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TNO report
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Effects of plant systems on air quality

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Summary

This report describes a study in which the air purifying efficiency of selected systems was investigated under realistic, reproducible laboratory conditions. The aim of this study was primarily to determine the potential of air-purifying plant systems (plants with ventilation systems) to remove particulate matter (PM) and volatile organic compounds (VOC) from air. There are no standard methods available to determine the effect of plant-based or other systems to improve indoor air. Therefore, an experimental set-up and method was developed and tested, which gives the opportunity to translate the results of the laboratory study to real life conditions. For this, a new experimental set-up (a climatic chamber) was used with high-end reference equipment to measure air quality and where specific concentrations of PM and VOC can be generated. The performance of several systems for improvement of indoor air quality was measured. For this project, 6 air purifying plant systems were selected (Natede, Clairy, iGreen backpack, Living Painting, Green Tower and Green Art Solutions wall), and 2 mechanic air purifying systems that use classical filters (Philips Aerasense and Dyson).

The approach in this study was as follows: 1) generate gases with formaldehyde, as an example VOC and aerosols, in the climatic chamber, 2) measure how fast the concentration of gases and aerosols in the chamber decrease with air purifying systems in the chamber and 3) determine how fast the concentration decreases in the absence of an air purifying system.

From our experiments we concluded that the mechanical air purifier systems have the highest removal rates for aerosols, followed by the Green Art Solutions wall, iGreen backpack, Green Tower and Natede. The Living Painting and Clairy showed no purification effect. The Green Art Solutions wall has the highest removal rate for formaldehyde, followed by the Aerasense, Green Tower and iGreen backpack, the Living Painting and Clairy. The Natede and the Dyson showed no removal.

The observed removal rates were extrapolated to a model living room with a realistic retention time of 120 minutes (a measure of the ventilation rate compared to the volume of the house). The impact of the system was estimated in a situation that would have been reached after a few hours of ventilation and a constant concentration in the ambient air concentration. Without an air purifying system, the aerosol concentration was reduced by 41%, this is due to atmospheric deposition on the walls and floor. For the plant systems the removal ranged between 41% and 50%. The mechanical systems showed a much higher aerosol removal ranging from 71% to 87%. This is related to their high flow rate.
In the absence of an air purifying system, the formaldehyde concentration was reduced by 25%. For the plant systems the removal ranged between 23% and 37%, except for the Green Art Solution wall, that had with 68% the highest removal percentage. This was even higher than the Aerasense which was 40%. The Dyson did not remove formaldehyde.

The setup and methods in this study are new and no comparable studies have been found in literature. The experiments were also limited in time, it is not clear how plant systems (where living plants form the base) perform in the longer term. More and longer experiments are needed to determine this. The extrapolation from a stainless

steel test chamber to a model living room should be considered indicative, since furniture and curtains will affect the removal rate in real life as well.

Even with these limitations, this simple and unique study show how plant systems can contribute to an improvement of the indoor air quality.

Contents

1 Introduction

People spend most of their time indoors. And indoor air pollution is therefore an issue regarding exposure of people. In recent years, various systems have been developed to improve indoor air quality. Some of these systems are equipped with classical filters, like High-Efficiency Particulate Air (HEPA) and activated carbon (AC) filters. Recently systems have been developed, in which plants are used in an airflow device to clean indoor air. This is extra interesting, because plants have an additional beneficial effect (“a feel-good effect”), in addition to the filtering effect.

This report describes a study, in which the air cleaning efficiency of the systems is investigated under realistic, reproducible laboratory conditions. The aim of this study is to determine the potential of air-purifying plant systems to remove particulate matter and secondly volatile organic compounds (VOC) from air.
The study was split up in two phases. In the first phase the set-up to determine the purifying effect of the systems on indoor air quality was built and tested. In the second phase, the actual performance of several air-purifying systems was measured, using the new set-up.

1.1 Tested plant systems

Within this project, 6 air purifying plant systems are selected, next to 2 mechanical air purifying systems. The mechanical system use filters. The tested systems were chosen and provided via Stichting Innovatie Glastuinbouw Nederland (SIGN), our contractor. Below a short description of the tested systems is given. It should be noted that parts of these descriptions have been taken from documentation provided by the manufacturer or seller and are no qualifications by TNO. These parts are shown in *italic*. A cost indication is given in Table 1.

Natede[1]
The Natede is natural air purifier for home and office. It uses advanced sensors and a photocatalytic filter covered with photo-active titanium dioxide to capture and eliminate VOCs, viruses, odors, and bacteria. Photocatalysis is a natural process that takes place when the light strikes a mineral such as titanium dioxide and activates a chemical process that decomposes the organic matter at the molecular level. The Natede amplifies the natural phytoremediation power of plants to eliminate VOCs from the air indoors. Natede features sensors that can accurately measure the temperature and humidity, as well concentrations of pollutants (VOCs), fine particulates (PM2.5), and carbon monoxide (CO). Natede Premium includes an additional sensor for carbon dioxide (CO_2) (http://www.natede.com/). The Natede, including a Blue Fern as tested in the climatic chamber, is shown in Figure 1. *The airflow is given as 400 L/min*.

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[1] It should be noted that parts of these descriptions have been taken from documentation provided by the manufacturer or seller and are no qualifications by TNO.

Figure 1 Natede with Blue Fern

Clairy[1]

The Clairy is the previous version of the Natede. *It is a filter less natural air purifier. A fan pulls air through the root zone of the plant, where it is then filtered. Sensors send information about air quality, temperature and humidity via Wi-Fi to an app on your phone. The product is easy to use, with no filters to replace and a handy self-watering system* (https://clairy.com/). The Clairy, including a Blue Fern as tested in the climatic chamber, is shown in Figure 2. *The airflow is given as 25L/min*.

Figure 2 Clairy with Blue Fern

'Living' Painting[1] *with fan*

The 'Living' Painting also has a fan to pull air from the roots of the plant, which is surrounded with a moistened cloth. Here the air is not going through the roots, but along the soil with the roots. It has six different types of plants as shown in Figure 3. *It has the same sensor unit for ventilation and air quality as the Clairy. Therefore, the airflow is also given as 25 L/min.*

Figure 3 ‘Living’ Painting with plants

iGreen backpack[1]

The iGreen, designed by Stichting Innovatie Glastuinbouw Nederland (SIGN), is a portable air purifier to be used by children (Fytagoras, year unknown). *The iGreen plant bag uses its natural filtration power to actively filter the air indoors and outside. An essential living filter that provides clear air. It filters particulate matter (smog, dust) as well as chemical pollutants (VOCs) from vehicle exhaust, industry and interior sources* (iGreen folder; SIGN).
A low-voltage electric fan directs ambient (polluted) air through moist soil with plant purifying microbes, a plant selected especially for its air cleaning properties and an additional mechanical HEPA filter. There are 3 natural processes at work: microbes on plant’s roots, the plants themselves and soil and water filtration. The natural filtration power is supercharged through ventilation. The soil functions as a prefilter of the HEPA filter too, thus increasing life span of the HEPA filter. Together with a dedicated mask, the iGreen provides clean air when going to school and at home or in the classroom (iGreen folder; SIGN). A schematic view of the iGreen is shown on the left side of Figure 4. On the right side a picture of the set-up, as used for the experiment, is presented. *For the iGreen an airflow of 60 L/min is given*.

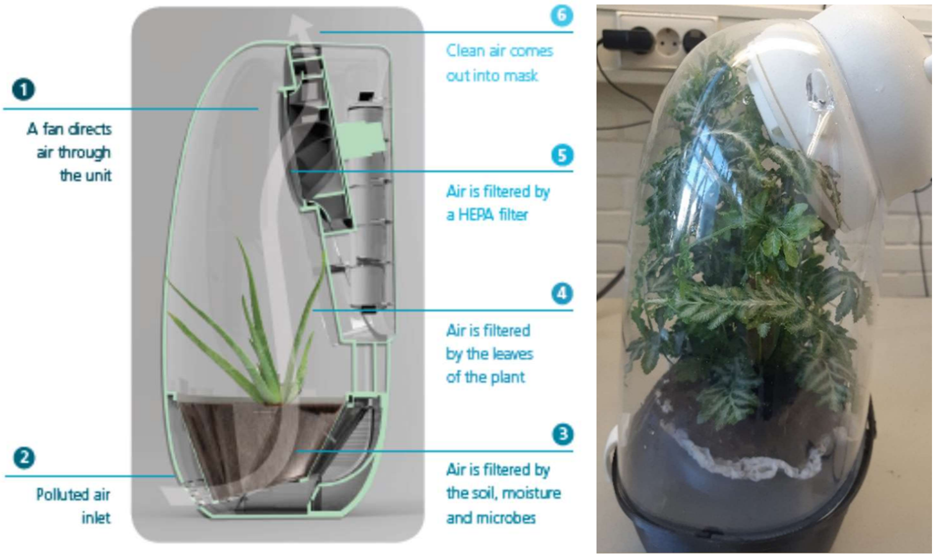

Figure 4 Left: Schematic view of the mechanism of the iGreen; right: iGreen as used for the experiments.

