plant of every species was selected to be measured (Figure 4.3).

FIG. 4.3 Scan and calculation of the leaf area: a. Peace Lily; b. Boston Fern.

Conversions for chemicals in air were made assuming an air pressure of 1 atmosphere and an air temperature of 25 degrees Celsius. The conversion factor was based on the molecular weight of the chemical and is different for each chemical in this case the molecular weight of formaldehyde is 30.031 g/mol and of the carbon dioxide (CO_2) is 44.01 g/mol:

Concentration [mg/m^3] = 0.0409 x concentration [ppm] x molecular weight [g/mol]
Concentration [ppm] = 24.45 x concentration [mg/m^3] ÷ molecular weight [g/mol]
Concentration [$\mu g/m^3$] = 0.0409 x concentration [ppb] x molecular weight [g/mol]
Concentration [ppb] = 24.45 x concentration [$\mu g/m^3$] ÷ molecular weight [g/mol]

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To stablish the statistical significance of the results, several Independent T-Tests were executed and the mean values and standard errors (± S.E.) were included. Finally, the one-way analysis of variance (ANOVA) was chosen to determine whether there are any statistically significant differences between the means of the tested variables. Additionally, a Pos-Hoc test was also required to confirm where the differences occurred. Based on the nature of this data set, Tukey HSD and the Student-Newman-Keuls were performed to execute a multiple comparison among the groups and to determine homogeneous sets.

4.3 Results

Figures 4.4 to 4.7 show the measured formaldehyde concentrations for the different test configurations. Figures 4.8 presents the measured CO_2 concentrations when the selected potted plants were included. Figure 4.9 presents the measured formaldehyde and CO_2 concentrations when the Boston ferns were included. In general, three measurements were executed for every test condition and the figures present the mean values including standard errors (± SE). In Tables 4.1 and 4.2, the CADRs of respectively formaldehyde and CO_2 depletion inside of the chamber for the different tests is presented. The CADRs were calculated using equations 1 and 2. Tables 4.3 and 4.4 present the statistical analysis of the CADR caused by the selected growth media and selected plants.

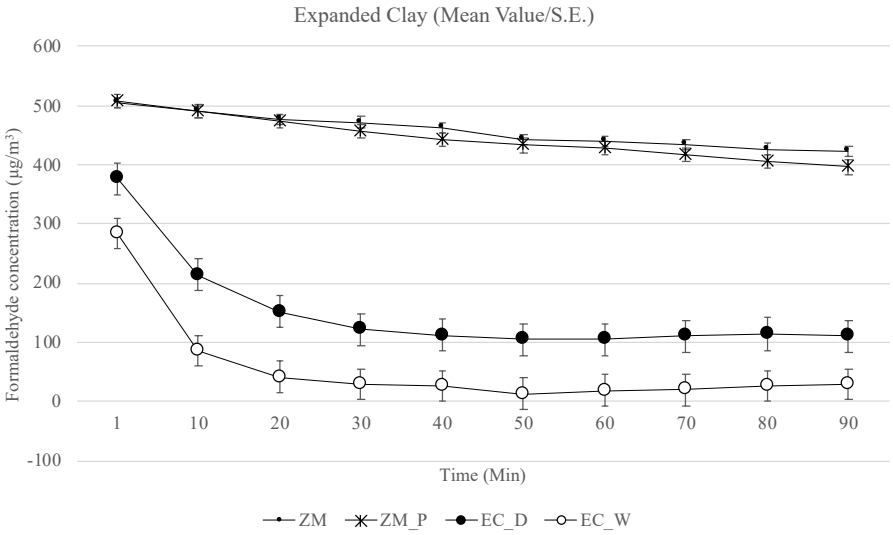

FIG. 4.4 Measured formaldehyde concentration [(μg/m³)/h] when expanded clay samples were tested: zero measurement (ZM), zero measurement with the plastic pot (ZM_P), dry expanded Clay (EC_D), wet expanded Clay (EC_W). Data means ± SE, n=3

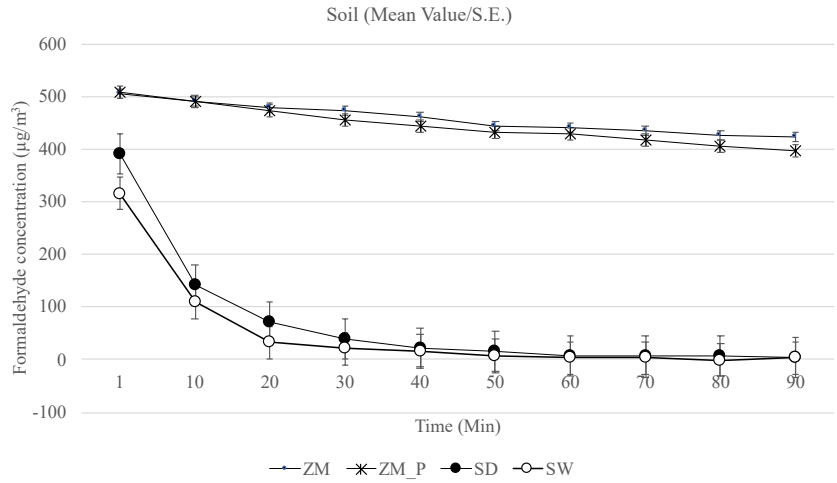

FIG. 4.5 Measured formaldehyde concentration [(μg/m³)/h] when soil samples were tested: zero measurement (ZM1), zero measurement with the plastic pot (ZM_P), dry soil (SD), wet soil (SW). Data means ± SE, n=3.

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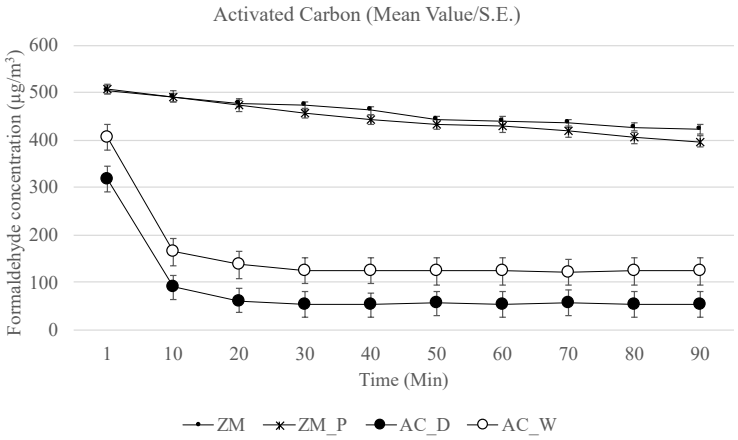

FIG. 4.6 Measured formaldehyde concentration [(µg/m^3)/h] when activated carbon samples were tested: zero measurement (ZM), zero measurement with the plastic pot (ZM_P), dry activated carbon (AC_D), wet activated carbon (AC_W). Data means ± SE, n=3 (AC_D) and, n=2 (AC_W; the third test was excluded).

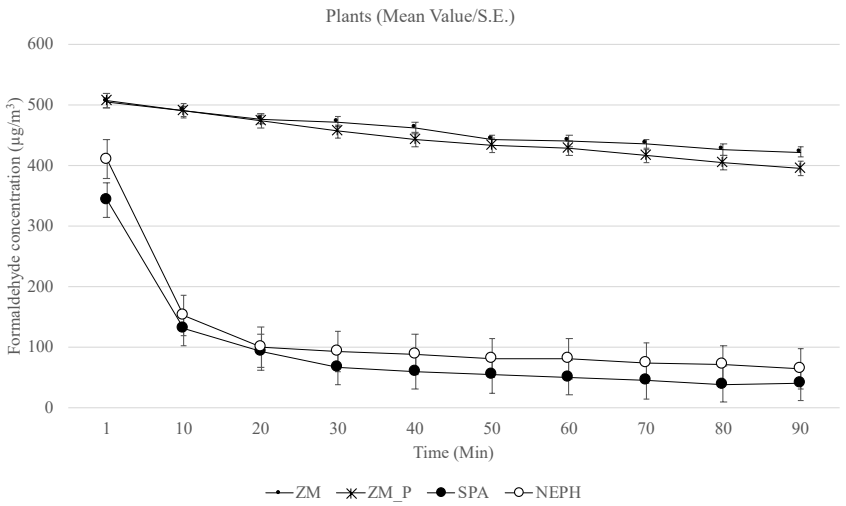

FIG. 4.7 Measured formaldehyde concentration [(µg/m^3)/h] when plant samples were tested: zero measurement (ZM), zero measurement with the plastic pot (ZM_P), Peace Lily (SPA), Boston Fern (NEPH). Data means ± SE, n=3.

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During the zero measurements of the setup, the sensor indicated the presence of around 30.7 µg/m^3 (25 ppb) of formaldehyde in the system. It is believed that this value was due to the calibration process. The zero measurement tests indicated that the formaldehyde decreased slowly in the chamber (Figures 4.4-4.7), which could be the natural decay of the gas or because it was partially adsorbed by the setup. When the plastic container was placed inside of the chamber the reduction slightly increased, which shows that the formaldehyde was adsorbed by the container. These two values have to be taken in account when analysing the real effect of the substrates and plants regarding formaldehyde depletion (Table 4.1). Therefore, to calculate the CADR and establish the real air-cleansing-impact of every test condition, the natural decay of the chamber ($\lambda n = 0.11\ h^{-1}$) and the decay rate of the plastic container ($\lambda p = 0.15\ h^{-1}$) were subtracted from the total decay rate (Tables 4.1 and 4.2).

Figure 4.4 presents the depletion of formaldehyde when expanded clay was tested, under dry and wet conditions, indicating that wet expanded clay was more effective on depleting formaldehyde than under dry conditions. Among all the conditions tested, soil was the most effective element to reduce formaldehyde in the chamber, especially under wet conditions (Figure 4.5). Figure 4.6 shows that activated carbon under dry conditions was more efficient than under wet conditions in reducing formaldehyde in the chamber.

Regarding formaldehyde depletion, potted plants (0.03 m^3/h) were as effective as dry activated carbon (0.03-0.04 m^3/h), less effective in general than soil (0.07-0.16 m^3/h), less effective than wet expanded clay (0.04-0.16 m^3/h) and as effective as dry expanded clay (0.02-0.04 m^3/h) (Table 4.1). The selected plants (Boston Fern and Peace Lily) present similar performance regarding formaldehyde removal (Figure 4.7).

With regards to CO_2 levels, potted plants seemed to be the only test condition that reduced CO_2, of which Boston fern was the most effective (Table 4.2). While in the case of activated carbon and soil, the levels of CO_2 seemed to increase in the chamber.

TABLE 4.1 CADR of formaldehyde depletion inside of the chamber.

Test N.	Test Condition		RH* (%)	T* (°C)	Time (h)	N(0) (mg/m^3)	N(t) (mg/m^3)	λe $(h)^{-1}$	λn $(h)^{-1}$	λp $(h)^{-1}$	CADR (m^3/h)	η (%)
1	**Zero measurement 1**	(ZM_1)	53	24	2.38	481.48			0.09			
2	**Zero measurement 2**	(ZM_2)	59	24	1.52	524.47			0.13			
3	**Zero measurement_Pot 1**	(ZMP_1)	43	24	2.10	498.68				0.16		
4	**Zero measurement_Pot 2**	(ZMP_2)	58	24	1.52	515.87				0.14		
5	**Dry Expanded Clay 1**	(EC_D_1)	85	25	1.55	363.57	98.26	0.84			0.02	73
6	**Dry Expanded Clay 2**	(EC_D_2)	83	24	1.13	335.32	70.01	1.38			0.04	79
7	**Dry Expanded Clay 3**	(EC_D_3)	57	24	1.60	431.12	116.69	0.82			0.02	73
8	**Wet Expanded Clay 1**	(EC_W_1)	93	26	1.10	308.30	1.23	5.02			0.16	100
9	**Wet Expanded Clay 2**	(EC_W_2)	92	25	1.10	368.48	22.11	2.56			0.08	94
10	**Wet Expanded Clay 3**	(EC_W_3)	95	24	1.65	174.41	17.20	1.40			0.04	90
11	**Dry Soil 1**	(S_D_1)	92	24	1.27	389.36	2.46	4.00			0.12	99
12	**Dry Soil 2**	(S_D_2)	93	24	1.50	336.55	4.91	2.82			0.08	99
13	**Dry Soil 3**	(S_D_3)	93	25	1.43	447.09	13.51	2.44			0.07	97
14	**Wet Soil 1****	(S_W_1)	91	25	1.07	197.75	1.00	4.96			0.16	99
15	**Wet Soil 2**	(S_W_2)	96	24	1.38	366.02	1.23	4.12			0.13	100
16	**Wet Soil 3**	(S_W_3)	93	24	1.48	381.99	1.23	3.87			0.12	100
17	**Dry Activated Carbon 1**	(AC_D_1)	41	25	1.42	296.01	39.30	1.43			0.04	87
18	**Dry Activated Carbon 2**	(AC_D_2)	43	24	1.52	297.24	45.45	1.24			0.03	85
19	**Dry Activated Carbon 3**	(AC_D_3)	50	24	1.49	358.65	67.55	1.13			0.03	81
20	**Wet Activated Carbon 1**	(AC_W_1)	95	25	1.57	383.22	126.51	0.71			0.01	67
21	**Wet Activated Carbon 2**	(AC_W_2)	93	26	1.25	428.67	128.97	0.96			0.02	70
22	**Wet Activated Carbon 3**	(AC_W_3)	91	24	0.75	356.20	1469.01	-1.89			-	
23	**Peace Lily 1**	(SPA_1)	95	24	1.77	311.98	41.76	1.14			0.03	87
24	**Peace Lily 2**	(SPA_2)	95	24	1.67	367.25	44.22	1.27			0.03	88
25	**Peace Lily 3**	(SPA_3)	94	24	1.72	348.83	46.67	1.17			0.03	87
26	**Boston fern 1**	(NEPH_1)	93	24	1.63	390.59	58.96	1.16			0.03	85
27	**Boston fern 2**	(NEPH_2)	94	24	1.58	413.93	67.55	1.14			0.03	84
28	**Boston fern 3**	(NEPH_3)	95	24	1.55	427.44	74.92	1.12			0.03	82

* Mean values

** The measured formaldehyde concentration was 0<, the value used for the calculation was N(t)=1 ($\mu g/m^3$)

Average values used for the calculations: $\lambda n=0.11(h)^{-1}$; $\lambda p=0.15(h)^{-1}$

TABLE 4.2 CADR of CO2 depletion inside of the chamber

Test N.	Test Condition		RH*	T*	Time	N(0)	N(t)	λe	λn	λp	CADR	η
			(%)	(°C)	(h)	(mg/m^3)	(mg/m^3)	(h)$^{-1}$	(h)$^{-1}$	(h)$^{-1}$	(m^3/h)	(%)
1	**Zero measurement 1**	(ZM_1)	53	24	2.38	756.00			0			
2	**Zero measurement 2**	(ZM_2)	59	24	1.52	887.40			0			
3	**Zero measurement_Pot 1**	(ZMP_1)	43	24	2.10	1024.21				0		
4	**Zero measurement_Pot 2**	(ZMP_2)	58	24	1.52	1054.81				0		
5	**Dry Expanded Clay 1**	(EC_D_1)	85	25	1.55	1368.01		0			-	
6	**Dry Expanded Clay 2**	(EC_D_2)	83	24	1.13	1297.81	1281.61	0.01			0.00	1
7	**Dry Expanded Clay 3**	(EC_D_3)	57	24	1.60	1243.81		0			-	
8	**Wet Expanded Clay 1**	(EC_W_1)	93	26	1.10	1018.81		0			-	
9	**Wet Expanded Clay 2**	(EC_W_2)	92	25	1.10	1051.21	1031.41	0.02			0.00	2
10	**Wet Expanded Clay 3**	(EC_W_3)	95	24	1.65	1351.81	1323.01	0.01			0.00	2
11	**Dry Soil 1**	(S_D_1)	92	24	1.27	977.40		-0.05			-	
12	**Dry Soil 2**	(S_D_2)	93	24	1.50	1146.61		-0.04			-	
13	**Dry Soil 3**	(S_D_3)	93	25	1.43	1099.81		-0.04			-	
14	**Wet Soil 1**	(S_W_1)	91	25	1.07	851.40		-0.13			-	
15	**Wet Soil 2**	(S_W_2)	96	24	1.38	932.40		-0.18			-	
16	**Wet Soil 3**	(S_W_3)	93	24	1.48	981.00		-0.14			-	
17	**Dry Activated Carbon 1**	(AC_D_1)	41	25	1.42	2190.61		-0.21			-	
18	**Dry Activated Carbon 2**	(AC_D_2)	43	24	1.52	1002.61		-0.06			-	
19	**Dry Activated Carbon 3**	(AC_D_3)	50	24	1.49	1033.21		-0.01			-	
20	**Wet Activated Carbon 1**	(AC_W_1)	95	25	1.57	1432.81		-0.48			-	
21	**Wet Activated Carbon 2**	(AC_W_2)	93	26	1.25	1222.21		-0.09			-	
22	**Wet Activated Carbon 3**	(AC_W_3)	91	24	0.75	1272.61		-0.17			-	
23	**Peace Lily 1**	(SPA_1)	95	24	1.77	1146.61	885.60	0.15			0.01	23
24	**Peace Lily 2**	(SPA_2)	95	24	1.67	1288.81	925.20	0.20			0.01	28
25	**Peace Lily 3**	(SPA_3)	94	24	1.72	1337.41	963.00	0.19			0.01	28
26	**Boston fern 1**	(NEPH_1)	93	24	1.37	1002.61	351.00	0.77			0.03	65
27	**Boston fern 2**	(NEPH_2)	94	24	0.97	1202.41	718.20	0.53			0.02	40
28	**Boston fern 3**	(NEPH_3)	95	24	0.92	1126.81	718.20	0.49			0.02	36

** Mean values measured in the chamber*

Table 4.1 shows that under dry conditions inside of the chamber, the selected soil adsorbed formaldehyde faster than the other substrates, while the performance of the dry expanded clay was the lowest. The wet soil and expanded clay performed better than the dry conditions tested. Furthermore, Table 1 shows that the selected plants together with the substrate did not perform as well as the wet substrates, but, in general, they performed better than the dry substrates with the exception of the dry soil. Regarding leaf area, the selected plants had similar characteristics in size and number of leaves, therefore, for every species one plant was selected and all its

leaves were measured. Consequently, it was considered that the area of the other two plants of the selected species were in the same area range. In general, the peace lilies (approx. 0.14 m^2) had more leaf area than the Boston ferns (approx. 0.11 m^2).

Table 4.3 presents the statistical analysis of the CADR of formaldehyde depletion caused by the selected growth media. It shows that soil has a better performance than the other samples. Regarding the data set of formaldehyde depletion, and once it was established the statistically significant differences between the means of the tested variables (P=0.00) with ANOVA, the differences between the variables were analysed in Tables 4.4 and 4.5. Table 4.4 presents the statistical difference among the variables.

It shows that mainly wet soil has statistical differences with the other analysed variables. Table 4.5 indicates three homogeneous subsets among the variables in terms of formaldehyde depletion. Within a subset there is no significance different while between subsets there is a significant difference. It is clear that Group 3 (wet soil, dry soil, wet expanded clay) is significantly different from Group 1 (wet activated carbon, dry activated carbon, dry expanded clay, peace lily, Boston fern).

TABLE 4.3 Statistical analysis of the CADR of the formaldehyde depletion caused by the selected growth media

	Dry expanded clay	Wet expanded clay	Dry soil	Wet soil	Dry activated carbon	Wet activated carbon
Mean	0.02	0.09	0.09	0.13	0.03	0.02
SD*	0.01	0.06	0.03	0.02	0.01	0.01
SE**	0.01	0.04	0.02	0.01	0.00	0.00

** SD: Standard Deviation*
*** SE: Standard Error*

TABLE 4.4 Multiple Comparisons (Tukey HSD); Dependent Variable: CADR for formaldehyde.

(I) What is the variable?	(J) What is the variable?	(I-J) Mean Difference	Std. Error	Sig.
Dry Expanded Clay	**Wet Expanded Clay**	-0.067	0.021	0.093
	Dry Soil	-0.063	0.021	0.122
	Wet Soil	-0.110*	0.021	0.002
	Dry Activated Carbon	-0.007	0.021	1.000
	Wet Activated Carbon	0.012	0.024	1.000
	Peace Lily	-0.003	0.021	1.000
	Boston Fern	-0.003	0.021	1.000

>>>

TABLE 4.4 Multiple Comparisons (Tukey HSD); Dependent Variable: CADR for formaldehyde.

(I) What is the variable?	(J) What is the variable?	(I-J) Mean Difference	Std. Error	Sig.
Wet Expanded Clay	Dry Expanded Clay	0.067	0.021	0.093
	Dry Soil	0.003	0.021	1.000
	Wet Soil	-0.043	0.021	0.488
	Dry Activated Carbon	0.060	0.021	0.159
	Wet Activated Carbon	0.078	0.024	0.070
	Peace Lily	0.063	0.021	0.122
	Boston Fern	0.063	0.021	0.122
Dry Soil	Dry Expanded Clay	0.063	0.021	0.122
	Wet Expanded Clay	-0.003	0.021	1.000
	Wet Soil	-0.047	0.021	0.403
	Dry Activated Carbon	0.057	0.021	0.205
	Wet Activated Carbon	0.075	0.024	0.090
	Peace Lily	0.060	0.021	0.159
	Boston Fern	0.060	0.021	0.159
Wet Soil	Dry Expanded Clay	0.110*	0.021	0.002
	Wet Expanded Clay	0.04	0.021	0.488
	Dry Soil	0.05	0.021	0.403
	Dry Activated Carbon	0.103*	0.021	0.004
	Wet Activated Carbon	0.122*	0.024	0.002
	Peace Lily	0.107*	0.021	0.003
	Boston Fern	0.107*	0.021	0.003
Dry Activated Carbon	Dry Expanded Clay	0.01	0.021	1.000
	Wet Expanded Clay	-0.06	0.021	0.159
	Dry Soil	-0.06	0.021	0.205
	Wet Soil	-0.103*	0.021	0.004
	Wet Activated Carbon	0.02	0.024	0.992
	Peace Lily	0.00	0.021	1.000
	Boston Fern	0.00	0.021	1.000
Wet Activated Carbon	Dry Expanded Clay	-0.01	0.024	1.000
	Wet Expanded Clay	-0.08	0.024	0.070
	Dry Soil	-0.08	0.024	0.090
	Wet Soil	-0.122*	0.024	0.002
	Dry Activated Carbon	-0.02	0.024	0.992
	Peace Lily	-0.02	0.024	0.998
	Boston Fern	-0.02	0.024	0.998

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TABLE 4.4 Multiple Comparisons (Tukey HSD); Dependent Variable: CADR for formaldehyde.

(I) What is the variable?	(J) What is the variable?	(I-J) Mean Difference	Std. Error	Sig.
Peace Lily	Dry Expanded Clay	0.00	0.021	1.000
	Wet Expanded Clay	-0.06	0.021	0.122
	Dry Soil	-0.06	0.021	0.159
	Wet Soil	-0.107*	0.021	0.003
	Dry Activated Carbon	0.00	0.021	1.000
	Wet Activated Carbon	0.02	0.024	0.998
	Boston Fern	0.00	0.021	1.000
Boston Fern	Dry Expanded Clay	0.00	0.021	1.000
	Wet Expanded Clay	-0.06	0.021	0.122
	Dry Soil	-0.06	0.021	0.159
	Wet Soil	-0.107*	0.021	0.003
	Dry Activated Carbon	-0.003	0.021	1.000
	Wet Activated Carbon	0.015	0.024	0.998
	Peace Lily	0.000	0.021	1.000

** The mean difference is significant at the 0.05 level.*

TABLE 4.5 Homogeneous Subsets; Dependent Variable: CADR for formaldehyde.

	What is the variable?	N	Subset for alpha = 0.05		
			1	2	3
Student-Newman-Keuls	Wet Activated Carbon	2	0.015		
	Dry Expanded Clay	3	0.027	0.027	
	Peace Lily	3	0.030	0.030	
	Boston Fern	3	0.030	0.030	
	Dry Activated Carbon	3	0.033	0.033	
	Dry Soil	3		0.090	0.090
	Wet Expanded Clay	3		0.093	0.093
	Wet Soil	3			0.137
	Sig.		0.914	0.072	0.116
Tukey HSD	Wet Activated Carbon	2	0.015		
	Dry Expanded Clay	3	0.027	0.027	
	Peace Lily	3	0.030	0.030	
	Boston Fern	3	0.030	0.030	
	Dry Activated Carbon	3	0.033	0.033	
	Dry Soil	3	0.090	0.090	0.090
	Wet Expanded Clay	3		0.093	0.093
	Wet Soil	3			0.137
	Sig.		0.056	0.110	0.437

Means for groups in homogeneous subsets are displayed.

TABLE 4.6 Statistical analysis of the CADR of formaldehyde and CO2 depletion caused by the selected plants.

	Formaldehyde		CO_2	
	Peace lily	Boston fern	Peace lily	Boston fern
Mean	0.03	0.03	0.01	0.02
SD*	0.00	0.00	0.00	0.00
SE**	0.00	0.00	0.00	0.00

** SD: Standard Deviation*
*** SE: Standard Error*

Table 4.6 presents the statistical analysis of the CADR of formaldehyde and CO_2 depletion caused by the selected plants. Regarding formaldehyde depletion, both species showed the same performance. Regarding CO_2 depletion, Boston ferns showed a better performance than Peace lilies. Regarding the data set of CO_2 depletion, independent T-tests were executed to establish whether a statistically significant difference occurred of the depletion of CO_2 between the selected plants, the results showed that Boston ferns depleted statistically significantly more CO_2 than the peace lilies (P=0.02).

4.4 Discussion

This study provides data for the characterization of the removal of formaldehyde by three different substrates and two different potted plants. Four series of zero measurements were executed to evaluate the setup. Two measurements of these series were executed with a plastic pot to evaluate the effect of this element in the depletion of the formaldehyde inside of the chamber. As expected, once the plastic pot was placed in the chamber the formaldehyde level was lower than the natural decay measured during the zero-measurement evaluation. This value was used to calculate the CADR for every test condition as shown in Tables 4.1 and 4.2.

4.4.1 Depletion of formaldehyde

Exploration of the potential of plants to purify air from pollutants started in the early 1980s[23,39] and to date several plant species have been studied and identified for use in formaldehyde removal. However, previous studies have tested extremely high concentrations of formaldehyde (over ~2000 mg/m^3),[21] higher than the

TOC

concentrations that are usually found in common indoor environments.[1] This study, presents the results of the uptake of formaldehyde with a concentration of 300 ppb (0.37 mg/m^3), which is within the boundaries of the detection threshold of formaldehyde indoors (0.03 mg/m^3-0.6 mg/m^3)[1] and close to the guideline value based on sensory effects (0.1 mg/m^3).[1] Furthermore, formaldehyde is soluble in water,[1] therefore, it may be depleted faster in wet environments.[25] In a study published in 2011, Aydogan and Montoya reported that activated carbon alone showed the highest formaldehyde removal and the four plant species studied demonstrated similar abilities to remove formaldehyde.[25] During this set of experiments, the reduction of formaldehyde concentration inside of the chamber was faster when wet substrates were present, the plant species have similar behaviour in formaldehyde removal (~0.03 m^3/h). However, activated carbon appeared to be a very unstable component. In none of the cases, activated carbon had an optimal performance. Figure 4.6 presents the results of the effect of dry activated (AC_D; n=3), and wet activated carbon (AC_W; n=2) on the depletion of formaldehyde in the chamber. The third sample of wet activated carbon was excluded because instead of reducing the formaldehyde concentration, the wet activated carbon released it into the chamber. The third sample of the wet activated carbon came from a different package than the other samples. The packaging material most likely was polluted, which might have caused the unstable behaviour of the selected substrate.

Previous studies suggest that the depletion of formaldehyde also occurs due to photosynthesis and metabolism of the plant at daytime.[40] A growing light was used during this test to ensure the optimal conditions of the plant.

Studies with potted plants in closed chambers continue to be useful for isolating factors that may enhance removal efficiency and contribute towards the improvement of plant-based systems (e.g., plant species and growth medium). Therefore, it is recommended to use the lessons learned from this study in creating a plant-assisted botanical purifier (“Biowalls” or active green walls), which mechanically forces the air to pass through the leaves and the roots.[23,41,42]

4.4.2 Depletion of CO_2

For the evaluation of the reduction of CO_2 levels inside of the chamber, it is important to mention that in general, plants regulate the internal CO_2 concentration through a partial stomatal closure when the CO_2 concentration is too elevated to maintain adequate internal CO_2 and optimize water use efficiency.[43] Stomata are pores on leaf epidermis for both water and CO_2 fluctuations that are controlled by two

major factors: stomatal behaviour and density.[44,45] The fast speed opening and closing of the stomata can save energy and increase photosynthesis and water use efficiency.[46] Taking this in account, Table 4.2 and Figure 4.8 present the depletion of CO_2 inside the chamber when the potted plants were present, and they show that even though the leave area of the Boston fern is lower than the peace lily, the depletion of CO_2 inside of the chamber was faster when the Boston fern was in the chamber. In order to ensure the optimal behaviour of the plant during the experiments levels of CO_2 were controlled.[43–45] Figure 4.8 shows that in order to provide the optimal conditions for the plant it was necessary to inject CO_2 inside of the chamber because the concentration was too low for the plants.[33,34] In each test condition, activated carbon permanently released CO_2 inside of the chamber, which, possibly could be compensated by the uptake of CO_2 by the plants.

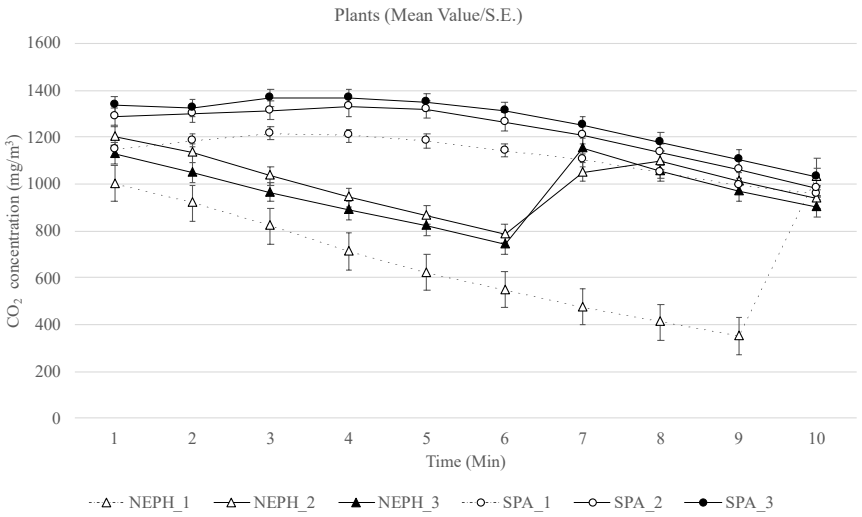

FIG. 4.8 Depletion of CO_2 (mg/m^3): for the three Boston Fern (NEPH_1, NEPH_2, and NEPH_3) and for the three Peace Lilies (SPA_1, SPA_2, and SPA_3). Data means ± SE, n=3.

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4.4.3 Plants vs. growth media

Formaldehyde and CO_2 were used as indicators of the effect of growth media and plants in reducing gaseous pollutants in a controlled environment. Table 1 shows that, in general, growth media were more effective in the depletion of formaldehyde inside of the chamber than the plants. Regarding CO_2 reduction inside of the chamber, as expected, Table 4.2 shows that plants were more effective than growth media: in most of the cases with only a growth medium present, CO_2 was released instead of reduced inside of the glass chamber. Figure 4.9 presents the different behaviours of the potted plants regarding these two elements. Even though the leave area of the Boston fern (approx. 0.11 m^2) was smaller than the peace lily (approx. 0.14 m^2), the Boston ferns reduced the concentration of CO_2 inside of the chamber faster than the peace lilies, which indicates that the stomatal conductance of the Boston fern was higher than the peace lily, opening the hypothesis about the uptake of more gaseous pollutants by the stomata. Regarding the depletion of formaldehyde, Tables 4.4 and 4.5 show that wet soil, dry soil and expanded clay perform similarly and they are more effective than the other variables tested (Table 4.3).

As mentioned before formaldehyde is soluble in water.[1] However, this study shows that high levels of humidity seemed to have no effect on the formaldehyde depletion inside of the chamber as in most of the test conditions the relative humidity level was above 90%. Nonetheless, it is important to mention that in the case of the plants, high humidity levels may affect the depletion of the CO_2 and the formaldehyde inside of the chamber due to the fact that plants close their stomata at high humidity levels.[44,45] The temperature was quite stable during the experiments (Table 4.1 and 4.2), therefore, it seemed to have no effect on the formaldehyde and CO_2 depletion, but in general in the presence of wet growth media the depletion of formaldehyde was faster. Regarding the effect of the growth media on the depletion of formaldehyde and CO_2, it is important to mention that when the substrate (wet or dry) was tested without the plant, the whole surface of the substrate was exposed directly to formaldehyde and CO_2. However, when the plants were included, the exposed surface of the selected substrate was reduced and the results show that the depletion also was lower, which indicates that the efficacy of the growth media, in some cases, was higher. This effect is produced by the microbial activity in the root zone, where bacteria absorb the gaseous pollutants and metabolise them.[22–25]

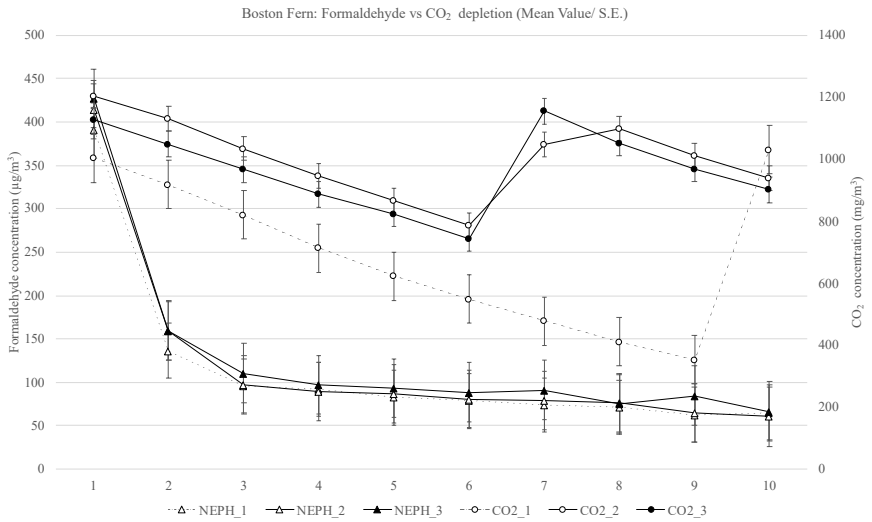

FIG. 4.9 Depletion of formaldehyde (NEPH_1, NEPH_2, and NEPH_3) vs depletion of CO_2 (CO2_1, CO2_2, and CO2_3): for the three Boston Ferns. Data means ± SE, n=3.

4.4.4 Potted plants and their effect in the indoor air quality

According to the ASHRAE standard 62.1-2016 the minimum ventilation rate in breathing zones in office spaces is 0.3 l/s, m^2 (1.08 m^3/h for every one square meter of floor space),[47] likewise, the standard NEN-EN 15251-2007 the minimum ventilation rate for new buildings and renovations is 0.35 l/s, m^2 (1.26 m^3/h for every one square meter of floor space) for very low polluting buildings.[48] Table 4.1 presents that the CADR for formaldehyde depletion of the potted plants is 0.03 m^3/h, therefore, it is necessary to have 42 plants for every square meter of floor space in order to meet the standards without any additional ventilation system. Besides, Table 4.2 presents that the CADR for CO_2 depletion of the potted plants is 0.01 m^3/h (Peace lily*)* and 0.02 m^3/h (Boston fern). Therefore, it is necessary to have >100 plants for every square meter of floor space in order to meet the standards without any additional ventilation system. Therefore, without any extra mechanical ventilation it is necessary an indoor forest to meet the minimum standards for ventilation rates in breathing zones just with plants, however, in real situations less plants will be required taking in account the size of the room and the ventilation system of every case.

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4.4.5 Limitations

One of the limitations of this group of tests is the size of the chamber. Even though it has the requirements of a sealed glass container with the necessary inlets, for future research it is recommended to execute the tests in a bigger sealed glass container to prevent or reduce the stress of the plant, avoiding the closure of its stomata and reducing its metabolism.

As mentioned before, plant stress should be minimized, therefore, for future experiments the plant should be placed in the chamber one day prior the execution of the test together with the activated growing light.

4.5 Conclusions and Recommendations

A series of tests was performed to evaluate the effect of potted plants on reducing formaldehyde and CO_2 levels in a controlled glass chamber. The outcome of the tests showed some clear advantages and disadvantages of the different test conditions to consider for the design of an indoor plant-based system.

In terms of air 'cleaning' of formaldehyde, the measurements and analysis showed that soil, in general, was most effective in reducing formaldehyde concentrations in the chamber (~0.07-0.16 m^3/h). Plants (~0.03 m^3/h) were as effective as dry expanded clay (0.02-0.04 m^3/h). Wet and dry soil, wet expanded clay and dry activated carbon performed better than the selected plants in formaldehyde depletion. In this study, it became clear that the substrate is an important ally in reducing gaseous pollutants, such as formaldehyde.

Regarding CO_2 reduction in the chamber, potted plants (Peace lilies - 0.01 m^3/h) (Boston ferns 0.02-0.03 m^3/h) were more effective than the other tests. Specially, Boston fern which has a higher stomatal conductance than the peace lily, indicating the possibility of allowing more gaseous pollutants to be absorbed in the long term.

Studies with potted plants in closed chambers showed to be useful for isolating factors that may enhance removal efficiency and contribute towards the improvement of plant-based systems (e.g., plant species and growth medium). However, the impact of one potted plant on the cleaning of the indoor air, was

insignificant. Therefore, several potted plants will be required to improve the IAQ taking in account the specific characteristics of the place such as, size and the ventilation system.

It must be noted, however, that in this study the formaldehyde was introduced in a glass chamber in which the plant and its substrate were located, hereby surrounding the plant and its substrate with formaldehyde. In a 'normal' indoor environment, usually the source of formaldehyde may not be close to the plant system. For the plant-system to take-up the formaldehyde, the polluted air needs to be transported to the vicinity of the plant. This could be realised, for example, by an active plant-substrate system, in which the contaminated air is forced to go through the plant-leaves and through the substrate-roots. Further research with active plant-based systems on the depletion of formaldehyde and other pollutants, is required.