Green Tower[1]

The Green Tower also uses a fan to pull air towards the roots area of the plant. It has three rows of 5 Ferns (15 plants in total) as shown in Figure 5. *The Green Tower has the same unit with ventilation and air quality sensors as the Clairy, blowing air from the top .The plants are placed in the tower without the pots and a cloth was wrapped around the soil with the roots to increase the air cleaning capacity. Here also an airflow of 25 L/min is given*.

Figure 5 Green Tower with 15 Ferns.

Green Art Solutions wall[1]

The Green Art Solutions wall as used in this project, is a prototype (scale model) of an even larger system (Figure 6). *The wall includes a ventilating system to pull air* *through the roots area of the plants*. The wall contains 4 trays with several different plants. A fifth tray, that can be placed at the bottom, can be used as a self-watering system. This tray is not used during the experiments, as it is heavy and laborious when replacing the whole system.

Figure 6 The Green Art Solutions wall including plants

*Philips Aerasense[1] air purifier (*AC2887)

The Philips Aerasence air purifier measures and purifies automatically (Figure 7). *It contains a sensor that detects particles smaller than 2.5 μm (PM2.5), including most present allergens in indoor air, to acquire the optimal air quality and has an AC-filter (Activated Carbon) and HEPA-filter (High-Efficiency Particulate Air). The Aerasense has 3 settings, the general modus, an extra sensitive allergen modus and an, extra strong, bacteria and virus modus and different fan rates. The Aerasense removes particles as small as 20 nm, and toxic gases such as formaldehyde, and compounds classified as TVOC (Total Volatile Organic Compounds) and odours and up to 99.9% of bacteria. An airflow up to 333 m^3/h (= 5550 L/min) is possible*.

Figure 7 The Philips Aerasense air purifier (AC2887).

Dyson[1]

The Dyson contains several sensors to measure air quality and automatically removes odours and particulate matter (Figure 8). Just as the Aerasense, the Dyson has a HEPA-filter. *An airflow up to 97 m*^{3}*/h (= 1617 L/min) is possible, which can be arranged by different positions of the fan rate*.

Figure 8 The Dyson Pure Cool Link Tower Blue

Table 1 Cost indication for the selected air purifying systems (data provided by SIGN).

System	Consumer price including VAT	Remarks
Clairy	€250	
Natede	€350	
Living Painting	€800	Prototype – expected price
iGreen	€250	Prototype – expected price
Green Tower	€1500	
Green Art Solutions wall	>€1500	Depending on desired surface
Philips Aerasense AC2887	€260	
Dyson Pure Cool Link Tower	€500	

2 Test set-up and method

2.1 Introduction

There are no standard methods available to determine the effect of plant-based or other systems to improve indoor air quality. Therefore, a new experimental set-up was developed. For this set-up, our climatic chamber is used where reference, high-end equipment to measure air quality can be used and accurate concentrations of PM and VOCs can be generated.

In the first phase the following activities were carried out:
1. set up the climatic chamber
2. install and test the monitoring equipment
3. test the generation of test gases and aerosols
4. design and test the whole set-up and procedures
5. and determine blank values

In the second phase the approach was as follows:
1. Generate gases in the chamber
2. See how fast the concentration of gases and aerosols decreases *with a*nd *without* the (plant) air purifying systems
3. Determine how fast the concentration decreases in the absence of an air purifying system. There are two reasons to determine this so-called blank rate:
    1. It is needed to correct the results with the systems for the blank (the decrease in concentration without the system)
    2. To determine the detection limit of the system. This value is needed to describe the results of experiments with systems in which no significant reduction of concentration is observed. The reduction capacity can then be described as: less than the detection limit.

2.2 Phase 1

2.2.1 *Climatic chamber, monitoring and generation of aerosols and VOC (formaldehyde)*

A climatic chamber is used with inner dimensions of 4 m length, 1.5 m width and 2 m height, made of stainless steel. The chamber can be ventilated with for example outdoor air and air can be mixed using fans. During the experiments described here, the chamber is closed. The chamber is filled with a defined concentration of the specific components, temperature and humidity are stabilized and the decrease of the concentration of the studied components with time is registered. A fan is placed in the chamber to circulate the air. A LED fluorescent light is placed above the plants to keep the condition of the plant systems optimal.

2.2.2 *Relative humidity and temperature*

Relative humidity (RH) is set to 50% +/- 10% with an ultrasound humidifier (TopCom Multifunctional Humidifier 1850). Humidity is set on a RH of 50% before the start of the experiment and then switched off to prevent the generation of extra particles, such as water droplets, that could influence the results.

It is not possible to control the temperature in the chamber within very narrow limits. During the experiments, temperature ranged between 20 and 24°C during the day.

2.2.3 *Instruments deployed*

To determine the particle size distribution[2] of the particles in the chamber and temperature and relative humidity (RH), a FIDAS (Palas) is used. This is an EN 16450[3] approved aerosol spectrometer for simultaneous measurement of PM1, PM2.5 and PM10 (particulate matter with size smaller than 1, 2.5 and 10 µm, respectively). The detection limit of the FIDAS is 5.0 µg/cm^3.
To determine the number concentration of particles (PM) a condensation particle counter (CPC (TSI)) is used. This instrument detects and counts aerosol particles by first enlarging them by using the particles as nucleation centres and create larger (easier detectable) droplets in a supersaturated gas. The detection limit of the CPC for the number of particles is 0.1 particles/cm^3.
A Quantum Cascade Laser (QCL) spectrometer (Aerodyne) is used to measure the concentration of formaldehyde (CH_2O), which is the VOC chosen to monitor.
The aerosol is generated and released in the climatic chamber with a Balustein Atomizing Modules (BLAM) generator.

Note
The experiments with aerosol and formaldehyde needed to be carried out in separate experiments to prevent the possible formation of hexamine (a reaction of formaldehyde and ammonium). This reaction can be expected as a part of the aerosol consists of ammonium sulphate.

2.2.4 *Aerosol composition*

In ambient air the composition of aerosols can vary in time, per location, and depending on weather conditions. The average PM composition in ambient air is shown in Figure 9 and exists of SO_4^{2-}, NO_3^-, NH_4^-, Cl^-, organic carbon (OC), elemental carbon (EC) and a remaining fraction (n.d.). Figure 10 shows the average PM concentration in ambient air in the Netherlands.

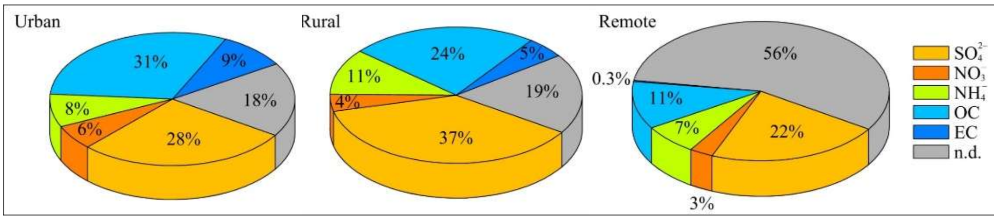

Figure 9 Chemical composition of PM in the atmosphere in different areas (Heitzenberg, 1994)

The aerosol mixture in our study contains SO_4^{2-}, NO_3^-, NH_4^-, Cl^- and organic carbon (OC) to create a composition that is representative for PM in the atmosphere. EC (soot) is not included at this stage, as it is difficult to generate and specially to clean after the experiments.

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[2] The concentration of particles from a certain size.
[3] This is the European standard for Ambient air. Automated measuring systems for the measurement of the concentration of particulate matter (PM10; PM2.5).

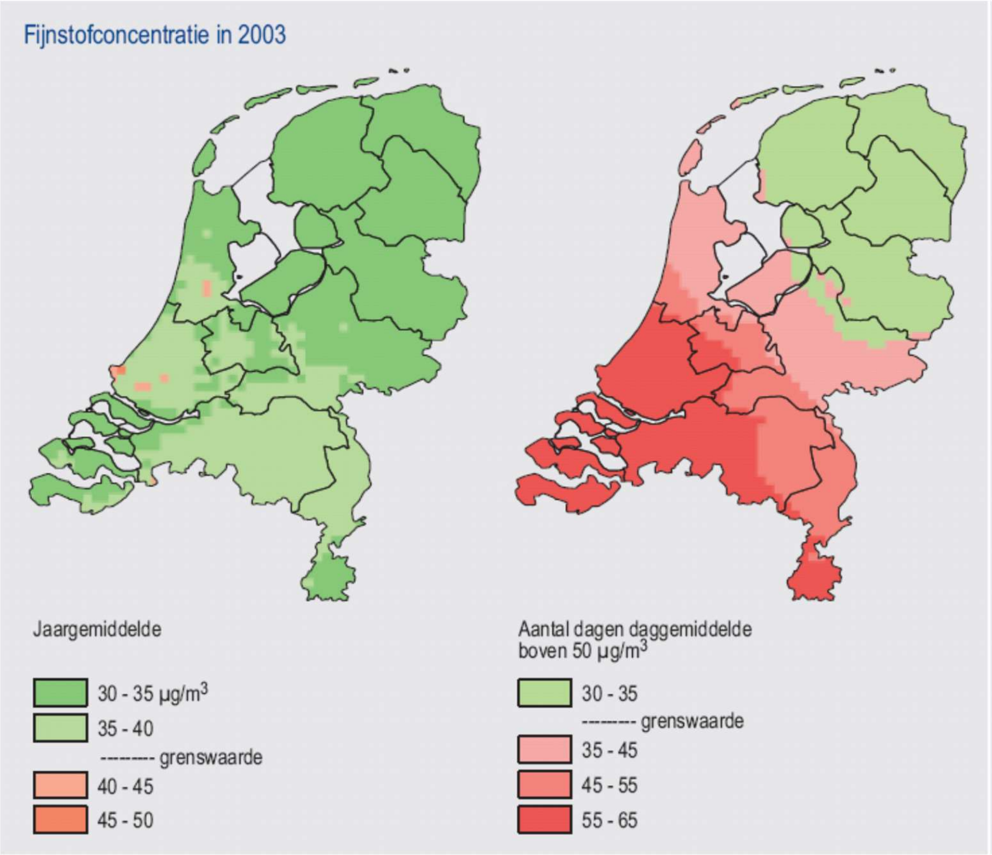

Figure 10 Aerosol concentration in the Netherlands (Singels et al, 2005).