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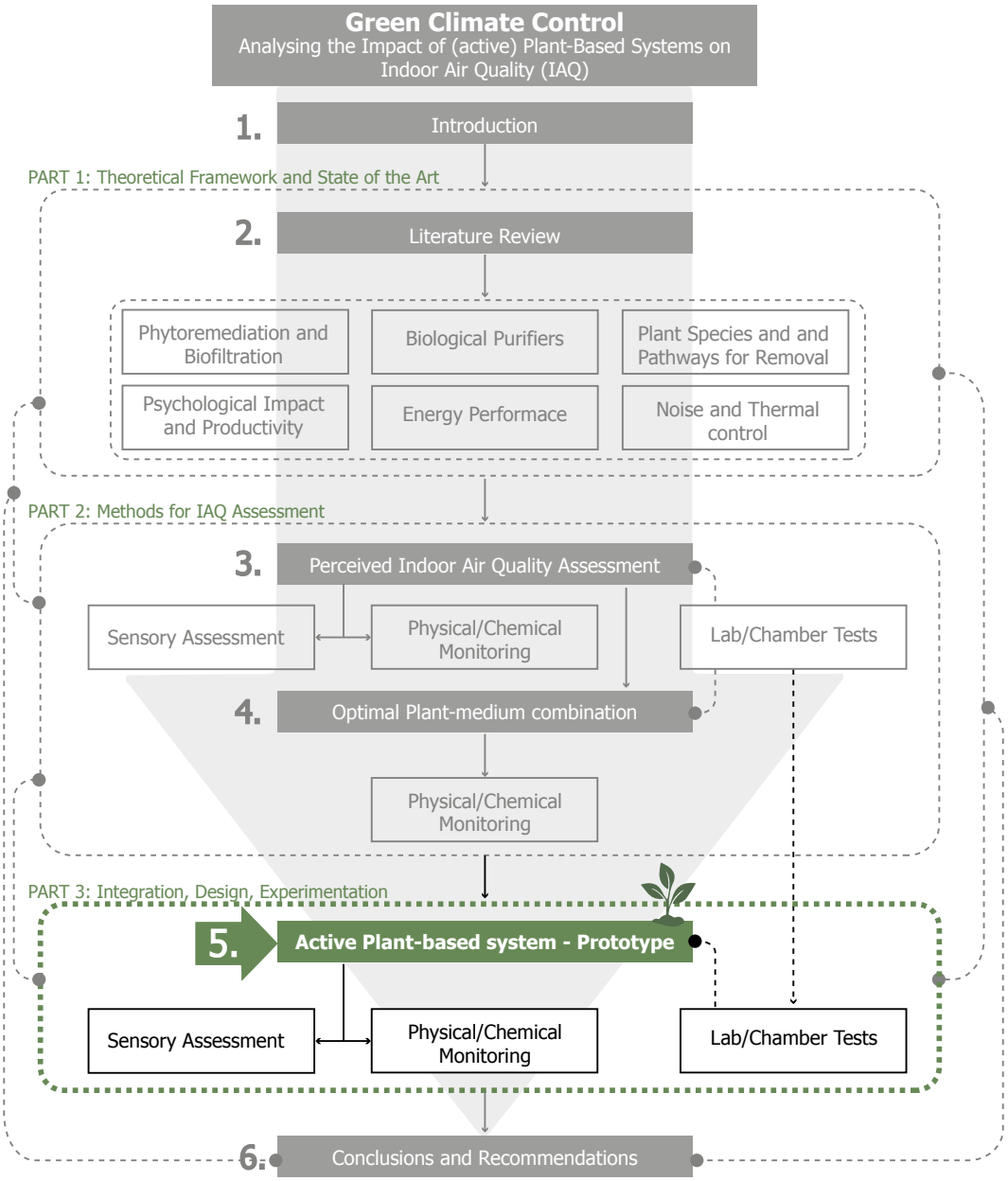
References

1 WHO. WHO guidelines for indoor air quality: selected pollutants. World Health Organization, 2010.
2 Kotzias D, Koistinen K, Schlitt C, et al. The INDEX Project: Final Report for Critical Appraisal of the Setting and Implementation of Indoor Exposure Limits in the EU. 2005. Ispra, Italy: Institute for Health and Consumer Protection.
3 Kotzias D. Indoor air and human exposure assessment - needs and approaches. Exp Toxicol Pathol 2005; 57: 5-7.
4 Brown SK, Sim MR, Abramson MJ, et al. Concentrations of Volatile Organic-Compounds in Indoor Air - a Review. Indoor Air-International Journal of Indoor Air Quality and Climate 1994; 4: 123-134.
5 Bluyssen PM, de Oliveira Fernandes E, Groes L, et al. European indoor air quality audit project in 56 office buildings. Indoor Air-International Journal of Indoor Air Quality and Climate 1996; 6: 221-238.
6 Bluyssen PM, Cochet C, Fischer M, et al. Evaluation of VOC emissions from building products: Solid flooring materials. Report no. Report No. 18, 1997. European Collaborative Action.
7 Sofuoglu SC, Aslan G, Inal F, et al. An assessment of indoor air concentrations and health risks of volatile organic compounds in three primary schools. Int J Hyg Envir Heal 2011; 214: 38-46.
8 Campagnolo D, Saraga DE, Cattaneo A, et al. VOCs and aldehydes source identification in European office buildings - The OFFICAIR study. Build Environ 2017; 115: 18-24.
9 Yu C and Crump D. A review of the emission of VOCs from polymeric materials used in buildings. Build Environ 1998; 33: 357-374.
10 Bluyssen PM. The Indoor Environment Handbook: How to make buildings healthy and comfortable. London, UK: Taylor&Francis, 2009.
11 Wolkoff P. Trends in Europe to reduce the indoor air pollution of VOCs. Indoor Air 2003; 13: 5-11.
12 IARC. Formaldehyde, 2-butoxyethanol and 1-tert-butoxy-2-propanol. Lyon: International Agency for Research on Cancer, 2006.
13 Nielsen GD and Wolkoff P. Cancer effects of formaldehyde: a proposal for an indoor air guideline value. Arch Toxicol 2010; 84: 423-446.
14 Salthammer T, Mentese S and Marutzky R. Formaldehyde in the Indoor Environment. Chem Rev 2010; 110: 2536-2572.
15 Knoeppel H ML, Seifert B. Indoor Air Pollution by Formaldehyde in European Countries. Report no. 7, 1990. European Collaborative Action.
16 Haghighat F and De Bellis L. Material emission rates: Literature review, and the impact of Indoor air temperature and relative humidity. Build Environ 1998; 33: 261-277.
17 Kaden D MC, Nielsen GD, Wolkoff P. Formaldehyde. WHO guidelines for indoor air quality: selected pollutants. World Health Organization, 2010, pp.103-156.
18 WHO. Organic pollutants. Air Quality Guidelines for Europe. Second Edition ed.: World Health Organization, 2000, pp.58-121.
19 Van Gemert LJ. Compilations of odour threshold values in air, water and other media. Part 1: Odour Threshold values in Air. The Nehterlands: Oliemans, Punter & Partners BV, 2011, pp.11-181.
20 Soreanu G, Dixon M and Darlington A. Botanical biofiltration of indoor gaseous pollutants - A mini-review. Chem Eng J 2013; 229: 585-594.
21 Dela Cruz M, Christensen JH, Thomsen JD, et al. Can ornamental potted plants remove volatile organic compounds from indoor air? - a review. Environ Sci Pollut R 2014; 21: 13909-13928.

22 Irga PJ, Pettit TJ and Torpy FR. The phytoremediation of indoor air pollution: a review on the technology development from the potted plant through to functional green wall biofilters. Rev Environ Sci Bio 2018; 17: 395-415.
23 Armijos Moya T, van den Dobbelsteen A, Ottelé M, Bluyssen PM. A review of green systems within the indoor environment. *Indoor Built Environ.* 2019;28(3):298-309.
24 Wolverton BC, Johnson A and Bounds K. Interior Landscape Plants for Indoor Air Pollution Abatement, Final Report NASA (NASA-TM-101766, NAS 1.15:101766). National Aeronautics and Space Administration 1989: 1-22. Technical Report.
25 Aydogan A and Montoya LD. Formaldehyde removal by common indoor plant species and various growing media. Atmos Environ 2011; 45: 2675-2682.
26 Sandhu A, Halverson LJ and Beattie GA. Bacterial degradation of airborne phenol in the phyllosphere. Environ Microbiol 2007; 9: 383-392.
27 Khaksar G TC, Thiravetyan P. Effect of endophytic Bacillus cereus ERBP inoculation into non-native host: potentials and challenges for airborne formaldehyde removal. Plant Physiol Bioch 2016: 326-336.
28 Wood RA, Orwell RL, Tarran J, et al. Potted-plant/growth media interactions and capacities for removal of volatiles from indoor air. J Hortic Sci Biotech 2002; 77: 120-129.
29 Orwell RL, Wood RL, Tarran J, et al. Removal of benzene by the indoor plant/substrate microcosm and implications for air quality. Water Air Soil Poll 2004; 157: 193-207.
30 Kim KJ, Kil MJ, Song JS, et al. Efficiency of volatile formaldehyde removal by indoor plants: Contribution of aerial plant parts versus the root zone. J Am Soc Hortic Sci 2008; 133: 521-526.
31 Wolverton BC and Wolverton JD. Plants and soil microorganisms: removal of formaldehyde, xylene, and ammonia from the indoor environment. Journal of the Mississippi Academy of Sciences 1993; 38: 11-15.
32 Liu YJ, Mu YJ, Zhu YG, et al. Which ornamental plant species effectively remove benzene from indoor air? Atmos Environ 2007; 41: 650-654.
33 IPCC. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, RK Pachauri and LA Meyer (eds)] 2014: 1-151.
34 NASA. Carbon Dioxide: Direct Measurements: 2005-present, https://climate.nasa.gov (2019, accessed 10-11-2019).
35 Zheng YP, Li F, Hao LH, et al. The optimal CO_2 concentrations for the growth of three perennial grass species. Bmc Plant Biol 2018; 18.
36 Irga PJ, Paull NJ, Abdo P, et al. An assessment of the atmospheric particle removal efficiency of an in room botanical biofilter system. Build Environ 2017; 115: 281-290.
37 EPA, U.S., Evaluation of In-Room Particulate Matter Air Filtration Devices. U.S. Environmental Protection Agency 2008, Washington, DC.
38 ANSI/AHAM-AC-1-2013, Method for Measuring Performance of Portable Household Electric Room Air Cleaners. 2015, Association of Home Appliance Manufacturers [AHAM]. Method for Measuring Performance of Portable Household Electric Room Air Cleaners.
39 Wolverton BC, Mcdonald RC and Watkins EA. Foliage Plants for Removing Indoor Air-Pollutants from Energy-Efficient Homes. Econ Bot 1984; 38: 224-228.
40 Teiri H, Pourzamani H and Hajizadeh Y. Phytoremediation of VOCs from indoor air by ornamental potted plants: A pilot study using a palm species under the controlled environment. Chemosphere 2018; 197: 375-381.
41 Darlington A, Chan M, Malloch D, et al. The biofiltration of indoor air: Implications for air quality. Indoor Air-International Journal of Indoor Air Quality and Climate 2000; 10: 39-46.
42 Cummings BE and Waring MS. Potted plants do not improve indoor air quality: a review and analysis of reported VOC removal efficiencies. Journal of exposure science & environmental epidemiology 2019: 1-9.
43 Van de Geijn SC and Goudriaan J. The effects of elevated CO_2 and temperature change on transpiration and crop water use. Global climate change and agricultural production. England: FAO and John Wiley & Sons, 1996, pp.101-121.
44 Wang Y, Chen X and Xiang CB. Stomatal density and bio-water saving. J Integr Plant Biol 2007; 49: 1435-1444.
45 Elliott-Kingston C, Haworth M, Yearsley JM, et al. Does Size Matter? Atmospheric CO_2 May Be a Stronger Driver of Stomatal Closing Rate Than Stomatal Size in Taxa That Diversified under Low CO_2. Front Plant Sci 2016; 7: 1253(1251-1212).

46 Grantz DA and Assmann SM. Stomatal Response to Blue-Light - Water-Use Efficiency in Sugarcane and Soybean. Plant Cell Environ 1991; 14: 683-690.
47 ASHRAE-62.1, Ventilation for Acceptable Indoor Air Quality. 2016, American Society of Heating, Refrigerating and Air Conditioning Engineers: Atlanta.
48 NEN-EN15251, Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. 2007, European Committee for Standardization: Brussels, Belgium.


Green Climate Control
Analysing the Impact of (active) Plant-Based Systems on Indoor Air Quality (IAQ)
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5 Active Plant-based system

The effect of an active plant-based system on perceived air pollution

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ABSTRACT Active plant-based systems are emerging technologies that aim to improve indoor air quality (IAQ). A person's olfactory system is able to recognize the perceived odour intensity of various materials relatively well, and in many cases, the nose seems to be a better perceiver of pollutants than some equipment is. The aim of this study was to assess the odour coming out of two different test chambers in the SenseLab, where the participants were asked to evaluate blindly the level of acceptability, intensity, odour recognition, and preference at individual level with their noses. Two chambers were furnished with the same amount of new flooring material, and one of the chambers, Chamber A, also included an active plant-based system. The results showed that in general, the level of odour intensity was lower in Chamber B than in Chamber A, the level of acceptability was lower in Chamber A than in Chamber B, and the participants identified similar sources in both chambers. Finally, the preference was slightly higher for Chamber B over Chamber A. When people do not see the interior details of a room and have to rely on olfactory perception, they prefer a room without plants.

KEYWORDS Plant monitoring, Indoor Air Quality, Pollution sources, Sensory Assessment, Active plant-based system, Phytoremediation

5.1 Introduction

The improvement of indoor air quality (IAQ) is a constant and significant concern among researchers. Indoor air pollutants can be emitted by several indoor sources, such as furnishings, building materials, and cleaning products.[1–5] Additionally, plants, which are generally not mentioned in the list of pollutant sources, can be, according to several findings, a source that can pollute as well as clean the air.[6] Furthermore plants have the potential to generate attractive and friendly environments that support social and emotional wellbeing.[7,8] Numerous studies have described, evaluated, and analysed the effect of passive plants on cleaning the indoor air.[9–14] In a previous study, in which the air cleaning effect of formaldehyde by potted plants was tested in a laboratory study, it was concluded that to meet the minimum ventilation rates in breathing zones, it is necessary to introduce at least 36–42 plants for every square meter of floor space.[15] In that study, formaldehyde was introduced in a glass chamber in which the plant and its substrate were located, hereby surrounding the plant and its substrate with formaldehyde. In a 'normal' indoor environment, usually the source of formaldehyde is not close to the plant system, and therefore, for the plant system to take-up the formaldehyde, the polluted air needs to be transported to the vicinity of the plant. This can, for example, be realised by an active plant-substrate system, in which the contaminated air is forced to go through the plant leaves and through the substrate roots.

On the other hand, health and comfort complaints have been associated with poor IAQ due to emissions from building materials and furnishings where people spend most of their time. These complaints can range from annoying smells to symptoms such as dry eyes, irritated skin, and airway problems, to carcinogenic effects.[16,17] These problems have been linked to sick building syndrome (SBS) (biological or psychological problems caused by the negative impact of buildings),[18] or building-related illness (BRI).[4] Odours may cause a variety of undesirable effects in users, fluctuating from annoyance and discomfort to acknowledged health and psychological stresses.[4,19] In the indoor environment, odorous VOCs (volatile organic compounds) are emitted from several construction and cleaning products.[20–22] In most situations, these emissions are present in very low concentrations that are difficult to measure chemically, but are perceived by the users. The human nose is capable of detecting certain odorous pollutants at ppm level and sometimes even at ppb level, while most chemical instruments monitor at ppm level.[23,24] However, there are also pollutants that cannot be assessed by people, but are still important to assess because of their toxic effects. Then, Yi et al. (2013) reported that indoor pollutants with the highest chemical concentrations

were not the most odour-active odorants.[25] It is therefore important to assess IAQ both by chemical instruments (chemical air pollution) and with the nose (sensory air pollution). Sensory assessment with people (trained or untrained)[20] has been used to assess indoor air quality in offices and the pollution emitted from different building and furnishing materials in several laboratory studies.[1,26]

The aim of the study was to test the effect of an active plant-based system on the perceived air quality of a recent furnished room. For this purpose, two identical test chambers of the SenseLab were furnished with new carpet tiles. In one of the chambers an active plant based-system was added. The SenseLab is a laboratory for testing and experiencing single and combinations of indoor environmental conditions located at Delft University of Technology[27].

5.2 Materials and methods

5.2.1 General

Based on previous studies, first an active plant system was designed and realised. Then two test chambers of the SenseLab[27] were furnished identically and in one of the test chambers the active plant system was installed. Then the test chambers were made ready for perception of the air by people without entering the chambers. Firstly, a pilot test was held to evaluate the set-up with 59 participants, followed by three sessions in April and May 2019, in which the untrained participants visited the SenseLab to participate in a 'sniffing test' to evaluate the air from the two test chambers (Table 5.1).

TABLE 5.1 Time schedule and assessments.

Session Number	Date	Number of participants	Assessment			
			Intensity	Acceptability	Recognition	Preference
Pilot Test	04-04-2019	59	x	x	x	-
Session 1	10-04-2019	44	x	x	x	x
Session 2	24-04-2019	57	x	x	x	x
Session 3	08-05-2019	46	x	x	x	x

5.2.2 Active plant-based system

From earlier conducted experiments on the depletion of formaldehyde by potted plants [15], it was concluded that the effect of potted plants on 'cleaning' indoor air is limited. It was suggested to investigate whether an active plant system could give better results. In addition, it was found that a) the growth medium has a big influence in the depletion of formaldehyde and b) the plant Nephrolepis exaltata L. in the medium expanded clay performed the best.

Therefore, for the prototype of the active plant-based system, 30 Nephrolepis exaltata L. (also known as Boston Fern) plants were re-potted on expanded clay. Besides having the best performance in the depletion of formaldehyde during the lab-tests, the density of this medium allows the air to go through the substrate easier than with other substrates (e.g., soil). The structure of the active plant-based system was built with low-emitting materials: aluminium frame together with Plexiglas elements that held the 30 plants.

Each of the 30 plants was then connected to a fan (80 mm diameter, airflow: 52.7 m^3/h, 0.16 A / 12 V, 1.92 W, sound level: 0.3 sone / 22.4 dB) that forced the air to go through the plant itself and through the growth medium. To keep the plants in the system alive and provide the right amount of light that the plants need to grow, a growing LED ((Light-emitting diode) light (0.31 m x 0.31 m x 0.035 m, 120 W, number of LED lamps: 1365 = 1131 red and 234 blue, wavelength red: 630-660nm, wavelength blue: 430-450nm, maximum surface illumination: 2-3 m^2, 2506 lux at 1.5 m distance from the lamp) was installed in Chamber A. The fans were activated for 12 hours every day during the whole experiment with the help of a plug-in mechanical timer, and the plants received water once per week. Figure 5.1 presents a section of the prototype. As mentioned before, the active plant-based system was activated for 12 hours per day, resulting in a total energy consumption of 778 kWh per year (252 kWh for the fans + 526 kWh for the growing LED light).

TOC

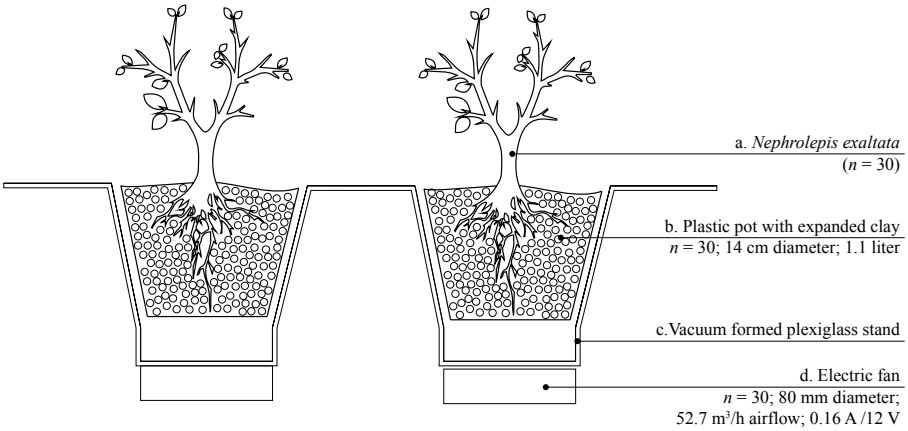

FIG. 5.1 Prototype section scheme of the active plant-based system.

5.2.3 The SenseLab and the test chambers

To evaluate the efficacy of the active plant-based system on the perceived air quality, two chambers in the SenseLab were selected to execute the experiment. The two test chambers have the same features and are constructed of low-emitting materials to ensure a good air quality. Each chamber, having a volume of 19.7 m^3 (floor area 9.36 m^2 × 2.1 m height), was furnished with 9.36 m^2 of new carpet tiles. Figures 5.2 and 5.3 illustrate the selected setup for each chamber. In Chamber A an active plant-based system was placed to evaluate the effect of that system on the (perceived) air quality (Figure 5.2). A 110 mm diameter flexible air duct was connected to the air outlet of each chamber to allow the participants to evaluate the air coming out of the chamber, without going into the chambers (and thus not seeing what they were assessing) (Figure 5.2 and 5.3).