In western Europe PM10 levels of 40 – 50 µg/m^3 are observed in ambient air (WHO, 2000). The Dutch and European norm for PM10 and PM2.5 are 40 and 25 µg/m^3 respectively as annual average (www.infomil.nl). For indoor concentrations RIVM mentions (based on EPA studies) values of 50 µg/m^3 for PM10 and 15 µg/m^3 for PM2.5 (Dusseldorp *et al*, 2007).

For particulate matter (PM) a composition of different aerosols was used (Table 2). The concentrations for the experiments in Phase 2 are 10 – 50 µg/m^3 with an aerosol size of 0.1 – 4 µm.

Table 2 Aerosol composition used for the experiments

Component	Formula	Amount (g/L)	Type	Density (g/cm^3)
Glucose	$C_6H_{12}O_6$	1	Organic	1.54
Ammonium sulphate	$(NH_4)_2SO_4$	1	Salt	1.77
Sodium chloride	NaCl	1	Salt	2.17

2.2.5 *Results of preliminary tests*

Immediately after the aerosol is generated and released into the empty climatic chamber, the concentration starts to decrease. This is a result of particle deposition to the chamber walls. This appears to be a well reproducible result as shown in Figure 11 for experiment 1, 2 and 3.

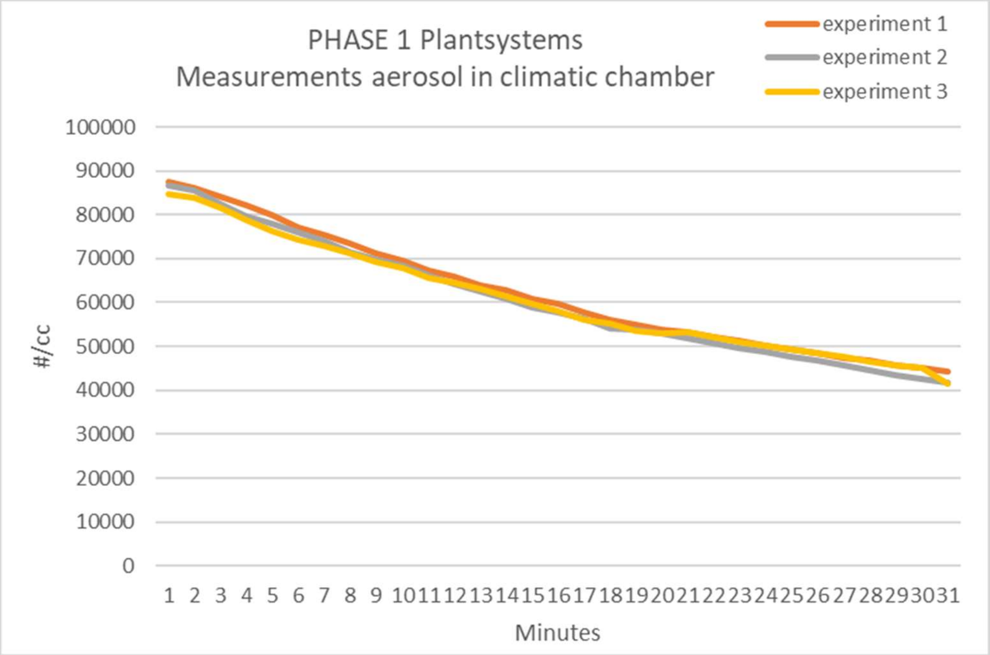

Figure 11 Decrease of the concentration of aerosol in time in the climatic chamber

The aerosol concentration is measured, using the FIDAS in 3 PM classes: PM1, PM2.5 and PM10. Figure 12 shows that most of the particles fall in the PM1 class. Figure 13 shows the mass size distribution indicating that most of the mass is present in the PM1 and PM2.5 classes. Larger particles are more difficult to generate and will be removed from air faster, because of their larger mass. These particles will settle faster due to gravity. The purifying effect of the plant systems can be determined more accurately for the smaller particles, as these particles will be present in the air for a longer time.

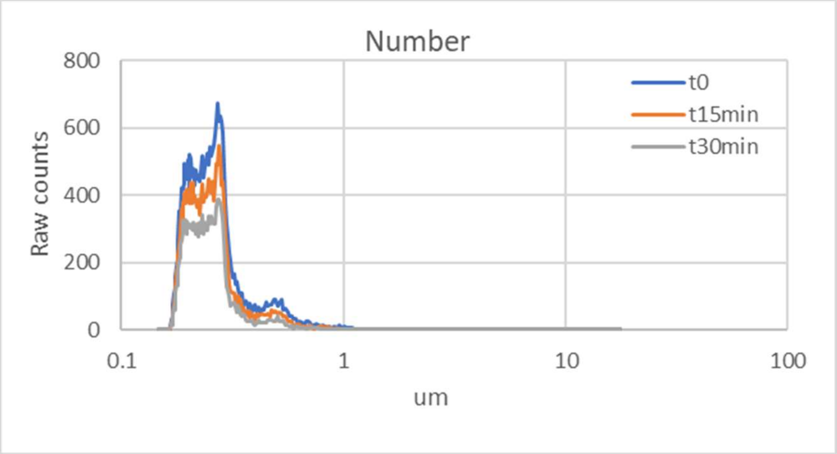

Figure 12 Particle number size distribution at the start of the experiment and after 15 and 30 minutes

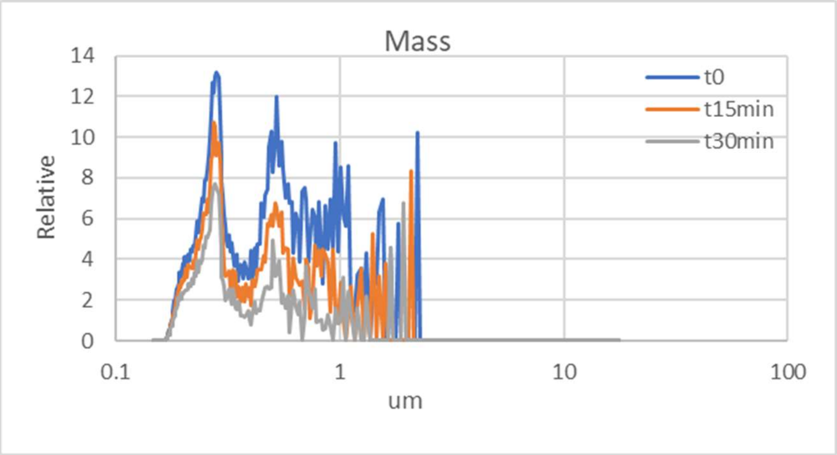

Figure 13 Particle mass size distribution at the start of the experiment and after 15 and 30 minutes

For Phase 2, the aerosol experiments are performed with an initial concentration of 3 g/L of the aerosol mix with a density of 1.79 g/cm^3 to be generated into the climatic chamber, to reach a concentration of 10 – 50 µg/m^3 with an aerosol size of 0.1 – 4 µm. This concentration seems realistic for ambient air, where the concentration is normally less than 50 µg/m^3 in West Europe (WHO, 2000).

2.2.6 *VOC reference – formaldehyde (CH_2O)*

Formaldehyde is commonly used as a reference for VOC's. Sources of formaldehyde are chipboard, MDF (medium density fiberboard), textile, cosmetics and tobacco smoke. Indoor concentrations of formaldehyde are often higher than ambient air concentrations. The concentration of formaldehyde in ambient air varies between 0.001 and 0.02 mg/m^3 whereas indoor air in a conventional home contains 0.03 – 0.06 mg/m^3. An air quality guideline value of 0.1 mg/m^3 as a 30-minute average is recommended (WHO, 2000). RIVM mentioned this value for formaldehyde of 100 µg/m^3 also for indoor air.
Formaldehyde is soluble in water whereas many VOC's are much less soluble. This may lead to biased results when systems contain much water and the removal rate could be much higher than for other less soluble VOC.

A 0.37% CH_2O (formaldehyde) solution is heated and evaporated and brought into the climatic chamber via a carrier gas (air, 6 L/min). The time needed to evaporate and mix all formaldehyde into the climatic chamber is 5 to 8 minutes. The concentration that will be used in Phase 2 is 100 ppb. This concentration can be measured quite well with the QCL monitor, since the detection limit of this monitor for CH_2O is 5 ppb (Table 3).

When formaldehyde is generated in the climatic chamber, an immediate decrease in the concentration is observed as well. This decrease appears to be reproducible for formaldehyde as well, as is shown in Figure 14, measurement 1, 2 and 3, at 100 ppb. With an initial concentration of 50 ppb, a comparable decline is shown (blue line). When the Philips Aerasense air purifier (AC2887) is turned on, a faster decrease is observed (green line).

Table 3 Concentration CH_2O injected and measured with QCL.

Injected concentration injected (ppb)	***QCL measured (ppb)***
0	*2.5*
50	*55*
100	*105*
200	*205*

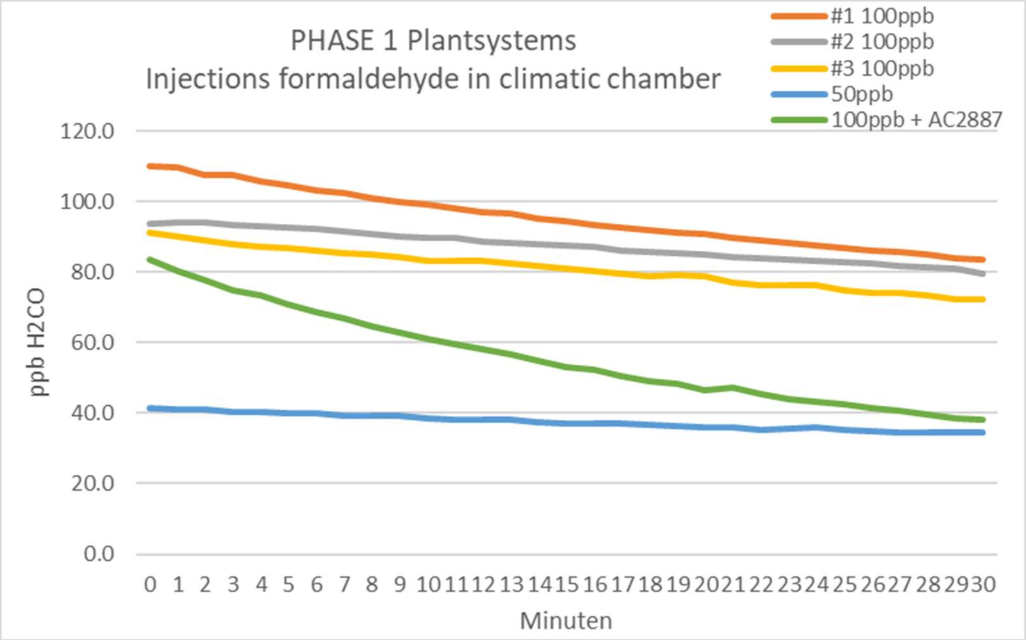

Figure 14 Measured decrease of the concentration of formaldehyde in the climatic chamber with time

For Phase 2, the experiments with formaldehyde are performed with 100 ppb (= 65 µg/m^3) formaldehyde, which is within the range of indoor concentration for formaldehyde presented by the WHO (WHO, 2000).

2.3 Phase 2

2.3.1 Procedure

Aerosol and formaldehyde instruments are installed (FIDAS, CPC and QCL).
Humidity is set on a RH of 50% before the start of the experiment and then the humidifier is switched off to prevent the generation of extra particles (200-300 particles/cm^3).
During the day, the air temperature in the chamber ranged from 20 and 24°C. Before starting each experiment with a selected plant system, a blank measurement is performed. This means that the decrease in concentration in the chamber is followed in the absence of air purifying systems. The result of this blank experiment is used to correct the corresponding experiment on that day.

The six plant systems and the two mechanical air purifier systems are tested individually. As mentioned in Paragraph 2.2, aerosol and formaldehyde experiments are performed separately. Between these experiments, the climatic chamber will be ventilated.

2.3.2 *Interpretation of the observed decrease in the concentration*

The rate at which the concentration of aerosol and formaldehyde decreases, should be determined. This is a first order process and can be described using an exponential decay with a removal rate *k*:

$$C_t = C_0 e^{-kt} \qquad (1)$$

Or

$$Ln\left(\frac{C_t}{C_0}\right) = -kt \qquad (2)$$

Where t is the time, C_t is the concentration at time t, and C_0 is the initial concentration.

3 Results

3.1 Temperature and relative humidity during experiments

Temperature and relative humidity are monitored during the whole series of experiments. The average, minimum and maximum temperature during the aerosol experiments is shown in Figure 15. Average, minimum and maximum relative humidity during each experiment is shown in Figure 16. It seems that some systems, such as “the wall”, have an impact on the humidity in the chamber.

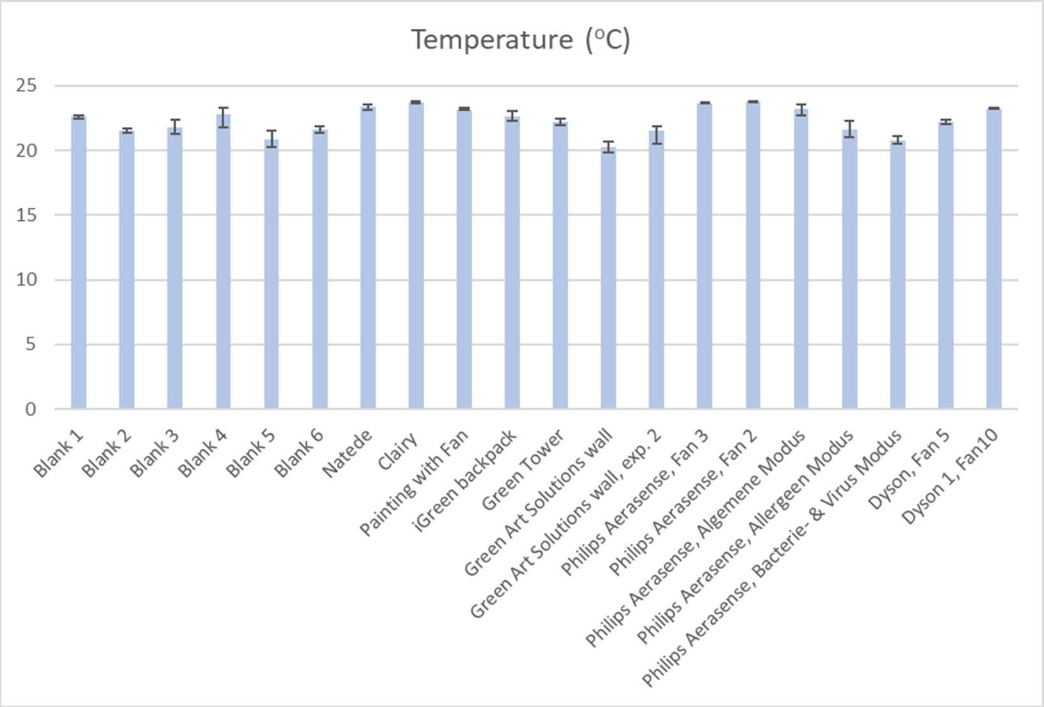

Figure 15 Average temperature during the aerosol experiments for all systems

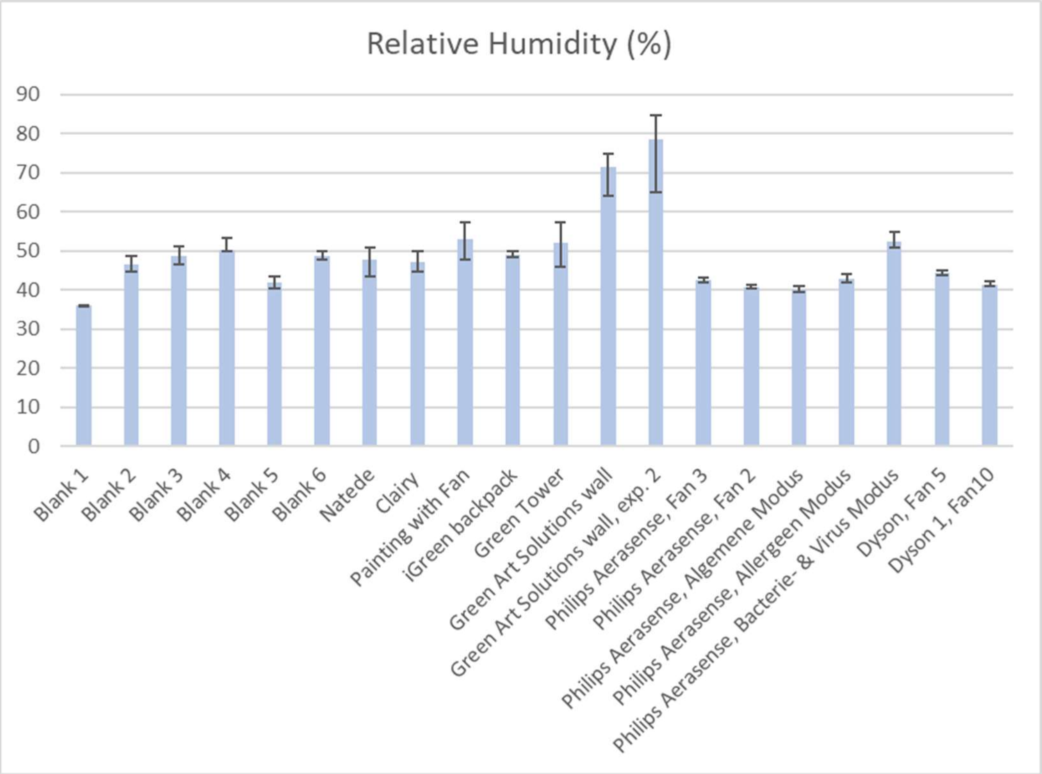

Figure 16 Average relative humidity during the aerosol experiments for all systems

3.2 Removal rate of aerosol

In the figures below, the results of the PM2.5 faction are shown. The removal rates of the PM1 and PM10 fraction (Figure 22) are within the same range as the removal rates of PM2.5, as shown in Figure 22. Figure 17 shows the results of all tested systems together in one graph. Figure 18 shows the same data, but excludes the Areasense and Dyson, to make a comparison of the plant systems clearer.