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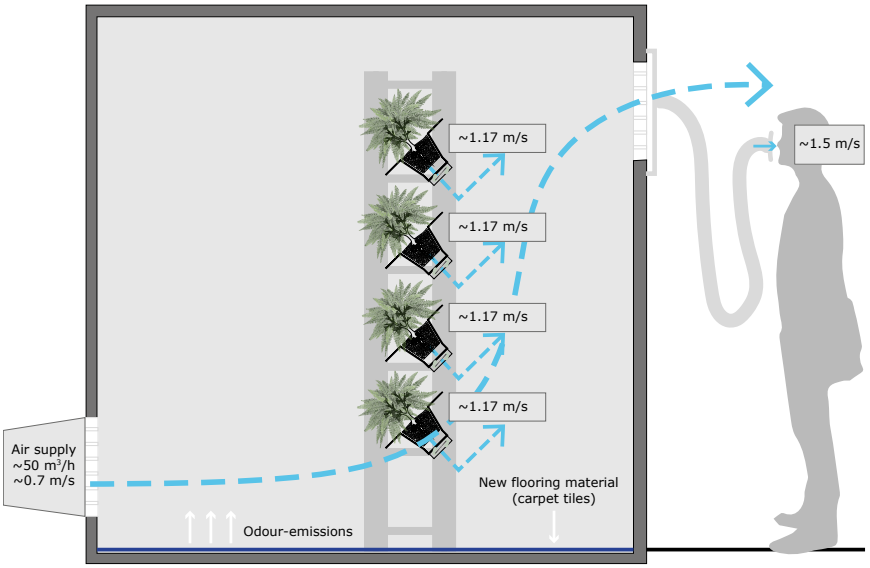

FIG. 5.2 Setup of Chamber A (including an Active plant-based system) (APPENDIX C)

The temperature (T), relative humidity (RH) and CO_2 levels were monitored during the whole experiment (from 04-04-2019 to 14-05-2019). Three sessions of evaluation with subjects were executed every two weeks. The sessions were executed during the same season around the same time to keep the variables as similar as possible. The changes in temperature and relative humidity inside of the chambers were monitored with two HOBO External data loggers and the CO_2 levels were monitored with HOBO® MX CO_2 loggers. Besides, a FlowFinder MK2 and ComfortSense Mini (compact anemometer for ventilation and draught measurements) were used to measure the air supply in the chambers and the air velocity in the (sniffing) tube, respectively. Additionally, a VOC-monitoring instrument (Photoionisation Detector (PID) ppbRAE 3000 with 11.7ev UV lamp) was used to measure the air pollutants coming out of both chambers. It is important to mention that all the instruments used during this study were calibrated and tested prior the experiments to obtain reliable data.

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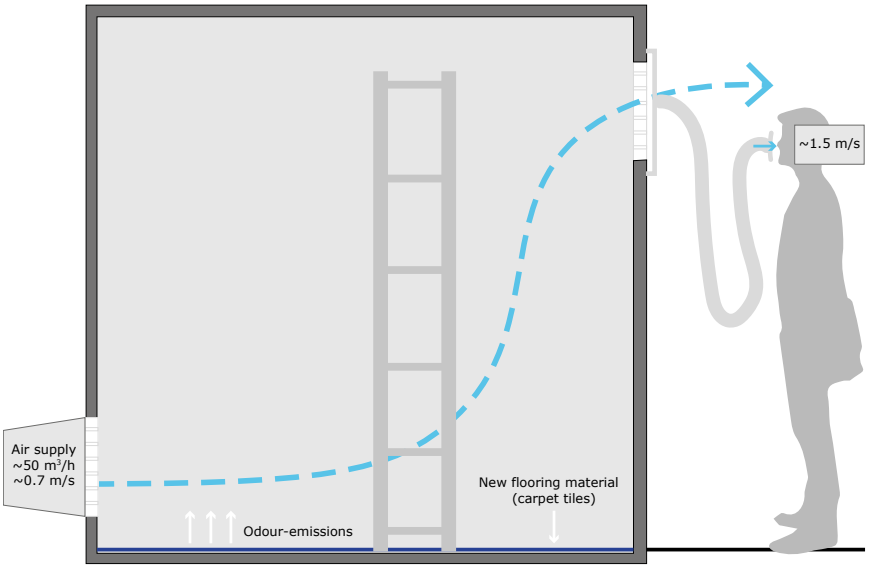

FIG. 5.3 Setup of Chamber B (APPENDIX C).

5.2.4 The questionnaire

To assess the perceived air quality coming out of the chambers a questionnaire was developed based on the questionnaire used by Gunnarsen and Fanger, 1992.[28] For this study intensity, acceptability, recognition of the odour and preference were assessed (Figure 5.4). The participants were asked: “How strong is the odour that you smell? Give your opinion with a cross or a dash on the scale below (Intensity)”; “Imagine being exposed to this odour during the day, how acceptable do you think this odour is? Give your opinion with a cross or a dash on the scale below (Acceptability)”; “What do you smell? You can choose more than one option (Odour recognition)”; and “Which funnel do you prefer? (Preference)”. Regarding Intensity, the perceived odour was assessed on a five-grade scale. The Acceptability level was assessed on a three-grade scale. The preference was assessed on an eight-point roulette were multiple choices were allowed. Finally, the participants had to choose which chamber they preferred.

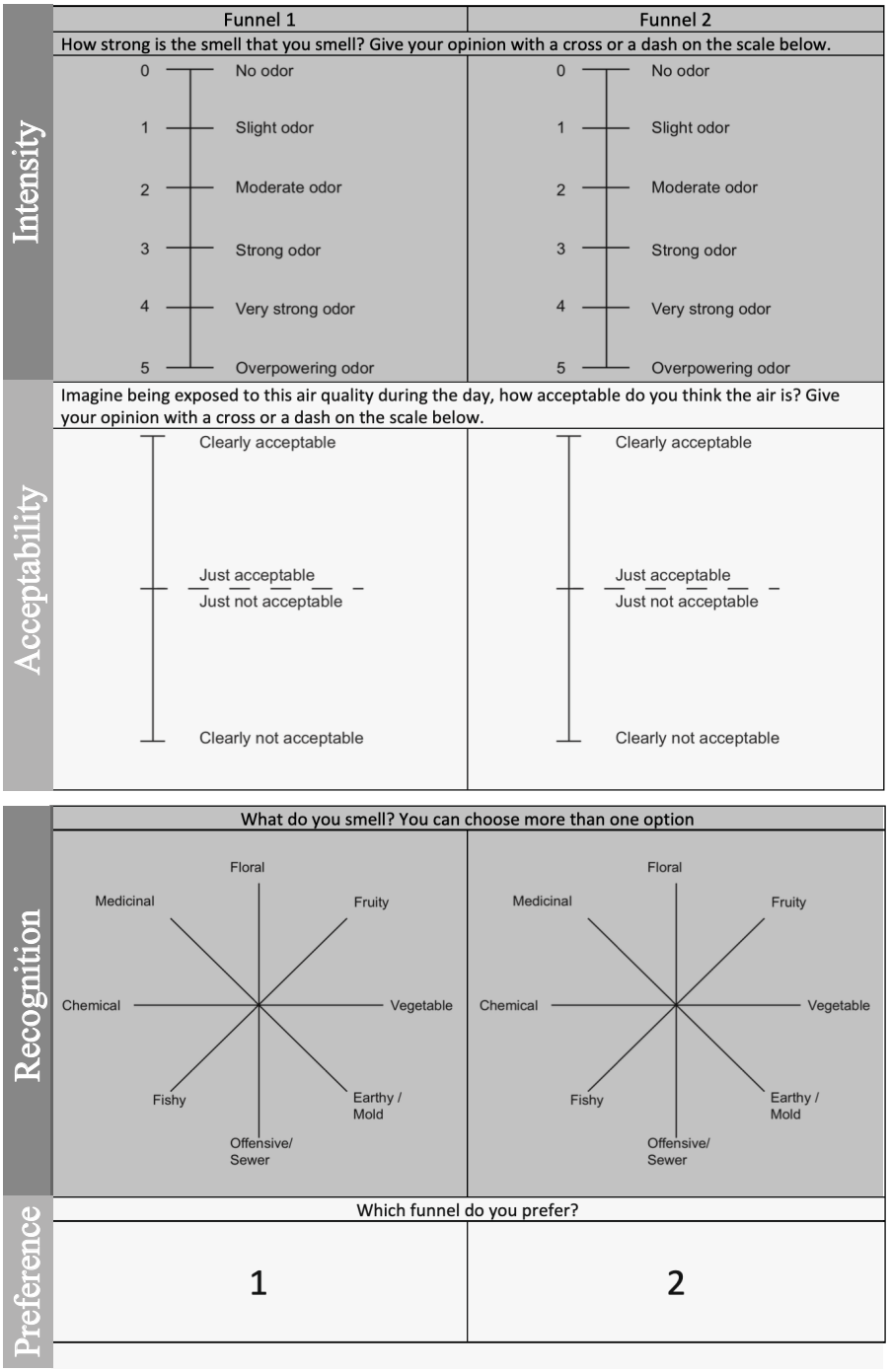

FIG. 5.4 Questionnaire: Intensity, Acceptability, Odour recognition and Preference assessments.

5.2.5 5.2.5. Pilot test

To evaluate the procedure and the questionnaire, a pilot test composed of three sections - Intensity, Acceptability and Recognition - was executed on April 4th 2019 with 59 participants. Before the participants completed the questionnaire, an explanation was given of the contents and purpose of the experiment and questionnaire. In general, it took the participants approximately 3-5 minutes to perform the test and complete the questionnaire. After the pilot test, the questionnaire was modified and the section 'Preference' was added in the last part of the questionnaire. Additionally, the air supply rate to all the test chambers (four in total) was changed from 1000 m^3/h to 500 m^3/h to reduce the amount of air (~130 m^3/h to ~50 m^3/h inside of the selected chambers); therefore, the air velocity also changed from 2.3 m/s to 1.5 m/s coming out of each funnel. During the pilot test, the velocity was found to be too high (2.3 m/s) for properly assessing the perceived air quality. It is important to mention that every funnel had a diameter of 0.11 m and with 1.5 m/s air velocity, therefore, 14 L/s (51.3 m^3/h) of air were coming out of the funnel.

5.2.6 Procedure

After the pilot test, the questionnaire was fixed and three sessions of assessments were performed, each with two weeks in between. The recruitment of the participants was on voluntary basis. When the participants arrived in the SenseLab, they were given a questionnaire with some general information about themselves and with some questions related with the assessment of the odour coming out of every chamber. The participants were assigned randomly where to start the assessment (e.g., Chamber A or Chamber B). The participants were asked to give their assessments of the air for each of the chambers by completing the questionnaire. For each question the participants were allowed to take only one sniff in order to avoid 'adaptation' to the smell coming out of the funnel.[28] After they finished the questions of the first chamber, they were asked to continue with the second chamber, and follow exactly the same procedure.

The participants took 5 minutes to perform the assessment and complete the questionnaire of both chambers.

5.2.7 Ethical aspects

The Ethics committee of the TU Delft provided approval for the study. Each participant received a voucher after they completed and handed in their completed questionnaire. By handing in the questionnaire, they gave consent for using their assessments.

5.2.8 Data management and analysis

All data from the questionnaires were manually typed in and stored in IBM SPSS Statistics version 25.0 and Microsoft Excel. First, comparisons of mean values were performed with independent t-tests, and standard deviation and standard errors were used to evaluate levels of intensity and acceptability of every chamber. These tests were used to evaluate whether statistically significant differences between different sessions and chambers occurred, in time. In addition, descriptive statistical analyses were executed to evaluate frequencies in odour recognition and preference, and chi-square tests were executed to evaluate the correlation between the starting funnel and the level of preference of the participants.

5.3 Results

5.3.1 VOC, Temperature, Relative Humidity and CO_2 monitoring

Although the participants pointed out to perceive an odour (in all of the sessions and for both chambers), the 11.7ev PID monitor used to measure the TVOC concentration, resulted in 0 ppb for both chambers. This could be due to the measurement range of the VOCs that the instrument can detect, or the detection limit of the instrument (range: 0.01 ppm to 2000 ppm; resolution: 10 ppb).

The temperature, relative humidity (RH) and CO_2 concentration inside of the chambers A and B at each of the session days, are presented in Figures 5.5 - 5.7, respectively. The figures also include the period where the participants executed the

experiment and filled in the questionnaires. Moreover, Table 5.2 presents the average temperature, RH and CO_2 concentration inside of the chambers A and B during the execution of the sessions. From the measurements can be seen that the RH levels are always higher in Chamber A than Chamber B. In general, the temperature levels inside of the Chamber A were always lower than in Chamber B. In Chamber A, with the active plant-based prototype, the CO_2 levels, were on average ~197 ppm higher than in Chamber B during the first session. Table 5.2 shows that the CO_2 levels in Chamber B during session 2 and 3 were quite similar while in Chamber A those levels presented a slight fluctuation. Finally, the air supply and the air velocity of the chambers were measured before the sessions (Air supply: ~50 m^3/h; air velocity: ~0.7 m/s) and it stayed constant throughout the execution of the experiment.

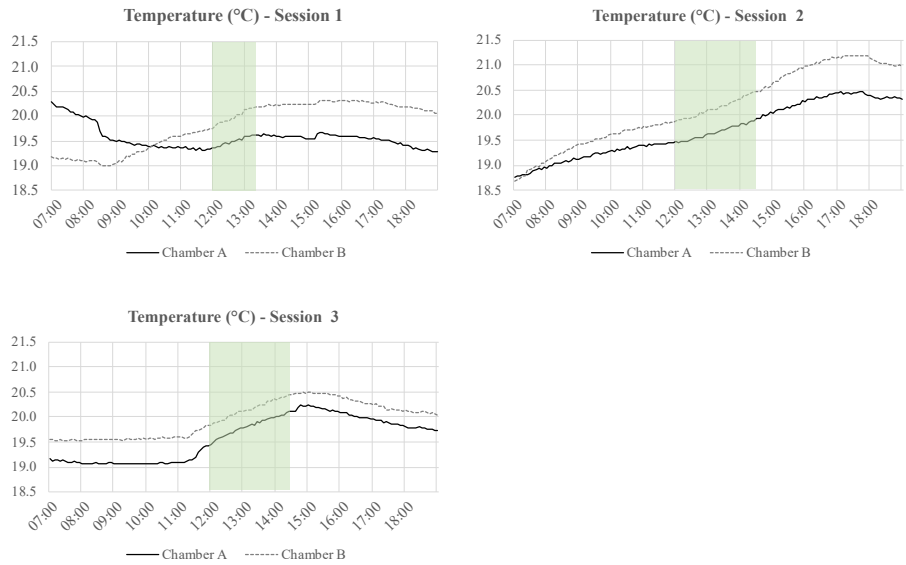

FIG. 5.5 Temperature (°C) at the days of the three sessions from 7.00 to 19.00 every 5 minutes. The highlighted section is the period when the participants executed the experiment and filled the questionnaires.

TABLE 5.2 Average temperature, relative humidity (RH) and CO2 concentration inside of the chambers A and B during the execution of the sessions.

	Session 1		Session 2		Session 3	
	Chamber A	Chamber B	Chamber A	Chamber B	Chamber A	Chamber B
Temperature (°C)	19.5	20.0	19.7	20.2	19.8	20.2
RH (%)	38.1	27.3	62.4	54.5	55.5	47.6
CO2 (ppm)	460.9	262.8	422.5	465.6	480.3	467.4

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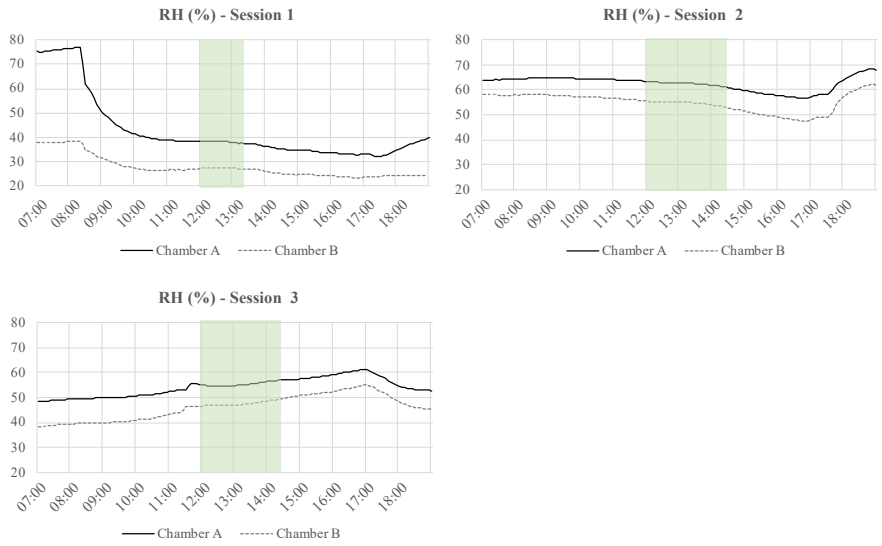

FIG. 5.6 Relative Humidity (RH) (%) at the days of the three sessions from 7.00 to 19.00 every 5 minutes. The highlighted section is the period when the participants executed the experiment and filled the questionnaires.

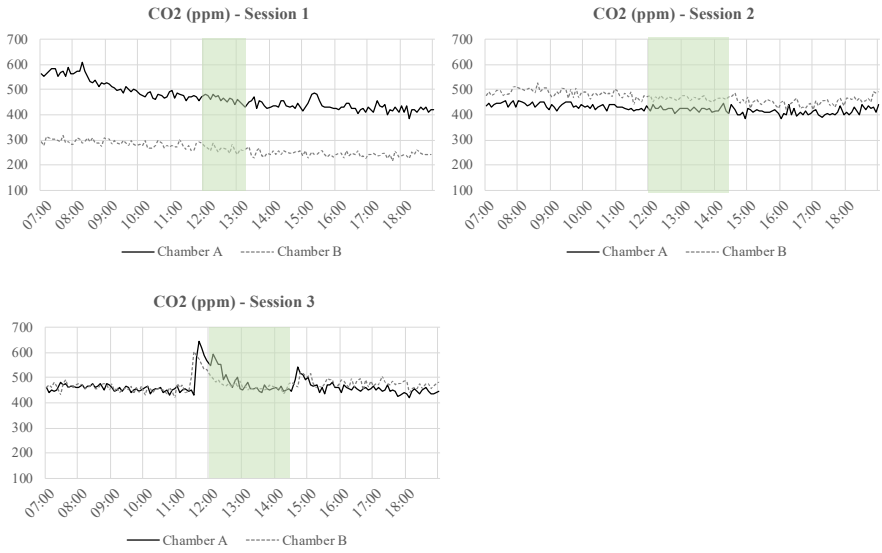

FIG. 5.7 CO_2 levels (ppm) at the days of the three sessions from 7.00 to 19.00 every 5 minutes. The highlighted section is the period when the participants executed the experiment and filled the questionnaires.

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5.3.2 Intensity

The participants were asked to take a sniff from one of the two funnels and to answer the following question: “How strong is the odour that you smell? Give your opinion with a cross or a dash on the scale below (Intensity)”. Table 5.3 presents the mean values of the intensity assessment of Chambers A and B together with standard deviations (S.D.) and standard errors (S.E.). From Figure 5.8 it can be seen that during the three sessions of assessment, in general, the participants evaluated the odour of Chamber A (in funnel A) stronger that the odour of Chamber B (in funnel B).

TABLE 5.3 Intensity Assessment.

	Chamber A			Chamber B		
	Session 1	Session 2	Session 3	Session 1	Session 2	Session 3
Mean Value	2.03	2.46	2.5	1.86	1.95	2.30
SD*	0.87	0.94	0.84	0.82	0.88	0.98
SE**	0.13	0.12	0.12	0.12	0.12	0.14

** Standard deviation.*
*** Standard error*

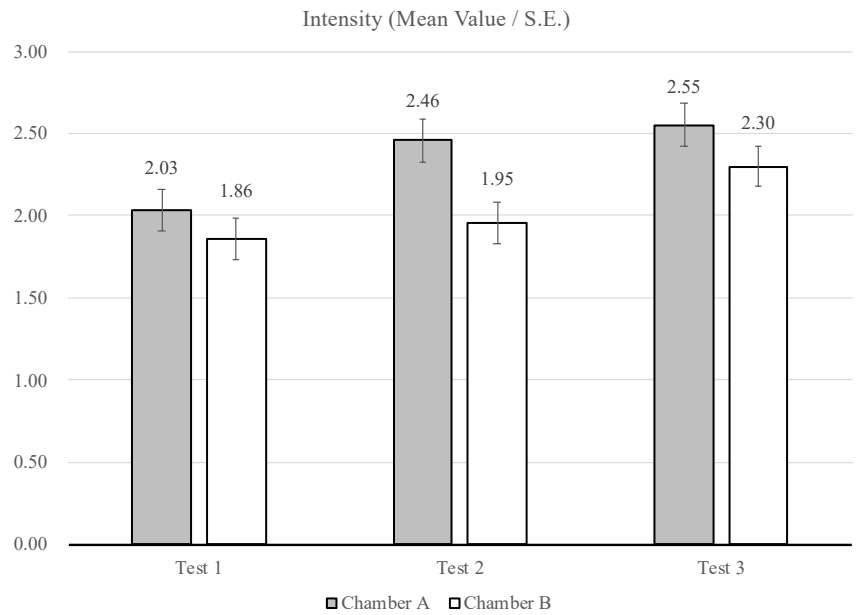

FIG. 5.8 Intensity assessment for the two chambers at the three sessions: mean values and standard errors (S.E.) (Session 1: n=44; Session 2: n=57; Session 3: n=46).