The decrease of the concentration of aerosol tested with the plant systems and the classical systems is shown in Figure 19. The plant systems are tested for at least one hour, the experiments with the Philips and Dyson systems are stopped within half an hour. In this short period the aerosol concentration of these two classic systems reached the detection limit, showing that these classic systems work comparatively well. Figure 20 shows the same data but excludes the Areasense and Dyson, to make a comparison of the plant systems easier.

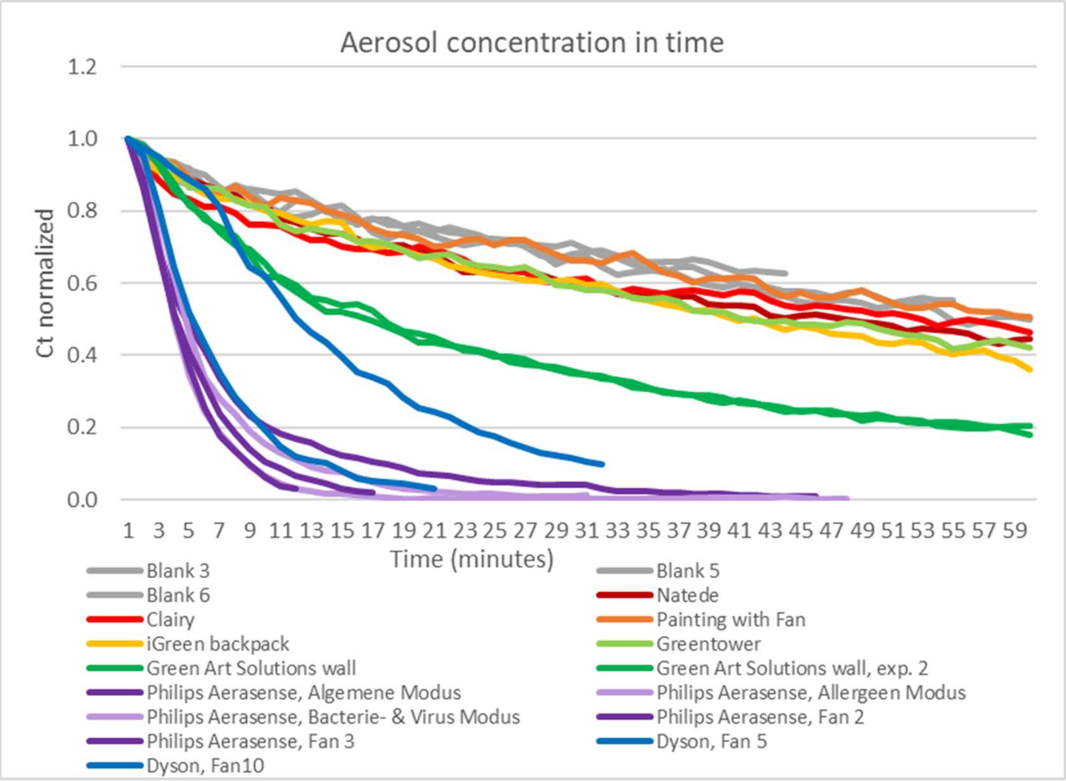

Figure 17 Removal of aerosol (PM2.5) in time for all systems normalised to the initial concentration i.e. C_t/C_0 are plotted

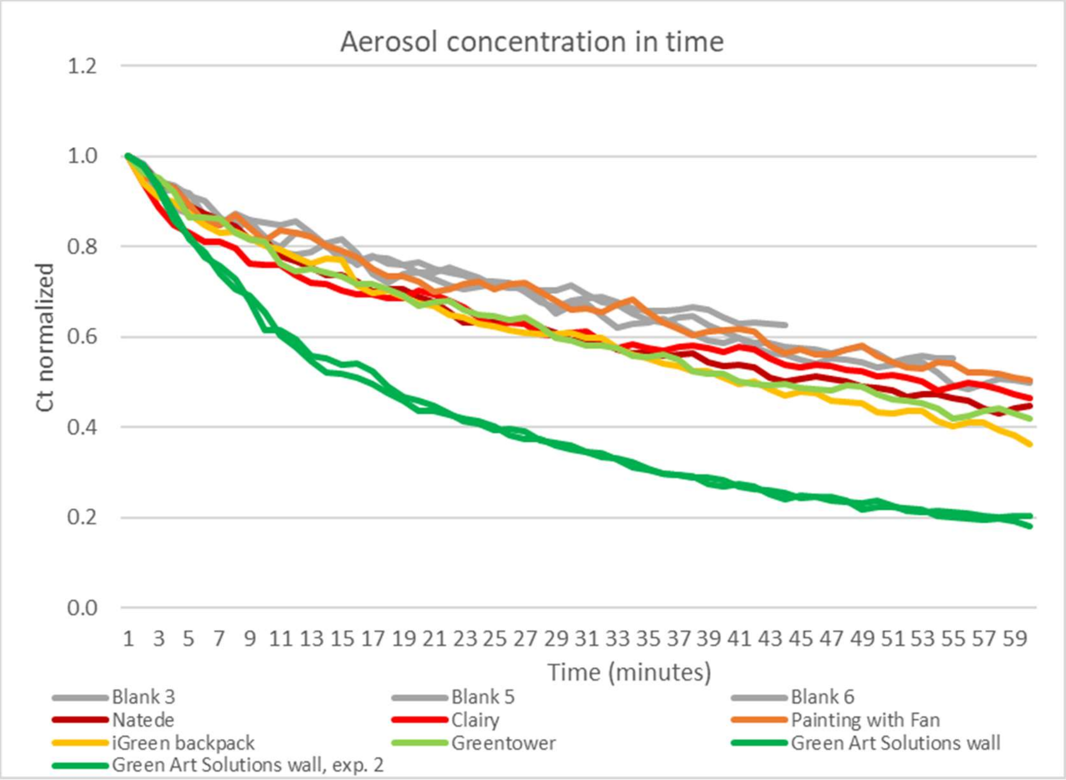

Figure 18 Removal of aerosol (PM2.5) in time for all plant systems normalised to initial concentration i.e. C_t/C_0 are plotted, excluding the classical systems

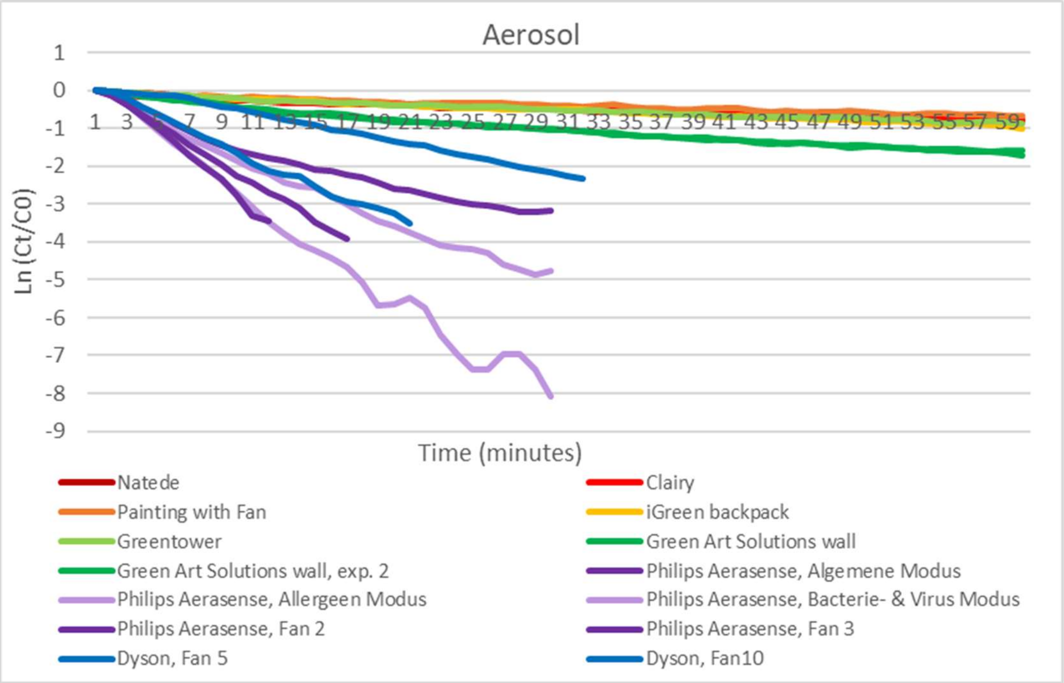

Figure 19 Decrease of the aerosol (PM2.5) concentration expressed as Ln(Ct/C0) in time for all tested systems together.

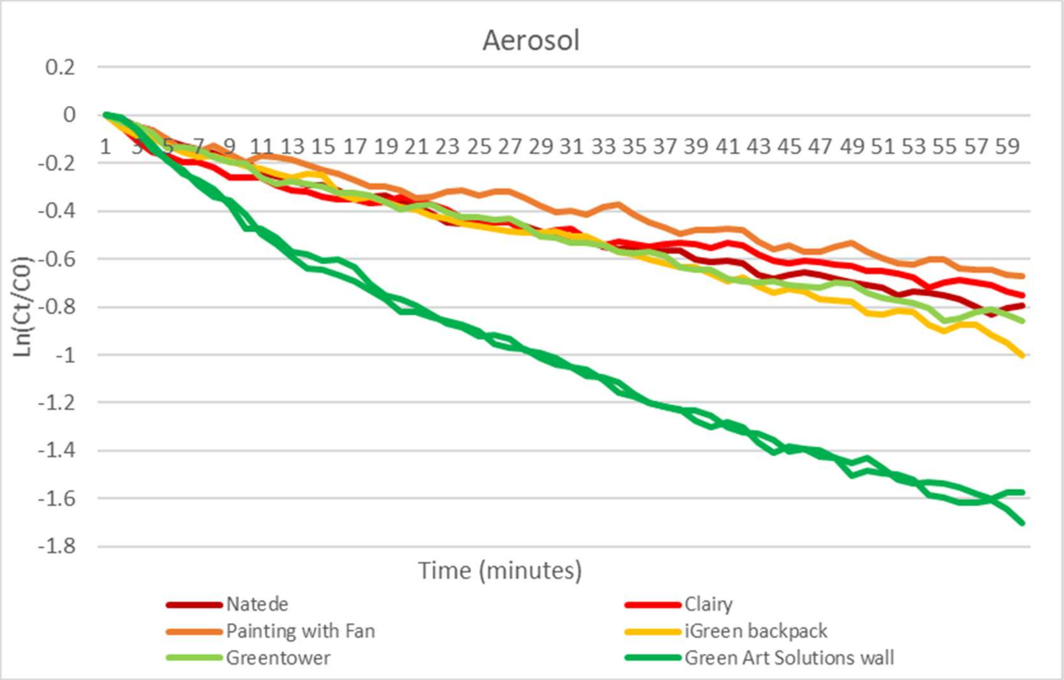

Figure 20 Decrease of aerosol (PM2.5) expressed as Ln(Ct/C0) for all tested plant systems i.e. excluding the Aerasense and Dyson.

When looking at the selected plant systems (Figure 20), the Green Art Solutions wall is most efficient in removing aerosols. Because it contains much more plants, it has a much larger surface area than the Natede, Clairy and iGreen. The green line from the Green Art Solutions wall is not totally linear, but enough to determine a removal rate.

Equation (2) (Paragraph 2.3.2) is used to determine the removal rate *k.* The removal rate *k* is shown in Figure 21. The mechanical air purifier systems have the highest removal rates for aerosol, followed by the Green Art Solutions wall. The Clairy and the Painting showed no effect in terms of removal rate.

Figure 22 shows the removal rates for PM1, PM2.5 and PM10, which indicates that the different particle size classes are removed evenly. This was expected from the experiments in Phase 1 (Figure 12 and Figure 13), showing that the majority is smaller than 1 µm. The results of the PM2.5 class is therefore representative for the aerosol removal.

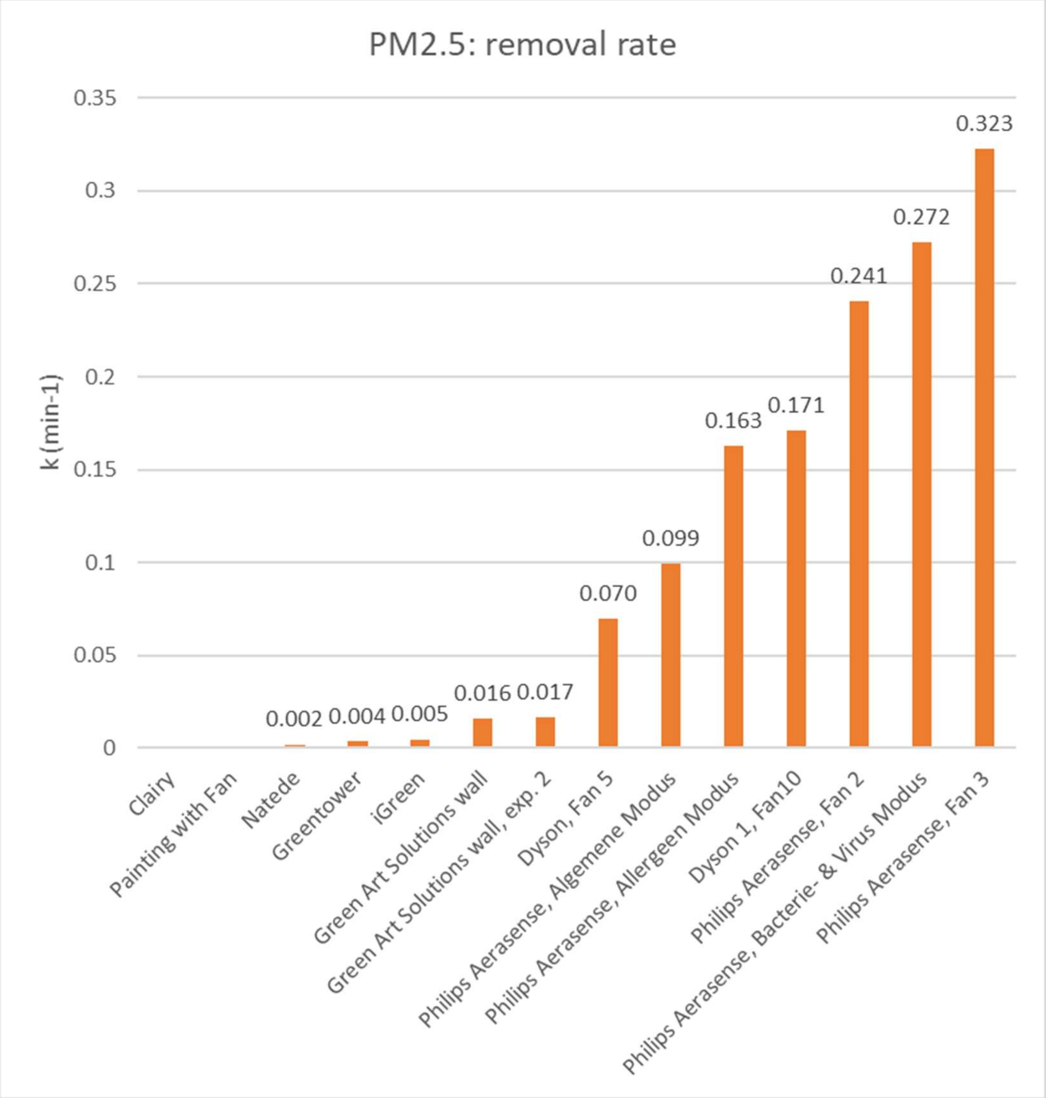

Figure 21 Removal rate of PM2.5 for all systems, with the blank values subtracted.