TOC

Several independent-samples t-tests were conducted to evaluate whether differences between the odour intensity assessments of chambers A and B were present during the sessions, and between the sessions. The analysis resulted in a statistically significant difference in odour intensity between the two chambers for Session 2 (P=0.004). Additionally, a statistically significant difference between Session 1 and Session 2 (P=0.02), and between Session 1 and Session 3 (P=0.005) was found for Chamber A, indicating the odour intensity became stronger over time. For Chamber B, a statistically significant difference between Session 1 and Session 3 (P=0.022) was found, showing that the odour intensity in Session 1 was significantly lower than in Session 3.

5.3.3 Acceptability

After having assessed the intensity, the participants were asked to take another sniff from the funnels and to answer the following question: “Imagine being exposed to this odour during the day, how acceptable do you think this odour is? Give your opinion with a cross or a dash on the scale below (Acceptability)”. For this analysis, the range of the acceptability scale considered is from clearly acceptable = 1 to clearly not acceptable = –1. Table 5.4 shows the mean values of the acceptability assessment of chambers A and B together with standard deviations (S.D.) and standard errors (S.E.). Additionally, Figure 5.6 illustrates that for each of the three sessions, the participants evaluated the air in funnel A less acceptable that the air in funnel B.

Several independent-samples t-tests were conducted to evaluate whether differences between the acceptability assessments of chambers A and B were present during the sessions, and between the sessions. A statistically significant difference between the chambers was found for Session 2 (P=0.045). In general, the participants evaluated the acceptability level of the air in funnels A and B to be less acceptable for each session (Figure 5.9). For Chamber A, a statistically significant difference for the acceptability of the air assessed in Session 1 and Session 2 (P=0.005) was found, as well as for Session 1 and Session 3 (P=0.012). For Chamber B, no statistically significant differences between the sessions was found.

TABLE 5.4 Acceptability Assessment.

	Chamber A			Chamber B		
	Session 1	Session 2	Session 3	Session 1	Session 2	Session 3
Mean Value	0.13	−0.11	−0.11	0.19	0.09	0.01
SD*	0.38	0.56	0.51	0.37	0.49	0.54
SE**	0.06	0.08	0.07	0.06	0.06	0.08

** Standard deviation.*
*** Standard error*

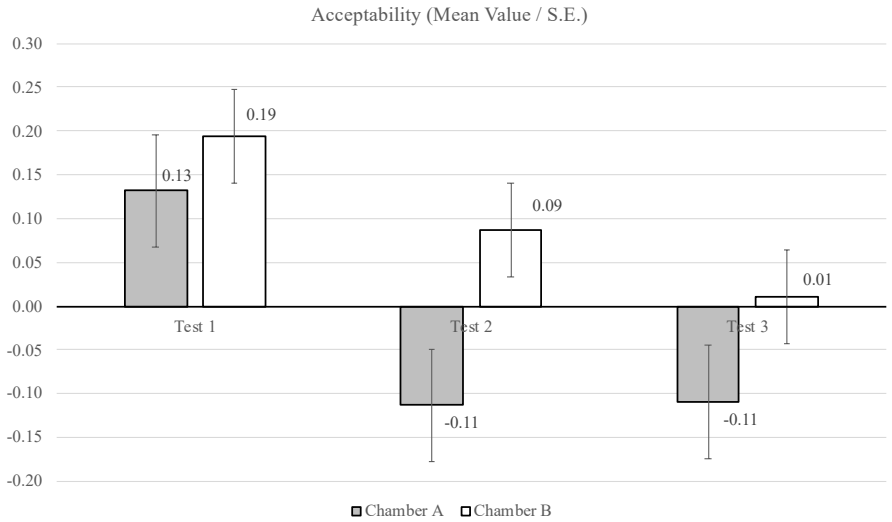

FIG. 5.9 Acceptability assessment for the two chambers during the three sessions: Mean values and Standard Errors (S.E.) (Session 1: n=44; Session 2: n=57; Session 3: n=46).

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5.3.4 Odour Recognition

The odour acceptability evaluation was followed by an odour recognition test. The participants were asked to take another sniff from the funnels and to answer the following question: “What do you smell? You can choose more than one option (Odour recognition)”. Figure 5.10 and 5.11 present how the participants identified the odours in funnel A and funnel B. In Session 1, the participants described the odour mainly as medicinal (55%), chemical (55%), and earthy (34%) for Chamber A (furnished with new carpet tiles and with the active plant-based system inside); and medicinal (59%), chemical (57%), and earthy (30%) for Chamber B (furnished with same amount of carpet tiles as Chamber A but without the active plant-based system inside). In Session 2, the participants described the odour mainly as chemical (25%), and earthy (60%) in Chamber A; and earthy (35%), chemical (40%), and medicinal (33%) for Chamber B. In Session 3, the participants described the odour mainly as medicinal (24%), chemical (28%), and earthy (37%) in Chamber A; and medicinal (41%), chemical (24%), and earthy (37%) in Chamber B.

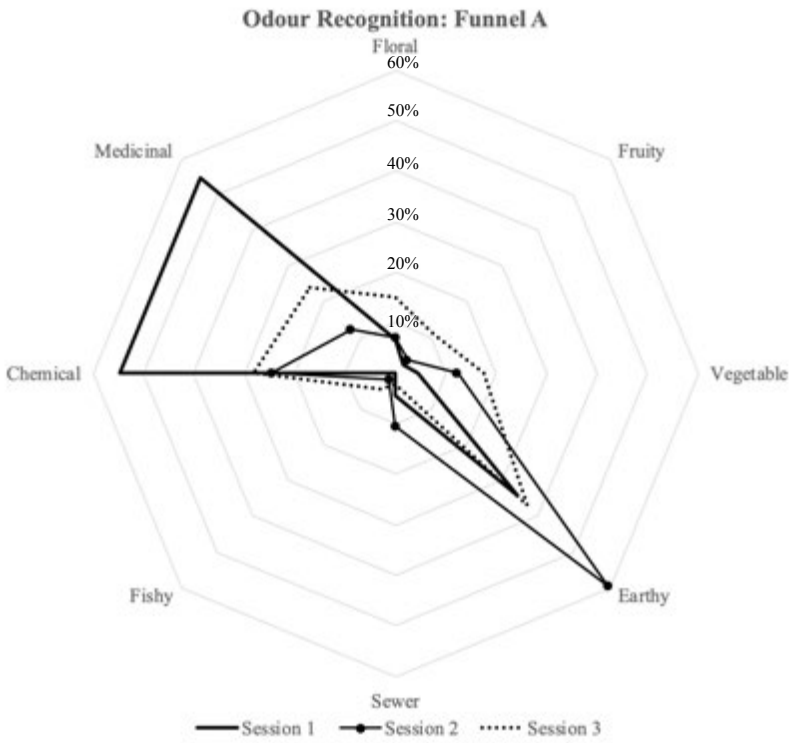

FIG. 5.10 Odour recognition assessment for chamber A.

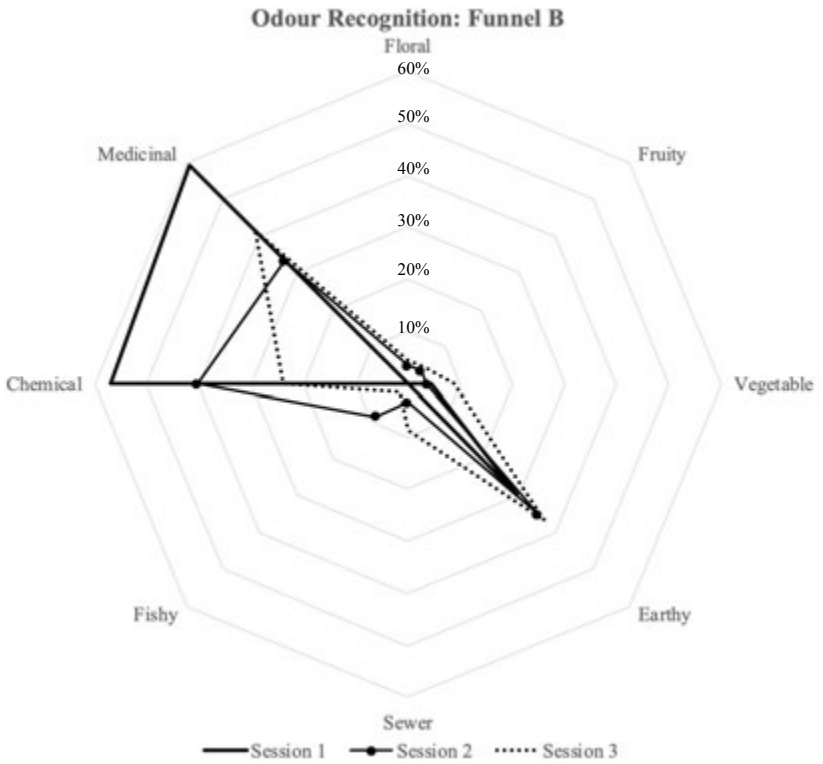

FIG. 5.11 Odour recognition assessment for chambers B.

5.3.5 Preference

Last but not least, the participants were asked to answer the following question (about preference): "Which funnel do you prefer? To evaluate the preference of the participants during the sessions, frequency analysis was performed. Table 5.5 shows the preference assessment for the two chambers in the three sessions. In Session 1, the participants preferred Chamber A (55%) over Chamber B (45%), while in Session 2 and 3, participants preferred Chamber B over Chamber A.

TOC

TABLE 5.5 Preference assessment for the two chambers in the three sessions.

Preference	Session 1		Session 2		Session 3	
	n = 44		*n* = 57		*n* = 46	
Funnel 1 (A)	24	55%	21	37%	17	37%
Funnel 2 (B)	20	45%	35	61%	28	61%
No preference			1	2%	1	2%
Total	44	100%	57	100%	46	100%

To evaluate whether there was a statistically significant relation between the starting funnel of the tests and the level of preference of the participants, Chi-square tests were performed. The outcome showed no correlation between the starting funnel and the preference level during the three sessions (Session 1: p=0.23; Session 2: p=0.35; Session 3: p=0.57).

5.4 Discussion

5.4.1 Impact of Temperature and Humidity in human perception

Previous studies have demonstrated that human sensory evaluation can be used to evaluate the perceived air quality[4,23]. It is well-known that people can use their noses to assess the perceived odour intensity of different materials relatively well, and, that in general the equipment that is available is not able to measure the low concentrations of chemical compounds as the nose can [23]. The results of the present study confirmed this: while the chemical measurements showed no VOCs present (emitted from the carpet tiles in the chambers), the participants smelled odours in the air coming out of both of the funnels.

With regards to the physical measurements executed inside of the chambers, the temperature was, in general, always slightly lower in Chamber A, with the plant-based system, than in Chamber B. In contrast, the relative humidity in Chamber A was always higher than in chamber B, which can be explained by the evaporative cooling effect created by the plant-based system placed in Chamber A[29,30]. During the sessions, the average temperature inside Chamber A was 19.7°C and the

average RH was 52%, while in Chamber B the average temperature was 20.1°C and the average RH was 43%. Taking this into account, it is important to mention that temperature and relative humidity levels of the environment may affect the perceived air quality and could therefore have affected the assessment of the air coming out of the chambers. A lower temperature makes it more difficult to assess the smell [20]. Furthermore, prior findings have shown temperature and humidity have a significant impact on the perception of IAQ. It is stated that the perceived air quality decreases with increasing air temperature and humidity at a constant pollution concentration[31,32].

In this study, the temperature levels in both chambers were rather similar, but the RH levels have a significant difference between the chambers (Table 5.2). It is important to mention that the outside air coming into both chambers had exactly the same properties, the flooring material in both chambers had the same composition and amount, and in Chamber A an active plant-based system was place to evaluate its impact in the perceived IAQ. Regarding the RH levels, it is important to mention that any vegetation system generates extra humidity in the environment[33].

5.4.2 Acceptability, Intensity, Odour Recognition and Preference

The main objective of this study was to test the effect of an active plant-based system on the perceived air quality of a recent furnished room. During the study, the participants were asked to fill in a questionnaire to assess the air coming out of two funnels from two different chambers. The assessment of the two chambers took approximately 5 minutes per person. This way of assessing was chosen to avoid adaptation to the smell coming out of funnels, since 'adaptation' improves acceptability of the air quality[28]. Besides, the participants were not allowed to enter nor see inside of the chambers in order to reduce bias created by an environment that includes the plants[34,35].

The evaluation of air quality expressed in acceptability reflects perceptual information in combination with psychological and social values. The present study showed that the level of acceptability given by the participants in Chamber A, with the plant-based system, was in general lower than Chamber B. The level of intensity of the odour in Chamber A was evaluated stronger than in Chamber B. Therefore, when the participants assessed the odour to be more intensive, they also assessed it to be less acceptable. These results are in good agreement with preceding studies[28,36].

With regards to odour recognition, there were three main elements identified by the participants inside of both chambers during the tests: chemical, medicinal and earthy (Figure 5.10 and Figure 5.11). The participants, in general, identified the same elements for the two chambers with slight differences. However, the levels of intensity and acceptability were assessed differently, as shown in Figures 5.8 and 5.9. Furthermore, for Sessions 2 and 3 it was seen that the participants preferred Chamber B over Chamber A (Table 5.5). This can be justified from a psychological point of view: each stimulation introduced in the indoor environment needs justification and explanation; therefore, elements (odours) that are present and that cannot be recognised will lead to some discomfort[37]. Previous studies have shown that perceptual reaction to different odours varies according to individual sensitivity, and in general, when the participants do not know the source of the smell or if they feel that the smell is potentially hazardous, they tend to reject the smell and show their discomfort[38]. Finally, the fact that an active plant-based system was introduced in Chamber A may introduce other pollutants and compounds into the chamber[20], such as mould[33].

5.4.3 Experiments in Semi-controlled Environments

The aim of the study was to evaluate the efficacy of the active plant-based system on the perceived air quality in a semi-controlled environment. To execute this assessment, two test chambers were furnished with the same amount of carpet tiles. Additionally, a plant-based system was placed in Chamber A as presented in Figure 5.2 Both chambers have the same characteristics and are constructed of low-emitting materials to guarantee a good air quality during the execution of experiments regarding IAQ and IEQ.[27]

On one hand, studies have shown that it is “easier” to assess the impact of plant-based systems in terms of IAQ when the experiments are executed in laboratories (closely controlled environments)[14,15] where higher concentrations of pollutants are normally used to evaluate the efficacy of the plants in terms of gaseous pollutant depletion from the air.[12–14] On the other hand, in real settings, the concentrations of the gaseous pollutants are lower and diverse, so it is more difficult to assess the efficacy of these systems. There- fore, this study was executed in a test chamber to evaluate the plant-based system in a semi-controlled environment where different features were evaluated in a more “real-setting environment”. However, just one floor material was evaluated, and the participants were not able to interact directly with the prototype, which would be different in a real-setting experiment where many more elements have to be considered and evaluated, such as different

materials, different pollutants, and different construction systems. From this study, it is clear that tests in semi-controlled environments are useful to evaluate isolated factors that can improve the removal efficacy of plant-based systems, However, it is also important to evaluate the overall effect of these systems in real settings to understand how these isolated factors will interact with real-setting environments.

5.4.4 Limitation

For this study, the concept of active biofiltration was built in one prototype with a fixed air flow rate created for the fans connected to the plants. It is, therefore, recommended that future studies test the effect of different air flow rates to choose the optimal option. Additionally, Figures 5.2 and 5.3 present the setup of the experiment in both chambers, where it is shown that the air coming inside of the chambers is located in the lower part of the wall directing the air to go over the carpet tiles and not through the system, which can explain the similar assessments of both chambers.

5.5 Conclusions

The aim of the study was to assess the perceived air quality coming out of two different test chambers in the SenseLab: Chamber A which was furnished with new carpet tiles and an active plant based-system and Chamber B which was furnished with the same amount of carpet tiles as in Chamber A, but without the active plant-based system. From the assessments performed in the three sessions can be concluded that the level of acceptability in Chamber A was lower than in Chamber B, and, the level of intensity was higher in Chamber A than in Chamber B. Besides, three main odours were identified in both chambers: medicinal, chemical and earthy. Finally, the participants expressed a slightly higher preference for Chamber B over Chamber A.

Although there are many possible factors that might have influenced the assessments, the outcome indicates that when people do not see the interior details of a room and have to rely on olfactory perception, they prefer a room without plants. The results also show that sensory evaluation is a necessary instrument

for the assessment of the indoor air quality because chemical and physical measurements and analysis alone cannot be used in the majority of the cases to predict how the pollutants and its emissions will be perceived by occupants.

Finally, even though previous lab studies have shown the chemical depletion of air pollutants in the close surrounding of the vegetation[10–13], from the results reported here, it can be concluded that the presence of this active plant-based system had a slightly negative effect on the perceived air quality.

References

1 Bluyssen PM, de Oliveira Fernandes E, Groes L, Clausen G, Fanger PO, Valbjørn O, Bernhard CA, Roulet CA. European indoor air quality audit project in 56 office buildings. *Indoor Air-International Journal of Indoor Air Quality and Climate* 1996; 6: 221-238.

2 Campagnolo D, Saraga DE, Cattaneo A, Spinazzè A, Mandin C, Mabilia R, Perreca E, Sakellaris I, Canha N, Mihucz VG, et al. VOCs and aldehydes source identification in European office buildings - The OFFICAIR study. *Build Environ* 2017; 115: 18-24.

3 Brown SK, Sim MR, Abramson MJ, Gray CN. Concentrations of Volatile Organic-Compounds in Indoor Air - a Review. *Indoor Air-International Journal of Indoor Air Quality and Climate* 1994; 4: 123-134.

4 Bluyssen PM, Cochet C, Fischer M, Knöppel H, Levy L, Lundgren B, Maroni M, Mølhave L, Rothweiler H, Saarela K, et al. *Evaluation of VOC emissions from building products: Solid flooring materials*. Report no. Report No. 18, 1997. European Collaborative Action.

5 Sofuoglu SC, Aslan G, Inal F, Sofuoglu A. An assessment of indoor air concentrations and health risks of volatile organic compounds in three primary schools. *Int J Hyg Envir Heal* 2011; 214: 38-46.

6 Yik FWH, Sat PSK and Niu JL. Moisture generation through Chinese household activities. *Indoor Built Environ* 2004; 13: 115-131.

7 Kaplan S. The Restorative Benefits of Nature - toward an Integrative Framework. *J Environ Psychol* 1995; 15: 169-182.

8 Han KT and Ruan LW. Effects of Indoor Plants on Self-Reported Perceptions: A Systemic Review. *Sustainability-Basel* 2019; 11.

9 Wolverton BC, Mcdonald RC and Watkins EA. Foliage Plants for Removing Indoor Air-Pollutants from Energy-Efficient Homes. *Econ Bot* 1984; 38: 224-228.

10 Wolverton BC, Johnson A and Bounds K. Interior Landscape Plants for Indoor Air Pollution Abatement, Final Report NASA (NASA-TM-101766, NAS 1.15:101766). *National Aeronautics and Space Administration* 1989: 1-22. Technical Report.

11 Darlington AB, Dat JF and Dixon MA. The biofiltration of indoor air: Air flux and temperature influences the removal of toluene, ethylbenzene, and xylene. *Environ Sci Technol* 2001; 35: 240-246.

12 Soreanu G, Dixon M and Darlington A. Botanical biofiltration of indoor gaseous pollutants - A mini-review. *Chem Eng J* 2013; 229: 585-594.

13 Dela Cruz M, Christensen JH, Thomsen JD, Müller R. Can ornamental potted plants remove volatile organic compounds from indoor air? - a review. *Environ Sci Pollut R* 2014; 21: 13909-13928.

14 Armijos Moya T, van den Dobbelsteen A, Ottelé M, Bluyssen PM. A review of green systems within the indoor environment. *Indoor Built Environ.* 2019;28(3):298-309.