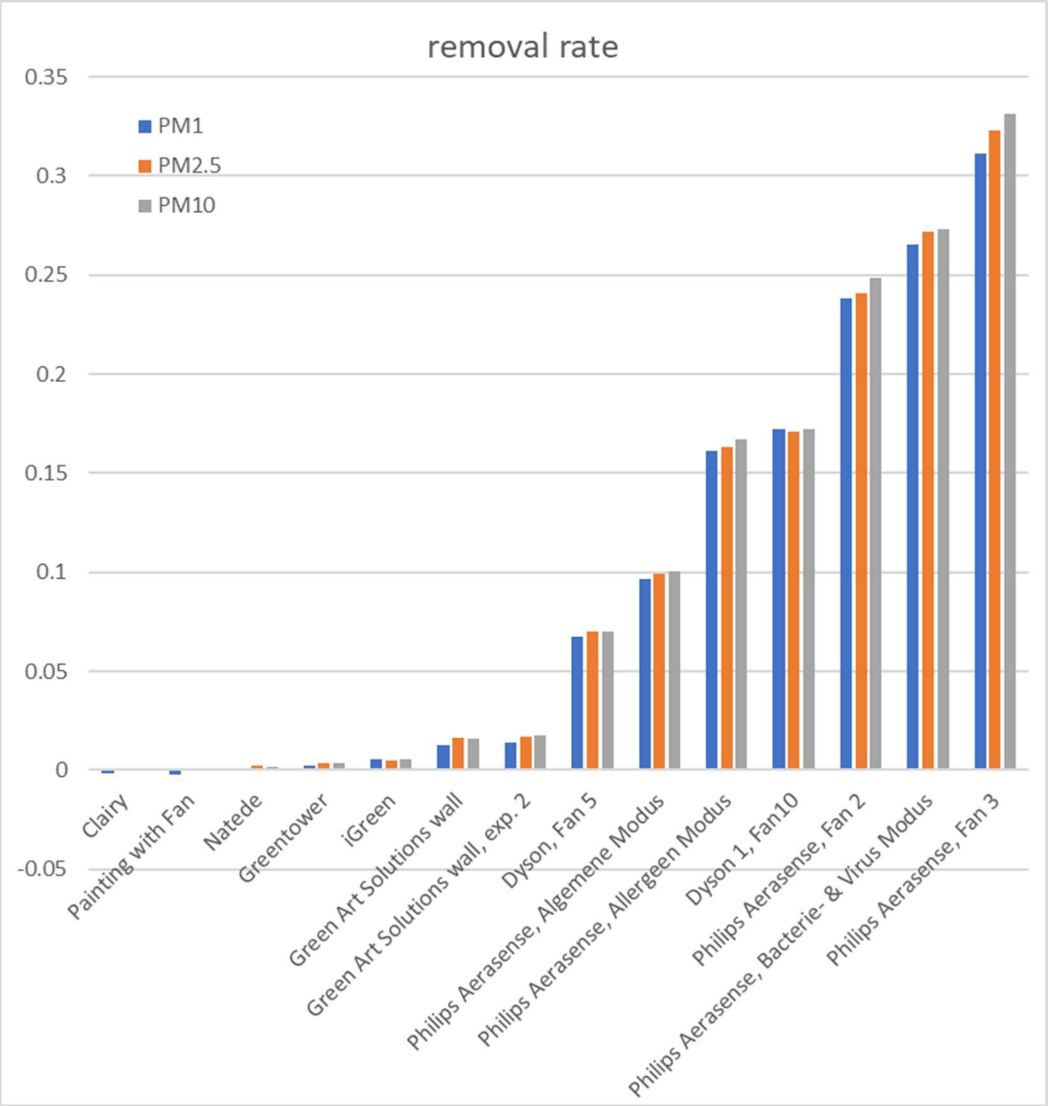

Figure 22 Removal rate of PM1, PM2.5 and PM10 for all systems, with the blank values subtracted.

3.3 Removal rate of formaldehyde

Figure 23 shows the removal of formaldehyde of all tested systems together.
The decrease of formaldehyde is shown in Figure 24. The plant systems are tested for half an hour, the Dyson was stopped within 10 minutes as there was no effect on formaldehyde seen. The gap shown in the iGreen backpack was caused by an error of the QCL.

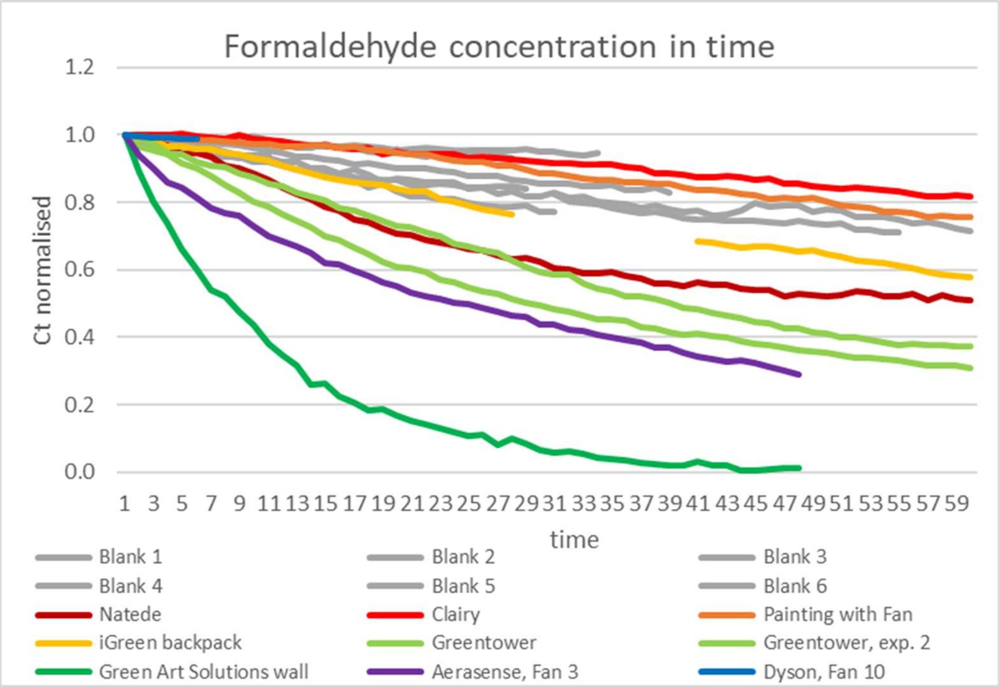

Figure 23 Decrease of formaldehyde concentration in time for all systems normalised to the initial concentration i.e. C_t/C_t are plotted.

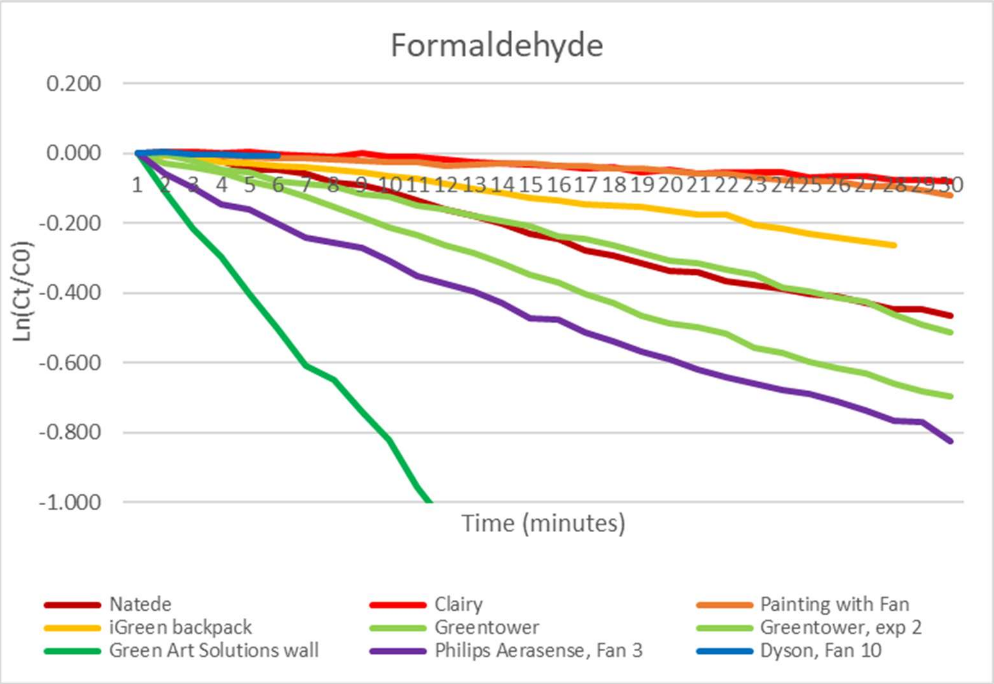

Figure 24 Decrease of formaldehyde expressed as Ln(Ct/C0) for all tested systems together.

When looking at the selected plant systems (Figure 23), the Green Art Solutions wall removes the formaldehyde concentration most efficient (even better than the Aerasense). It is noted that, because it contains much more plants, the surface area is much larger than that of the Natede, Clairy and iGreen.

The removal rate is shown in Figure 25. The Green Art Solutions wall has the highest removal rate for formaldehyde, followed by the Aerasense, Green Tower and iGreen backpack. The Natede and the Dyson showed no effect in terms of removal.

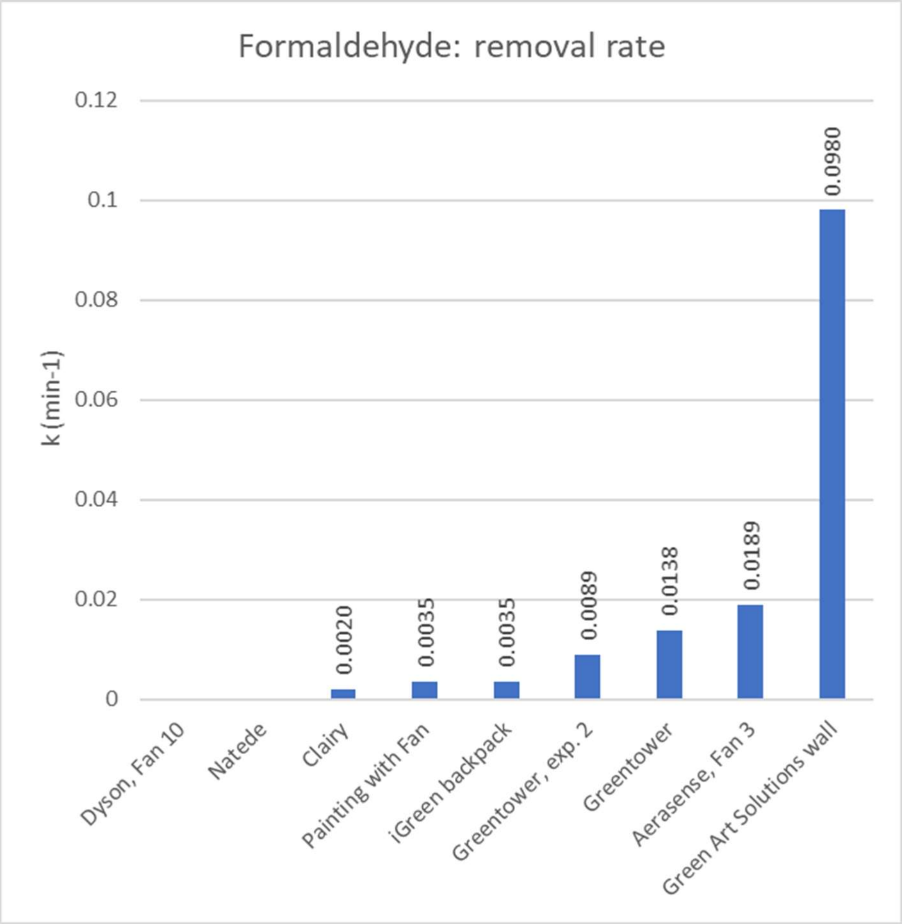

Figure 25 Removal rate of formaldehyde for all systems.