15 Armijos Moya T, de Visser P, van den Dobbelsteen A, Ottelé M, Bluyssen PM. Air cleaning performance of two species of potted plants and different substrates.*(Under review)*. 2020, doi: 10.21203/rs.3.rs-314387/v1

16 Bluyssen PM. *All you need to know about indoor air – A simple guide for educating yourself to improve your indoor environment*. Delft, The Netherlands: Delft Academic Press: Delft, the Netherlands, 2015.

17 Kotzias D. Indoor air and human exposure assessment - needs and approaches. *Exp Toxicol Pathol* 2005; 57: 5-7.

18 Vural M and Balanlı A. Sick Building Syndrome from an Architectural Perspective. In: Abdul-Wahab SA (ed) *Sick Building Syndrome*. Springer-Verlag Berlin Heidelberg, Germany, 2011, pp.371-391.

19 Herz RS. Influences of odors on mood and affective cognition. In: Rouby C, Schaal B, Dubois D, et al. (eds) *Olfaction, taste, and cognition*. Cambridge: Cambridge University Press: Cambridge, UK, 2002.

20 Berglund B, Bluyssen PM, Clausen G, Garriga-Trillo A, Gunnarsen L, Knoppel H, Lindvall T, MacLeod P, Molhave L, Winneke G. *Sensory evaluation of indoor air quality*. Report no. 20, 1999. European Commission Report: European Collaborative Action: Indoor Air Quality and its Impact on Man: Luxembourg city, Luxembourg, 1999.

21 De Oliveira Fernandes E, Bluyssen PM, Clausen GH, Saarela K, Maupetit F, Kirchner S, Molina JL, Bischoff W, Knudsen HN. MATHIS - Materials for healthy indoor spaces and more energy efficient buildings. *Indoor Air 99*. Edinburgh, Scotland,: TNO Bouw, 1999, p. 628-633.

22 Bluyssen PM, de Oliveira Fernandes E and Molina JL. Database for sources of pollution for healthy and comfortable indoor environment (SOPHIE): Status 2000. *Healthy Buildings 2000*. Espoo, Finland, 2000, p. 385-390.

23 Bluyssen PM. Sensory evaluation of indoor air pollution sources. In: P P (ed) *Indoor Air Pollution*. Germany: Springer, Berlin, Heidelberg, Germany, 2004, pp.179-217.
24 Meilgaard MC, Civille GV and Carr BT. *Sensory Evaluation Techniques*. 4th ed. Boca Raton: FL: CRC Press: Boca Raton, FL, USA, 2006.
25 Yi Q, Liu JM, Wang GH, Zhang, Y. Evaluation of indoor air quality based on qualitative, quantitative and olfactory analysis. *Chinese Sci Bull* 2013; 58: 986-991.
26 Armijos Moya T and Bluyssen PM. Appraisal and identification of different sources of smell by primary school children in the air quality test chamber of the SenseLab. *Intelligent Buildings International* 2019, 13:2, 142–155.
27 Bluyssen PM, van Zeist F, Kurvers S, Tenpierik M, Pont S, Wolters B, Van Hulst L, Meertins D. The creation of SenseLab: a laboratory for testing and experiencing single and combinations of indoor environmental conditions. *Intell Build Int* 2018; 10: 5-18.
28 Gunnarsen L and Fanger PO. Adaptation to indoor air pollution. *Environ Int* 1992; 1: 43-54.
29 Armijos Moya T, van den Dobbelsteen A, Ottelé M, Bluyssen PM. Using indoor living wall systems as a climate control method in hot humid climates. In *Proceedings of the international scientific conference Healthy Buildings 2017 Europe*, Lublin, Poland, 2017. *[0066]*.
30 Armijos Moya T, van den Dobbelsteen A, Ottelé M, Bluyssen PM. Green air conditioning: Using indoor living wall systems as a climate control method. *Rehva Journal* 2017: 3, 27-31.
31 Fang L, Clausen G and Fanger PO. Impact of temperature and humidity on the perception of indoor air quality. *Indoor Air-International Journal of Indoor Air Quality and Climate* 1998; 8: 80-90.
32 Fang L, Clausen G and Fanger PO. Temperature and Humidity: Important Factors for Perception of Air Quality and for Ventilation Requirements. *ASHRAE transactions* 2000; 106(2): 503-510.
33 Siebielec S, Wozniak M, Galazka A, Siebielec G. Microorganisms as Indoor and Outdoor Air Biological Pollution. *Adv Microbiol-Ny* 2020; 59: 115-127.
34 Bringslimark T, Hartig T and Patil GG. The psychological benefits of indoor plants: A critical review of the experimental literature. *J Environ Psychol* 2009; 29: 422-433.
35 White EV and Gatersleben B. Greenery on residential buildings: Does it affect preferences and perceptions of beauty? *J Environ Psychol* 2011; 31: 89-98.
36 Fanger PO. Introduction of the olf and the decipol units to quantify air pollution sources perceived by humans indoors and outdoors. *Energ Buildings* 1988; 1: 1-6.
37 Vroon PA. *Psychologische aspecten van ziekmakende gebouwen [Psychological Aspects of Building Related Illness]*. Utrecht, The Netherlands: Rijkuniversiteit Utrecht, the Netherlands, 1990.
38 Dalton P. Odor perception and beliefs about risk. *Chem Senses* 1996; 21: 447-458.

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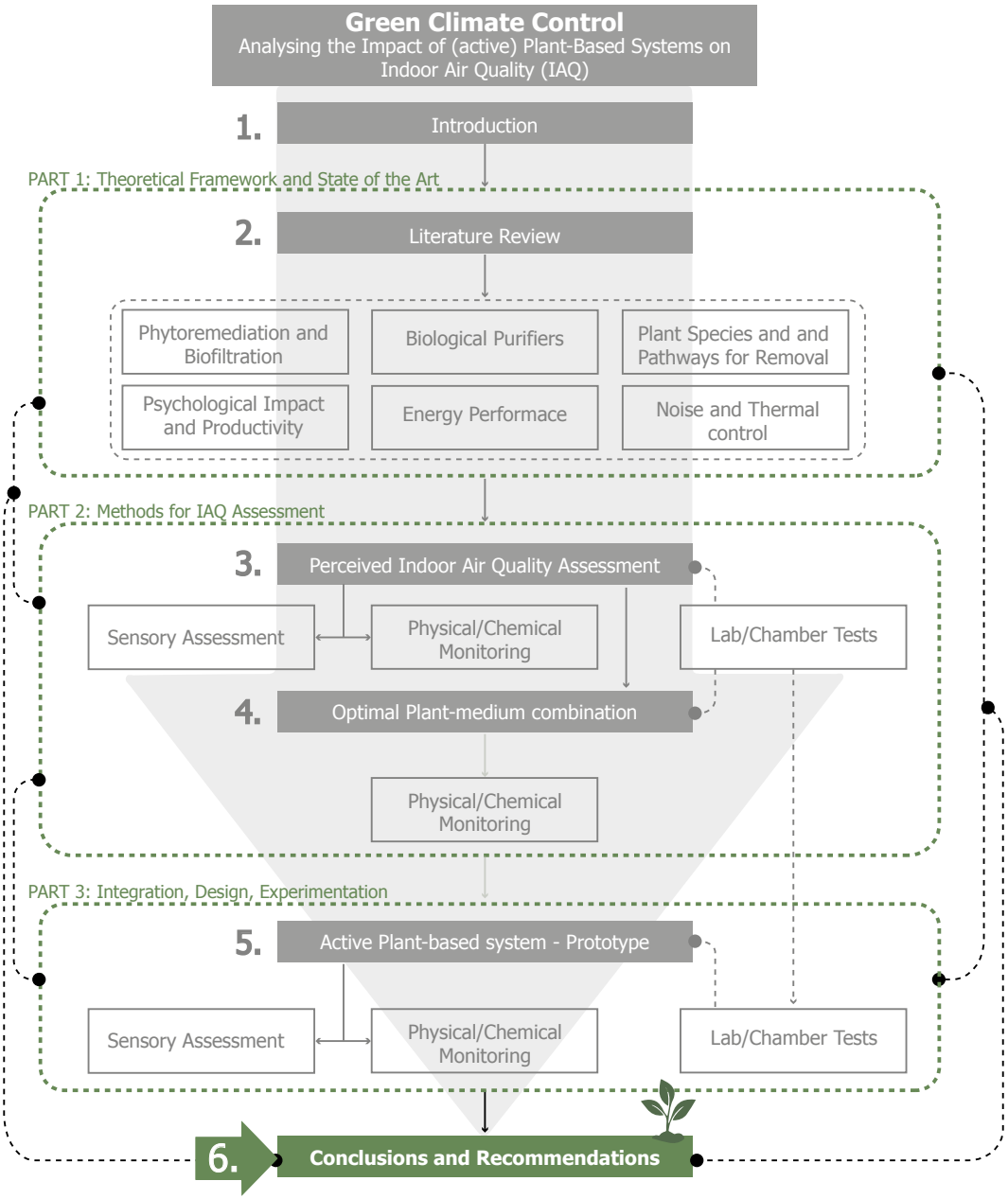
Green Climate Control
Analysing the Impact of (active) Plant-Based Systems on Indoor Air Quality (IAQ)
1.
Introduction
PART 1: Theoretical Framework and State of the Art
2.
Literature Review
Phytoremediation and Biofiltration
Biological Purifiers
Plant Species and and Pathways for Removal
Psychological Impact and Productivity
Energy Performace
Noise and Thermal control
PART 2: Methods for IAQ Assessment
3.
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6 Conclusions and Recommendations

6.1 Introduction

The main goal of this PhD study was to explore and evaluate the efficacy of an active plant-based system in terms of IAQ. This was achieved through laboratory studies of several plant-based systems, including both chemical and sensorial measurement techniques as well as qualitative and quantitative assessments. This final section summarises and discusses the main outcomes of the dissertation. First, responses to the research questions are presented, starting with the sub-questions and their specific findings as partial outcomes that lead to a wide-ranged response to the main research question. Furthermore, this chapter defines the scientific contributions and limitations of the study. Finally, this chapter will propose recommendations for future developments and research regarding the implementation of (active) plant-based systems in the indoor environment at individual and room levels.

6.2 Conclusions: Answers to the research questions

6.2.1 Sub-Research Questions

— What is the available knowledge regarding indoor greenery in the built environment? (Chapter 2)

This first sub-question aimed to present a general overview of the state of the art of plant-based systems in the indoor environment as a starting-point for this dissertation, identifying relevant studies and existing knowledge and scientific gaps to expand the background of this study. Based on scientific studies from the past 30 years, a review of the state of art of green systems and their effect on the indoor environmental quality (IEQ) was made[1]. In general, indoor greenery provides many benefits to users in the indoor environment. For instance, biophilic workspaces and interaction with plants may change human attitude and behaviour, and they may improve productivity and overall wellbeing[2–5]. Besides, evapotranspiration from plants helps lowering the temperature around the planting environment and this can be utilised for air cooling and humidity control[6,7]. Moreover, indoor green systems can be used to reduce sound levels as a passive acoustic insulation system[8]. Figure 6.1 summarises the known and unknown effects of indoor vegetation, which is based on previous studies.

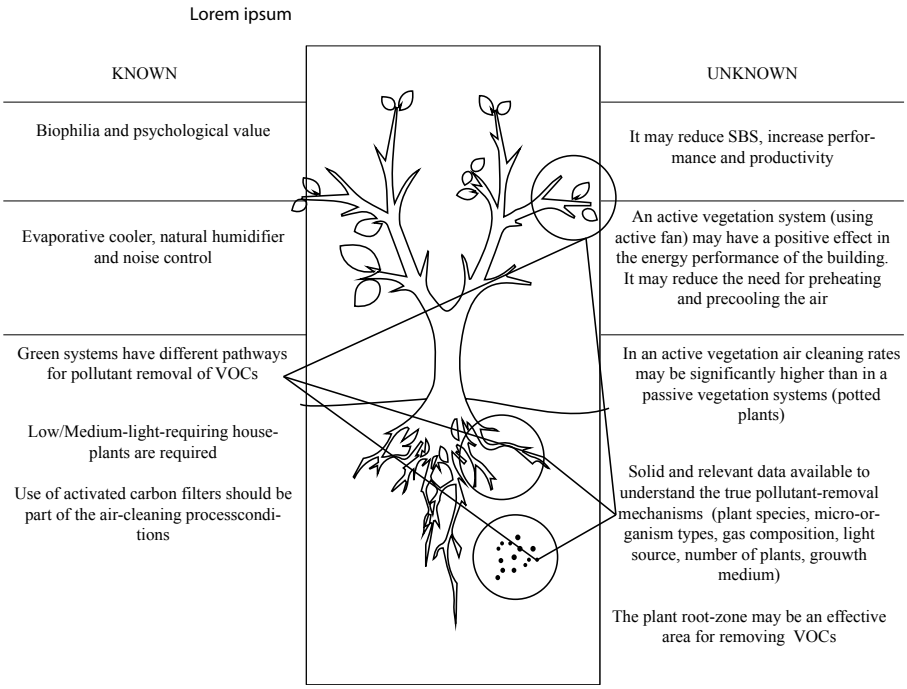

FIG. 6.1 Summary of known and unknown effects of indoor vegetation (See Chapter 2)[1].

Throughout this literature review it was clearly identified that living wall systems, in combination with biofiltration, are emerging technologies that provide beneficial effects on the improvement of IEQ[1]. In fact, the effects of green systems in combination with mechanical elements such as conventional ventilation and air conditioning would need to be studied, and the full capacity of plants in real-life settings will need to be clarified to establish the true pollutant-removal mechanisms and the general effect on IEQ. Taking this into account, it is important to establish the requirements to build an optimum plant-based system, such as the type of plants to be used, optimal lighting and climate conditions and optimal growth medium. Figure 6.2 summarises the plant requirements and its benefits within the indoor environment.

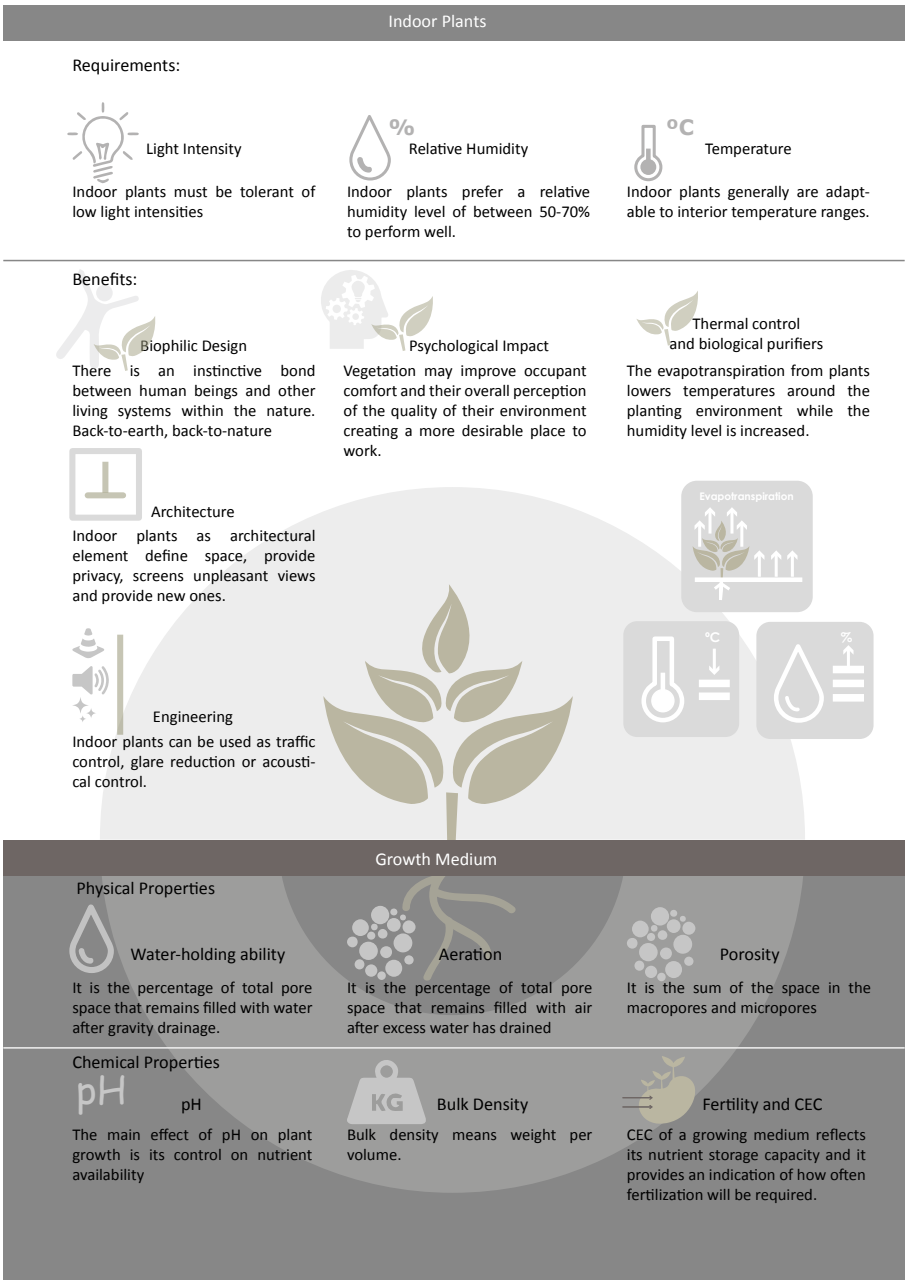

FIG. 6.2 Summary of plant requirements and benefits in the indoor environment (Figure adapted from Armijos Moya et al., 2017)[1,9].

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— How to properly assess plant-based systems in the indoor environment in terms of perceived IAQ? (Chapter 3)

This question aimed to identify proper methods to assess plant-based systems in the indoor environment. After a literature review, it was established that different methods are available for assessing IAQ, such as chemical and physical monitoring and sensory assessment[10]. Overall, the concentrations of the pollutants are usually lower than the instrument detection limit[11,12]. Furthermore, the intensity of odour or smell emitted by different indoor materials was introduced as a measure to assess the VOCs emitted, as some VOCs that are commonly present indoors have been associated with odour and can also cause a variety of undesirable reactions among people, ranging from annoyances and irritations to documented health issues.[11,13]

Sensory assessment of IAQ using human noses as measurement instruments has been used to establish the appropriate ventilation rates that bring body odour intensity to acceptable levels. It also has been used to assess various processes to improve IAQ, based on the use of different materials. Furthermore, people's olfactory system is able to recognise relatively well the perceived odour intensity of various materials and in many cases the nose seems to be a better monitor of pollutants than some equipment[11,14–17]. It is concluded that the optimal method to assess IAQ is to combine scientific instruments (e.g., sensors, PID monitors, emissions detectors, etc.) together with odour measurement procedures.[18,19]

To evaluate different methods for assessing IAQ, an experiment was executed in the Air Quality chamber of the SenseLab[20]. This experiment was conducted as part of a series of experiments related with the indoor environmental quality in classrooms.[21,22] The aim of this experiment was to expose 335 primary-school children to different sources of smell, and ask them to evaluate and identify those sources at individual level with their noses, including the possible effect of plants on the reduction and/or production of smells. Selected sources of odour were placed in different containers and the children were asked how they felt about the smell and to identify their source. These sources of smell were elements commonly found in the indoor environment: perfume, mint leaves, carpet, MDF, vinyl and crayons. Prior to the exposure of the smells to the children, a photoionization detector, ppbRAE300 11.7eV, was used to measure the VOCs emitted by the selected sources of smell[10]. The instrument measured 0 ppb for most of the materials with the exception of the perfume (1800 ppb) and the mint leaves (8 ppb).

The results showed that even though the chemical measurement instrument could not measure any emission in most of the cases, children could perceive clearly smells coming out of the containers, confirming the need of performing both assessments:

sensory evaluations and chemical and physical measurements, to assess IAQ properly. In addition, the study presents statistically significant differences among children's evaluations of different smells, a link between preference and recognition of odours, and no statistical difference in the assessment of the smells when the potted plants were placed inside the CLIMPAQ. The results of the study present that the level of acceptability to the different sources of smell increased when the children were more familiar with it and when they had visual contact with the source.

Finally, the effect of (passive) plants on the perception of smells showed minimal or no impact. Previous lab studies suggested the positive effect of vegetation in IAQ.[23,24] However, all these experiments and studies were executed in control environments without including the user as part of the evaluation process. Therefore, there is no existing data that includes the evaluation of the odour depletion or/and production by indoor vegetation. In this study, potted plants were placed together with new materials to evaluate if the children could identify the same material that was hidden in the sniffing table and which was the effect of the potted plant in this evaluation. The results showed no statistically significant differences with or without the plant present. The setup for this part of the experiment changed every session and the plants were placed with the material for a limited amount of time prior the execution of the assessments. Consequently, for future studies, it is recommended to perform tests with a plant system, over a longer period of time. It might take time for the plant to 'clean' the air, and an active green system might improve the air quality faster than a passive one.

— Which (plant-based) systems or combinations are suited as a solution for improving IAQ? (Chapter 4)

To answer this question and to define the best combinations to develop a plant-based prototype, a laboratory test was executed following a specific protocol to evaluate the biofiltration capacity of two potted plants (Peace Lily and Boston Fern) and three different substrates (expanded clay, soil and activated carbon) to deplete formaldehyde and CO_2 in a glass chamber.

For this study, formaldehyde and CO_2 were selected as indicators to evaluate the biofiltration efficacy of eight different test conditions (1. Boston fern, 2. Peace Lily, 3. Dry expanded clay, 4. Wet expanded clay, 5. Dry soil, 6. Wet soil, 7. Dry activated carbon and 8. Wet activated carbon) throughout 28 evaluations where also relative humidity (RH) and temperature (T) were monitored. To evaluate the efficacy of every test, the Clean Air Delivery Rate (CADR) was calculated. Overall, soil had the best performance in removing formaldehyde (0.07-0.16 m^3/h), while plants were more

effective in reducing CO_2 concentrations (Peace lily 0.01 m^3/h) (Boston fern 0.02-0.03 m^3/h). On average, plants (0.03 m^3/h) were as effective as dry expanded clay (0.02-0.04 m^3/h) in depleting formaldehyde from the chamber. Regarding air cleaning performance, Boston ferns presented the best performance among the plant species, and the best performing substrate was the soil. Figure 6.3 presents a summary and a comparison of the CADR of the 8 test conditions. Based on the results from the tests, the following is concluded:

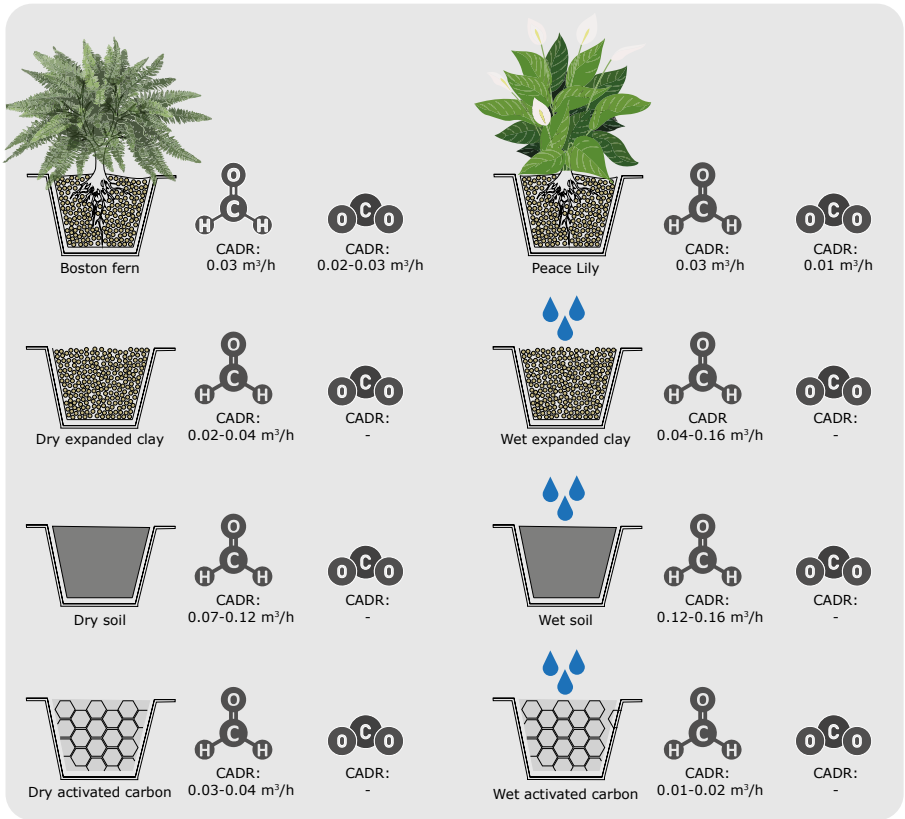

FIG. 6.3 CADR of formaldehyde and CO_2 in the chamber.

— Both plants have similar behaviour on formaldehyde depletion, but Boston ferns depleted CO_2 faster than the Peace Lilies, showing that Boston fern in general has a higher stomatal conductance than the Peace Lily are going to be chosen for future experiments, suggesting the possibility of more absorption the gaseous pollutants in the long term.

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- Growth media had no effect on CO_2 depletion. In some cases the CO_2 levels increased inside the chamber during the tests.

- In terms of formaldehyde depletion, soil was, in general, the most effective among all the tested conditions; wet soil was the most effective. However, in order to develop an effective botanical biofilter, a hydroponic system is required; therefore, it is recommended to use expanded clay so the air can be filtered easier through the growth media, taking into account properties such as aeration, porosity and water holding capacity.

- Lab tests with potted plants in closed chambers are useful to evaluate isolated factors that could improve the removal efficacy of plant-based systems. However, it is also important to evaluate the overall effect of these systems in real settings.

- Does an active plant-based system prototype have the potential to improve IAQ in a semi-lab environment? (Chapter 5)

  This question was answered through the development of an active plant-based system, followed by a study on the performance of the active plant-based system prototype, through quantitative and qualitative assessments by physical measurements and sensory evaluations respectively. The aim of this study was to assess the odour coming out of two different test chambers in the SenseLab, where an untrained human panel completed a questionnaire in four different sessions (Chapter 5). The participants were asked to blindly evaluate the level of acceptability, intensity, odour recognition and preference at individual level with their noses while the temperature, relative humidity and CO_2 levels were constantly monitored.

  Both chambers were furnished with the same amount of new flooring material, while Chamber A also included an active plant-based system. The active plant-based system consisted of 30 potted plants and each plant had a direct connection with its own fan (80 mm diameter, airflow: 52.7 m^3/h, 0.16 A / 12 V, 1.92 W, sound level: 22.4 dB), which was in charge of sucking air through the plant-based system. Figures 6.4 and 6.5 present the diagrams of the setup in chamber A and in chamber B respectively.

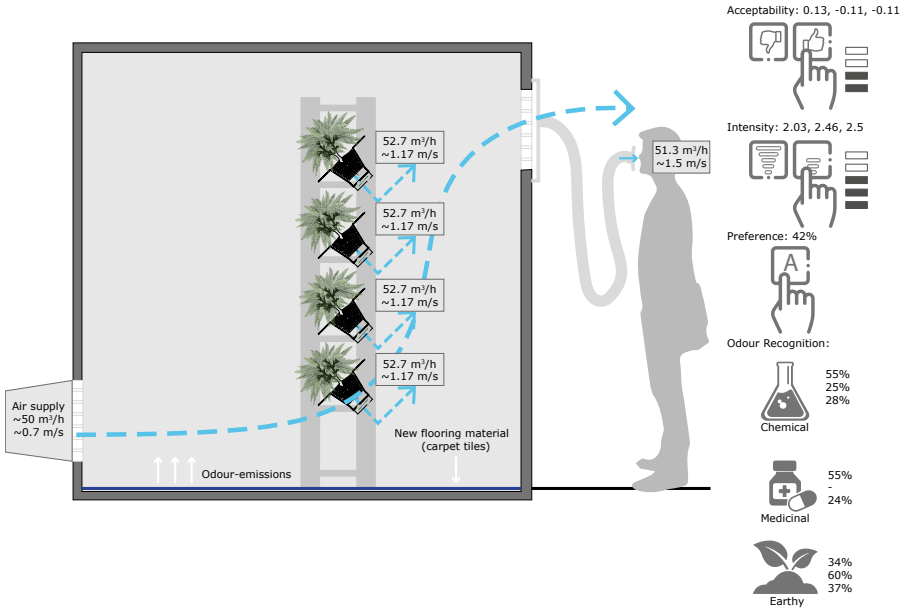

FIG. 6.4 Sensory assessment of chamber A.

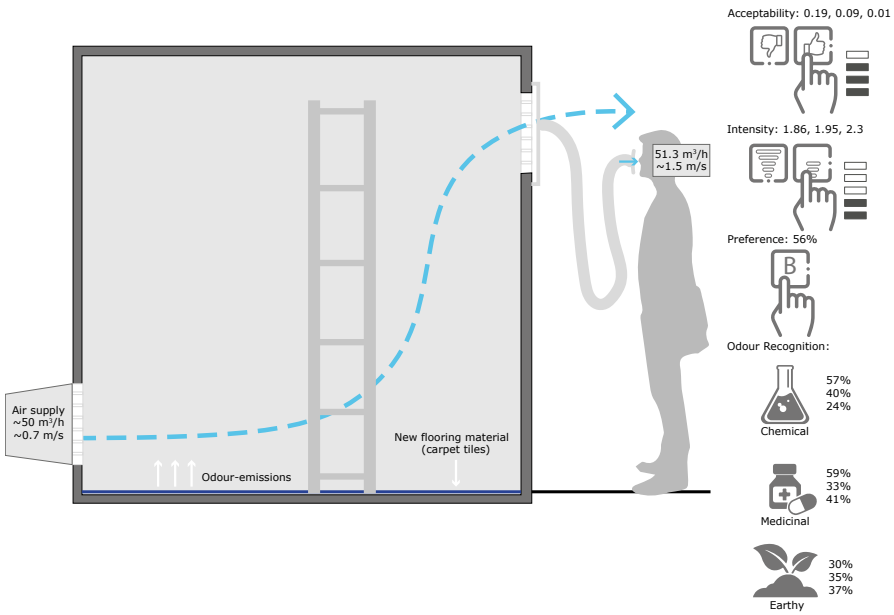

FIG. 6.5 Sensory assessment of chamber B.

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Based on the results from the experiment, the following is concluded (Figures 6.4 and 6.5):

- The level of odour intensity was lower in the chamber without plant (Chamber B).
- The level of acceptability was lower in the chamber with plant (Chamber A).
- The participants identified similar sources in both chambers: chemical, medicinal and earthy.
- The preference was slightly higher for Chamber B over Chamber A. During the first session, the participants showed slightly more preference for Chamber A, but that shifted during session 2 and 3.

In this study, when people did not see the interior details of the room and had to rely on their olfactory perception, they slightly preferred a room without plants over a room with plants. A similar phenomenon was seen and described in Chapter 3, in which primary school children evaluated different sources of smell. The results of that study showed that the level of acceptability of the different sources of smell increased when the children had visual contact with the source and when they felt more familiar with it.[10]

Furthermore, this study confirmed the need to use the human nose as measurement instrument in order to detect volatile organic compounds in terms of perceived air quality, while the chemical measurement instrument was not able to. While the participants identified a 'chemical' - 'medicinal' - 'earthy' smell coming out the chambers, the chemical instrument could not detect any VOCs present in the room.

Another aspect to analyse is the impact of the temperature and the humidity levels in the human perception during the experiment. During the execution of the experiment both chambers were always monitored. In general, Chamber A (average: 19.7°C) was slightly colder than Chamber B (average: 20.1°C) and the RH was also higher in Chamber A (average: 52%) than in Chamber B (average: 43%). Prior studies have shown that changes in temperature and relative humidity levels of the environment may affect the perceived air quality[14,25,26] and could therefore have affected the assessment of the air coming out of the chambers. In fact, the perceived air quality decreases with increasing air temperature and humidity at a constant pollution concentration.[25,26]

Finally, the assessment of both chambers was quite similar according to the participants. This similarity can be explained in Figures 6.4 and 6.5 where the setup of the experiment in both chambers is illustrated. These diagrams show that the air coming inside of the chambers is located in the lower parts of the walls of the rooms directing the air to go directly over the carpet tiles and then out and not through the system, which can explain the similar assessments of both chambers.

6.2.2 Main Research Question

— **Can an active plant-based system improve the indoor air quality (IAQ)?**

The main motivation of this research project was to evaluate and assess the impact of active plant systems in the indoor environment, mainly in terms of IAQ. The aim was to use current assessment methods to evaluate the efficacy of plant-based systems while identifying its technical challenges for the proper application of these systems in the indoor environment.

To sum up, the answer to the main research question "Can an active plant-based system improve the indoor air quality (IAQ)?" is that based on the results of the experiments executed in closed and controlled environments: (1) lab-experiments executed in Wageningen Plant Research at Wageningen University and Research (WUR) and (2) the test-chamber experiments executed in the SenseLab at TU Delft, it is clear that active-plant based systems have an effect in the uptake of gaseous pollutants in the close surrounding of the plant/plant-system. However, important technical constraints need to be solved to conceive a feasible plant-based system for application in buildings. During this research project the following outcomes were identified:

— First of all, to develop an effective plant-based system the proper selection of its components is essential (Chapters 2 and 4) in order to allow a proper biofiltration process. This includes a proper selection of:
  — the plants with a high stomatal conductivity,
  — the growth media that allows the filtration of the air while providing the proper porosity, aeration, and water holding properties to the plants;
  — the materials used for the construction of the system, which should comprise of low emission materials;
  — the air flow through the system in relation to the indoor environment and location of the system.

- In real settings, the concentration of the gaseous pollutants is present in lower levels and current equipment are not able to detect them. During this research project different sensors and equipment were used to measure the concentration of pollutants in the air. For instance, during the chamber experiment in the Senselab, a state-of-the-art photoionization detector (ppbRAE300 11.7eV) was used during the assessment of the active vegetation system. This equipment was not able to measure any VOCs present in the chambers when it was clear that certain pollutants were emitted from the flooring material based on the sensory assessment of the participants in the experiment executed in the SenseLab (Chapter 5). On the other hand, it was easier to measure the effect of VOC depletion from the air in lab studies (Chapter 4) where a higher number of concentrations was used to evaluate the efficacy of the plants in terms of VOCs depletion from the air. Therefore, it is clear and confirmed that physical, chemical and sensory assessments are crucial to evaluate the real impact of plant-based system in the IAQ (Chapters 3, 4 and 5).

- In this research project, different substrates and plants were tested and it became clear that the substrate is an important ally in reducing gaseous pollutants, such as formaldehyde. In terms of air 'cleaning' of formaldehyde, the measurements and analysis showed that in general, the soil was most effective in reducing formaldehyde concentrations in the chamber (~0.07-0.16 m^3/h). Plants (~0.03 m^3/h) were as effective as dry expanded clay (0.02-0.04 m^3/h). Wet and dry soil, wet expanded clay and dry activated carbon performed better than the selected plants in formaldehyde depletion (Chapter 4).

- The polluted air needs to be transported to the vicinity of the plant-based system to be able to uptake the gaseous pollutant (Chapter 4). Therefore, an active plant-based system is needed to potentialize the impact of such systems in the IAQ since the air has to be forced to go through the system in order to achieve the biofiltration process (Chapter 4 and 5).

- An indoor forest is required to meet the minimum standards for ventilation rates in breathing zones just with plants without any extra mechanical ventilation. However, in real situations less plants will be required taking into account the size of the room and the ventilation regime of every situation (Chapter 4).

- Considering the evaluation of the impact of indoor plant-based systems on IAQ, experiments executed in controlled environments such as laboratories and test-chambers are important to isolate and analyse different parts of the system without interference of other aspect. In that way, it is possible to establish the different possibilities and limitations of the system (Chapters 4 and 5).

— Regarding the uptake of gaseous pollutants, the location of the plant-based system within the room is a fundamental factor to take into account. For the assessment of the performance of an active-plant based system in real settings, it is important to identify the location and character of potential sources of pollution. For instance, flooring material creates emissions in the area above the floor, which will rise and mix in the room, depending on the ventilation regime. Therefore, it is important to evaluate the ventilation regime of every situation to evaluate the best option for the location of the plant-based system (Chapter5 and 6).

6.3 Scientific contribution

Next to the specific outcomes from each chapter, aiming at particular knowledge gaps, one of the main scientific contributions of this dissertation is the systematic approach proposed to assess and integrate methodically different strategies in the evaluation of a plant-based systems in terms of IAQ. Previous studies have just focused in the physical and chemical evaluation of the systems without including sensory evaluations and the user perception.

Currently, active plant-based systems and their future integration into the built environment are emerging technologies which impact in real settings and in the users is still under development, which opens an opportunity for further research to optimize the active system at individual level and room level.

6.4 Limitations of the research

While the results provide comprehensive answers to the research questions, certain limitations of the study need to be discussed to take these recommendations for future research. Two main limitations are identified throughout the study; they are discussed here.

First of all, one of the aims of this research was to have an overall analysis of the system and its effect on IAQ. Therefore, including sensory assessments by human subjects were essential for this study. Considering this matter, the evaluation of the active plant-based system should be executed during different seasons to analyse the real effect of the system regarding the human perception. The sensory methods used during this study (category scaling and descriptor profiling) involve a small/large panel size and a non-trained panel,[14] therefore, it would be easier to replicate the test during different seasons.

As mentioned before, active botanical biofiltration systems are relatively new technologies and most of the evaluations of these systems have been performed through (lab/chamber) experiments because it is difficult to model the real physiological effect and behaviour of the plants in the built environment, especially in terms of IAQ. Taking this in account, the development of a prototype was essential for this study to evaluate the impact of an active plant-based system in the IAQ. Subsequently, the concept of active botanical biofiltration was built in one prototype with a fixed airflow rate created for the fans connected to the plants (Figure 5.1). Additionally, Figures 6.4 and 6.5 present the setup of the experiment described in Chapter 5 together with some results of the evaluations in both chambers. These figures show that the room air is supplied in the lower part of the wall of the chamber directing the air to flow over the carpet tiles and not through the system. This airflow pattern might be the reason for the similar perceived air quality assessments of both chambers. It was assumed that the emissions from the new carpet would mix homogeneously in the test chambers. Unfortunately, with this ventilation regime (mechanical air supply below, exhaust through overpressure high), the emissions from the carpet might have been exhausted before passing the plant systems, producing several non-statistically relevant results. Therefore, future prototypes should be tested under different ventilation regimes and different pollution sources, to identify the optimal location, number of active plant systems, for different ventilation regimes and pollution sources, as well as the optimal airflow capacity of the plant system.

6.5 Recommendations for further development

There are three main recommendations for further research and development of active plant-based systems in the indoor environment considering IAQ as it is explained as follows:

First of all, there are two ways of tackling further research, one is based on the effects of plant-based systems at individual level (Figure 6.6) and the other at room level (Figure 6.7). In both situations, there is still the need for further research on how to integrate properly the mechanical component in the vegetation system and which is the appropriate airflow that creates the proper biofiltration effect. In that sense prototyping is needed to proper integrate this active system in the built environment at personal and/or room level. Fundamental research on new prototypes including different airflows, integrated building components, modular components, or/and plug and play units would enhance the potential for proper application of the systems in the built environment.

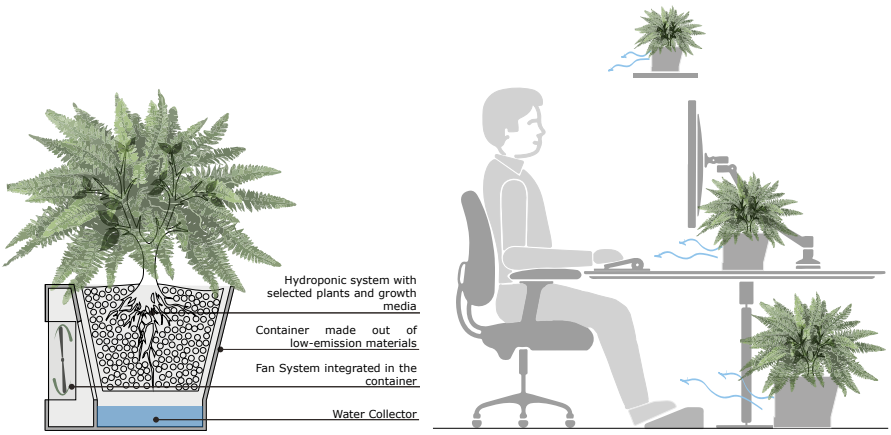

FIG. 6.6 Active plant-based system diagram at personal level.

Figure 6.6 presents a schematic diagram of a personal comfort system (PCS) based on a plant-based system, thus, allowing the evaluation of the system at individual level while enabling the users to control their individual comfort perception[27].

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This relatively new technology should consider users for future evaluations of the system. This assessment should include thermal sensation, acceptability and preference, together with air movement acceptability and preference, providing thermal comfort and help improving the air quality acceptability at an individual level. Furthermore, several PCSs may be required to create a real impact on the perceived IAQ. This is based on the results presented in this research project where it was shown that an indoor forest is required to accomplish the goal of improving IAQ, without considering or/and including any mechanical assistance (e.g., ventilation systems).[28] To establish the number of PCSs based on plants (Figure 6.6) needed to improve the IAQ, a similar experiment presented in Chapter 4 should be executed.

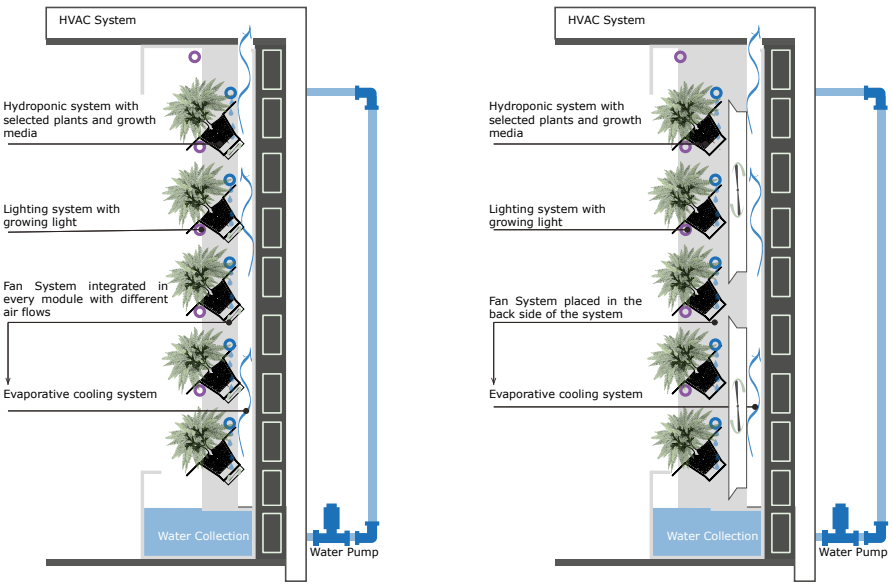

FIG. 6.7 Building-integrated plant-based systems possibilities (room level).

Figure 6.7 presents schematic diagrams of active plant-based systems integrated in the building, including different possibilities of air flow. It is recommended that future studies test different airflow rates to choose the optimal option to improve the active plant-based system. Moreover, to establish the efficacy of these systems in real settings in terms of IAQ, according to the regulations and standards certain aspects should be consider such as, number of occupants present and their activity and clothing behavior; pollution caused by materials used in the building; information regarding smoking; available outdoor air quality; cooling/heating load caused by occupants, machines, illumination, solar radiation, etc.[29] The evaluation of these

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parameters together with the active-plant based system will provide a clear overview of the impact of these systems in the IEQ.

Furthermore, it is fundamental to include the user in the evaluation of the system, not just including the psychological impact of biophilic designs but also scientist should consider other physical impacts of the systems in the user since plants are also producers of indoor pollutants themselves. Therefore, a multidisciplinary team is recommended for further assessment of the system.

Finally, the market of biophilic design and indoor landscape is growing and well established. Therefore, research on innovative business models for the better integration of these systems in the built environment could create new incentives for the development and application of these active plant-based systems. Taking in account this point it is fundamental to evaluate the efficacy of plant-based systems in terms of energy consumption and general costs.

References

1 Armijos Moya T, van den Dobbelsteen A, Ottelé M, Bluyssen PM. A review of green systems within the indoor environment. *Indoor Built Environ.* 2019;28(3):298-309.

2 Gray T, Birrell C. Are Biophilic-Designed Site Office Buildings Linked to Health Benefits and High Performing Occupants? *Int J Env Res Pub He.* Dec 2014;11(12):12204-12222.

3 Lohr VI, Pearson-Mims CH, Goodwin GK. Interior plants may improve worker productivity and reduce stress in a windowless environment. *Journal of Environmental Horticulture.* 1996;14:97-100.

4 Relf PD. Psychological and Sociological Response to Plants - Implications for Horticulture. *Hortscience.* Jan 1990;25(1):11-13.

5 Shoemaker CA, Randall K, Relf PD, Geller ES. Relationships between Plants, Behavior, and Attitudes in an Office Environment. *HortTechnology.* 1992;(2):205-206.

6 Davis MM, Hirmer S. The potential for vertical gardens as evaporative coolers: An adaptation of the 'Penman Monteith Equation'. *Build Environ.* Oct 2015;92:135-141.

7 Armijos Moya T, van den Dobbelsteen A, Ottelé M, Bluyssen PM. Using indoor living wall systems as a climate control method in hot humid climates. In *Proceedings of the international scientific conference Healthy Buildings 2017 Europe,* Lublin, Poland, 2017. *[0066].*

8 Davis MJM, Tenpierik MJ, Ramirez FR, Perez ME. More than just a Green Facade: The sound absorption properties of a vertical garden with and without plants. *Build Environ.* May 2017;116:64-72.

9 Armijos Moya T, van den Dobbelsteen A, Ottelé M, Bluyssen PM. Green air conditioning: Using indoor living wall systems as a climate control method. *Rehva Journal* 2017: 3, 27-31.

10 Armijos Moya T and Bluyssen PM. Appraisal and identification of different sources of smell by primary school children in the air quality test chamber of the SenseLab. *Intelligent Buildings International* 2019, 13:2, 142–155.

11 Bluyssen PM. Sensory evaluation of indoor air pollution sources. In: P P, ed. *Indoor Air Pollution.* Springer, Berlin, Heidelberg; 2004:179-217.

12 Yan LC, Liu JM, Jiang S, Wu CD, Gao KW. The Regular Interaction Pattern among Odorants of the Same Type and Its Application in Odor Intensity Assessment. *Sensors-Basel.* Jul 2017;17(7)

13 Nicell JA. Assessment and regulation of odour impacts. *Atmos Environ.* Jan 2009;43(1):196-206.

14 Berglund B, Bluyssen PM, Clausen G, Garriga-Trillo A, Gunnarsen L, Knoppel H, Lindvall T, MacLeod P, Molhave L, Winneke G. *Sensory evaluation of indoor air quality.* Report no. 20, 1999. European Commission Report: European Collaborative Action: Indoor Air Quality and its Impact on Man: Luxembourg city, Luxembourg, 1999.

15 Bluyssen PM. *Air quality evaluated by a trained panel.* Doctoral Dissertation. Technical University of Denmark; 1990.

16 Knudsen HN, Clausen G, Fanger PO. Sensory characterization of emissions from materials. *Indoor Air-International Journal of Indoor Air Quality and Climate.* Jun 1997;7(2):107-115.

17 Meilgaard MC, Civille GV, Carr BT. *Sensory Evaluation Techniques.* 4th ed. FL: CRC Press; 2006.

18 Brattoli M, de Gennaro G, de Pinto V, Loiotile AD, Lovascio S, Penza M. Odour Detection Methods: Olfactometry and Chemical Sensors. *Sensors-Basel.* May 2011;11(5):5290-5322.

19 Walker JC. The performance of the human nose in odour measurement. *Water Sci Technol.* 2001;44(9):1-7.

20 Bluyssen PM, van Zeist F, Kurvers S, et al. The creation of SenseLab: a laboratory for testing and experiencing single and combinations of indoor environmental conditions. *Intell Build Int.* 2018;10(1):5-18.

21 Bluyssen PM, Zhang D, Krooneman AJ, Freeke A. The effect of wall and floor colouring on temperature and draught feeling of primary school children. presented at: Clima 2019; 2019; Bucharest, Romania.

22 Bluyssen PM, Zhang Dd, Kurvers S, Overtoom M, Ortiz-Sanchez M. Self-reported health and comfort of school children in 54 classrooms of 21 Dutch school buildings. *Build Environ.* Jun 15 2018;138:106-123.

23 Dela Cruz M, Christensen JH, Thomsen JD, Muller R. Can ornamental potted plants remove volatile organic compounds from indoor air? - a review. *Environ Sci Pollut R.* Dec 2014;21(24):13909-13928.

24 Soreanu G, Dixon M, Darlington A. Botanical biofiltration of indoor gaseous pollutants - A mini-review. *Chem Eng J.* Aug 1 2013;229:585-594.

25 Fang L, Clausen G, Fanger PO. Impact of temperature and humidity on the perception of indoor air quality. *Indoor Air-International Journal of Indoor Air Quality and Climate.* Jun 1998;8(2):80-90.

26 Fang L, Clausen G, Fanger PO. Temperature and Humidity: Important Factors for Perception of Air Quality and for Ventilation Requirements. *ASHRAE transactions*. 2000;106(2):503-510.
27 Rawal R, Schweiker M, Kazanci OB, Vardhan V, Jin Q, Lin DM. Personal comfort systems: A review on comfort, energy, and economics. *Energ Buildings*. May 1 2020;214
28 Armijos Moya T, de Visser P, van den Dobbelsteen A, Ottelé M, Bluyssen PM. Air cleaning performance of two species of potted plants and different substrates.*(Under review)*. 2020, doi: 10.21203/rs.3.rs-314387/v1
29 NEN-NPR-CR-1752. Ventilation for buildings - Design criteria for the indoor environment. Delft, the Netherlands: *Nederlands Normalisatie-instituut*; 1999.

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Appendices

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APPENDIX A

Chapter 3 / Questionnaire: Perceived Indoor Air Quality Assessment

Luchtkwaliteit

School naam: Groep:
Person ID: _____ Datum:

Welkom in de luchtkamer! In deze kamer kun je je geurzintuig testen. Je krijgt een aantal verschillende geuren te ruiken en daarover zullen een aantal vragen worden gesteld.

Je mag een paar keer ruiken aan elk van de trechters. Probeer tussendoor even een pauze te nemen om niet gewend te raken aan de geur en te zorgen dat je de volgende geur nog kan ruiken.

Trechter 1: Hoe vind je de geur?

☐  ☐  ☐  ☐  ☐ 

Wat denk je dat het is? _____

Trechter 2: Hoe vind je de geur?

☐  ☐  ☐  ☐  ☐ 

Wat denk je dat het is? _____

Trechter 3: Hoe vind je de geur?

☐  ☐  ☐  ☐  ☐ 

Wat denk je dat het is? _____

Trechter 4: Hoe vind je de geur?

☐  ☐  ☐  ☐  ☐ 

Wat denk je dat het is? _____

Grote Trechter 5: Hoe vind je de geur?

☐  ☐  ☐  ☐  ☐ 

Welke andere trechter heeft dezelfde geur als deze?
Trechter 1 ☐ Trechter 2 ☐ Trechter 3 ☐ Trechter 4 ☐

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APPENDIX B

Chapter 5 / Questionnaire: Active Plant-based system (NL/EN)

Questionnaire: Active Plant-based system (NL)

Groep: Datum:

Geurtest

Het doel van deze geurtest is het beoordelen van lucht die verontreinigd is met bronnen die je tegenkomt in het binnenmilieu. De antwoorden zullen worden gebruikt voor de PhD studie van Tatiana Armijos Moya. Alle verzamelde gegevens zullen vertrouwelijk worden gebruikt.

Persoonlijke informatie

1. Leeftijd: _____ jaar
2. Je bent een ☐ vrouw ☐ man
3. Ben je op dit moment verkouden? ☐ ja ☐ nee
4. Lijd je aan astma, COPD of andere longaandoening? ☐ ja ☐ nee

Beoordelingen: Je wordt gevraagd te ruiken aan twee trechters. Neem een snif van 1 van de trechters en beoordeel hieronder hoe sterk je de geur vindt en hoe acceptabel je de luchtkwaliteit vindt. Daarna neem je een snif van de tweede trechter en doe je hetzelfde. Vervolgens kun je op de achterkant aangeven waarnaar de geur ruikt.

Trechter 1	Trechter 2
Hoe sterk is de geur die je ruikt? Geef je oordeel middels een kruisje of streepje op de schaal hieronder.	
0 Geen geur 1 Zwakke geur 2 Geur 3 Sterke geur 4 Erg sterke geur 5 Overweldigende geur	0 Geen geur 1 Zwakke geur 2 Geur 3 Sterke geur 4 Erg sterke geur 5 Overweldigende geur
Stel je voor dat je gedurende de dag wordt blootgesteld aan deze luchtkwaliteit, hoe acceptabel vind je dan de lucht? Geef je oordeel middels een kruisje of streepje op de schaal hieronder.	
Duidelijk acceptabel Net acceptabel Net niet acceptabel Duidelijk niet acceptabel	Duidelijk acceptabel Net acceptabel Net niet acceptabel Duidelijk niet acceptabel

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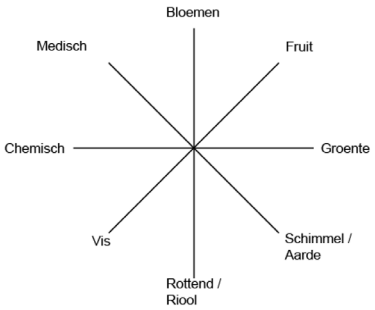
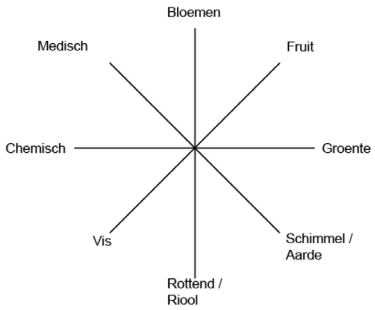
Groep: Datum:

Wat ruik je? Omcirkel de beschrijving of beschrijvingen.	
	
Welke trechter heeft je voorkeur?	
1	2

Questionnaire: Active Plant-based system (EN)

Date: _____

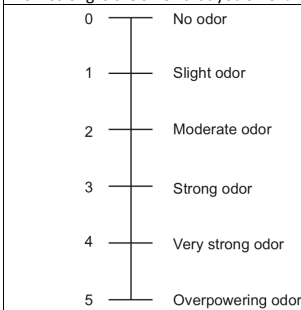
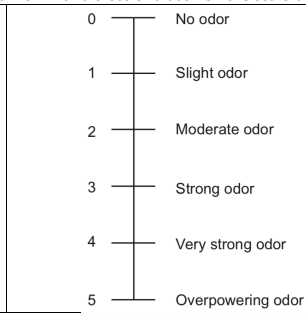
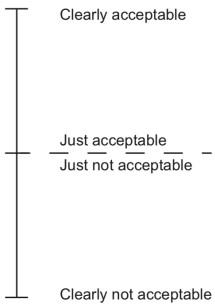
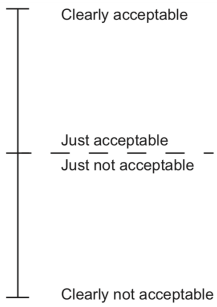
Sniffing test

The purpose of this test is to assess air that is exposed to sources that you encounter in the indoor environment. The answers will be used for the PhD study of Tatiana Armijos Moya. All data collected will be used confidentially.

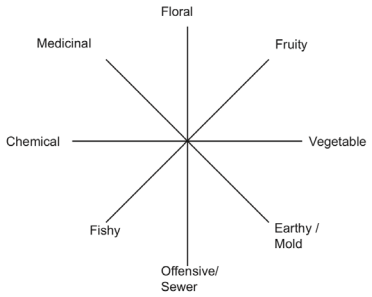
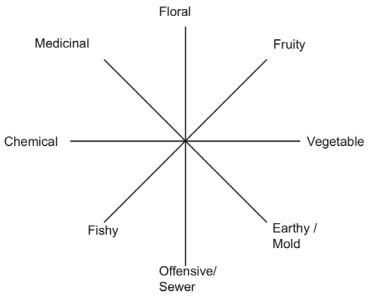
Personal Information

1. Age: _____
2. Gender: ☐ woman ☐ man
3. Are you currently suffering from a cold? ☐ yes ☐ no
4. Do you suffer from asthma or other lung disease? ☐ yes ☐ no

Assessments: You are asked to smell two funnels. Take a sniff of funnel 1 and assess how strong you find the smell and how acceptable you find the air quality. You can then indicate what the scent smells like and your preference. Then you take a sniff from funnel 2 and do the same.

Funnel 1	Funnel 2
How strong is the smell that you smell? Give your opinion with a cross or a dash on the scale below.	
	
Imagine being exposed to this air quality during the day, how acceptable do you think the air is? Give your opinion with a cross or a dash on the scale below.	
	

Date: _____

What do you smell? You can choose more than one option	
	
Which funnel do you prefer?	
1	2

Chapter 5 / Experiment Set-Up

Chamber A: Including the active plant-based system

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Chamber B:

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Sniffing Test in the SenseLab:

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Curriculum Vitæ

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List of Publications

Armijos Moya T, Ottelé M, van den Dobbelsteen A, Bluyssen PM. The Effect of an Active Plant-Based System on Perceived Air Pollution. *Int. J. Environ. Res. Public Health* 2021,18, 8233. https:// doi.org/10.3390/ijerph18158233

Armijos Moya T, de Visser P, van den Dobbelsteen A, Ottelé M, Bluyssen PM. Air cleaning performance of two species of potted plants and different substrates. *(Under review)* . 2021, doi: 10.21203/rs.3.rs-314387/v1

Armijos Moya T and Bluyssen PM. Appraisal and identification of different sources of smell by primary school children in the air quality test chamber of the SenseLab. *Intelligent Buildings International* 2019, 13:2, 142–155.

Armijos Moya T, Zhang D, Bluyssen PM. Perceived Air Quality of different sources of smell evaluated by primary school children. *E3S Web of Conferences*, 2019, 111, [06043]. *https://doi.org/10.1051/e3sconf/201911106043*

Armijos Moya T, van den Dobbelsteen A, Ottelé M, Bluyssen PM. A review of green systems within the indoor environment. *Indoor Built Environ.* 2019;28(3):298-309.

Armijos Moya T, van den Dobbelsteen A, Ottelé M, Bluyssen PM. Botanical Biofiltration: Experimental Protocol and Method. Abstract from Indoor Air 2018: *15th Conference of the International Society for Indoor Air Quality and Climate (ISIAQ)*, Philadelphia, United States. 2018

Armijos Moya T, van den Dobbelsteen A, Ottelé M, Bluyssen PM. Using indoor living wall systems as a climate control method in hot humid climates. In *Proceedings of the international scientific conference Healthy Buildings 2017 Europe,* Lublin, Poland, 2017. *[0066].*

Armijos Moya T, van den Dobbelsteen A, Ottelé M, Bluyssen PM. Green air conditioning: Using indoor living wall systems as a climate control method. Rehva Journal 2017: 3, 27-31.

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Green Climate Control

Analysing the impact of (active) Plant-based Systems on Indoor Air Quality

Tatiana Armijos Moya

Several studies have demonstrated the potential of botanical biofiltration and phytoremediation to remove indoor pollutants and improve overall comfort. However, there is a lack of evidence on how indoor greenery affects the Indoor Environmental Quality (IEQ), particularly on Indoor Air Quality (IAQ). The main goal of this research project was to explore and evaluate the efficacy of an active plant-based system in terms of IAQ and being able to answer the main research question: "Can an active plant-based system improve the Indoor Air Quality (IAQ)?" This was achieved through laboratory studies of several plant-based systems, including chemical, physical and sensorial evaluations as well as qualitative and quantitative assessments. Some of the outcomes of this research are described below:

- To develop an effective plant-based system the proper selection of its components is essential.
- In real settings, the concentration of the gaseous pollutants is present in lower levels and current equipment are not able to detect them. Therefore, it is clear and confirmed that physical, chemical and sensory assessments are crucial to evaluate the real impact of plant-based system in the IAQ.
- In this project, different substrates and plants were tested and it became clear that the substrate is an important ally in reducing gaseous pollutants, such as formaldehyde.
- The polluted air needs to be transported to the vicinity of the plant-based system to be able to uptake the gaseous pollutant. Therefore, an active plant-based system is needed to potentialize the impact of such systems in the IAQ since the air has to be forced to go through the system to achieve the biofiltration process.
- An indoor forest is required to meet the minimum standards for ventilation rates in breathing zones just with plants without any extra mechanical ventilation.

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