3.4 Effects on indoor air quality

Although the experiments were carried out in rather realistic conditions there is a need to consider the use of the results in a real-life situation. In real life houses are ventilated with outdoor air and the concentrations that result from ventilation and the effect of the systems will differ from those observed in the experiments. And although the volume of the chamber used for the experiments is rather large, living rooms are usually larger. This also leads to differences in the effect of the systems in our chamber and the effect in real life conditions. To account for these differences, some calculations were carried out to illustrate the effect of the systems in a more realistic room. We assume a situation with an equilibrium between indoor and outdoor, starting with 100% of the measured component as the initial percentage to measure the removal of. If the outdoor concentration remains constant, this situation could be reached in a few hours depending on actual conditions.

A mass balance approach is used to calculate the effect of the retention time and size of the room:

Rate of change in material in room **=** *material entering room trough ventilation* **–** *(the material leaving the room by ventilation and the material leaving the room by uptake at the walls and by the system)*

Therefore, to determine the removal of aerosol or formaldehyde in a conventional living room which is ventilated, the following equation is used[4] (Deng *et al*, 2017):

$$V\frac{dc}{dt} = q \cdot C_{in} - (q + k \cdot A) \cdot C_t \qquad (3)$$

Where C_t is the concentration in µg/m^3, C_{in} is the concentration outside in µg/m^3, V is the volume of the room in m^3, A is the surface area of the room in m^2, q is the flow in m^3/min, k is the removal rate in min^{-1}, V/q is the retention time (*T; tau*). It is assumed that the concentration in ambient air C_{in} is constant in time and there are no internal sources (such as cooking).

To estimate the effect of the selected systems with the removal rates determined in Phase 2 in a representative living room, we assume a situation with an equilibrium between indoor and outdoor, with $dc/dt = 0$, then equation (3) can be rearranged to:

$$C_t = \frac{C_{in}}{1 + k \cdot \frac{A}{V} \cdot \tau} \qquad (4)$$

First, we correct the removal rate for the volume-surface area ratio, by using the removal rate of the blank and multiply with *A/V* ratio of the living room (V = 80 m^3, A = 124 m^2) divided by the *A/V* ratio of the climatic chamber (V = 12 m^3, A = 34 m^2).

$$k_{corr} = k_{blank} \cdot \frac{1.55}{2.83} \qquad (5)$$

Then the removal (C_t) is determined by equation 4. The resulting removal in % for aerosol for the selected systems is shown in Figure 26 and for formaldehyde in Figure 27.

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[4] The term $q.C_{in}$ in this equation is used to simulate the effect of the ventilation with outdoor air. For formaldehyde with internal sources another approach would perhaps describe the situation better. At this stage the current approach is assumed to provide a good picture. This term stands for production of formaldehyde

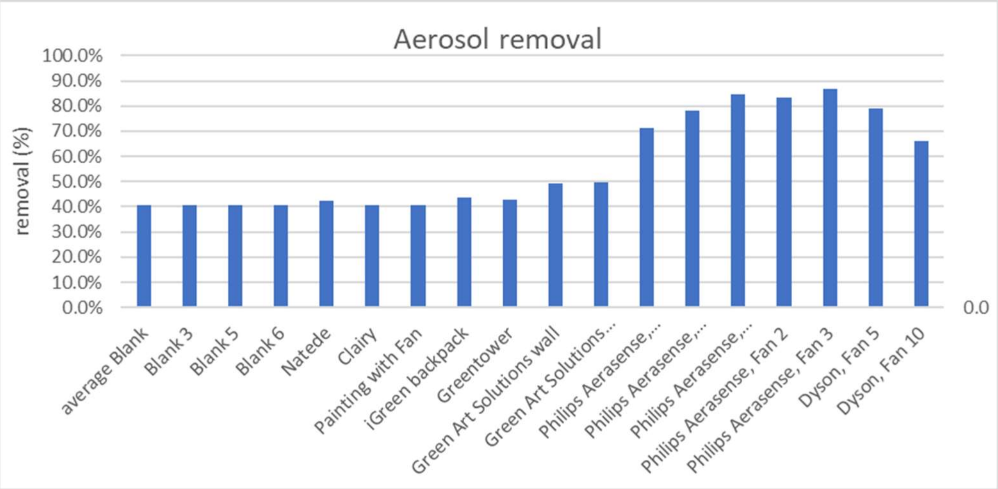

Figure 26 Aerosol concentration calculated in an equilibrium situation with outdoor air and a retention time equal to 120 min in a conventional living room with a dimensions of 80 m^3.

Figure 26 shows that in absence of an air purifying system, the aerosol concentration will reduce by 40%. The Natede, Clairy and Living Painting show comparable results, when only looking at the total aerosol removal. With the iGreen backpack and the Green Tower, the removal increased slightly and the Green Art Solutions wall performed best of all plant systems in terms of total aerosol removal. The mechanical systems show a much higher aerosol removal.

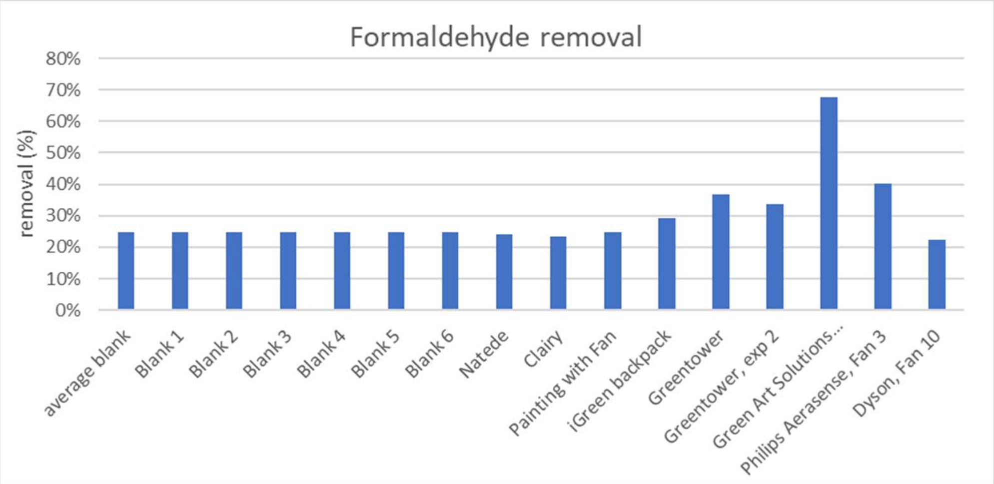

Figure 27 Formaldehyde concentration calculated in an equilibrium situation with outdoor air and an retention time equal to 120 min in a conventional living room with a dimensions of 80 m^3.

Figure 27 shows that in absence of an air purifying system, the formaldehyde concentration will reduce by 25%. The Natede, Clairy and Living Painting show comparable results, when only looking at the total formaldehyde removal. With the iGreen backpack and the Green Tower de removal increased, and he Green Art Solutions wall performed best of all plant systems in terms of total formaldehyde removal. The removal percentage of mechanical systems show that the Aerasense can remove formaldehyde comparable to the Green Tower and the Dyson is not capable of removing formaldehyde.

Guidelines
When starting with 50 µg/m^3 aerosol, and use the percentage removal of the systems in a living room, the aerosol concentration decrease for all systems, including no system at all, below the Dutch guideline for PM10 in ambient air, which is 40 µg/m^3, as shown in Figure 28. This is not yet below the Dutch guideline for PM2.5 of 25 µg/m^3, but it is with an ambient air concentration for PM2.5 of 35 µg/m^3 as assumed in Dusseldorp *et al.* (2007).
For indoor concentrations RIVM used (based on EPA studies) guidelines of 50 µg/m^3 for PM10 and 15 µg/m^3 for PM2.5 (Dusseldorp *et al*, 2007). For formaldehyde 100 µg/m^3 is mentioned as a guideline (Figure 29).

The resulting concentrations shown in Figure 28 and Figure 29 are listed in Table 4. To judge the representativity of the calculations, a comparison with observed concentrations would be needed. Unfortunately, only a limited number of data of indoor concentration measurements is available, especially for formaldehyde. For PM10 aerosol Dusseldorp *et al*. (2007) gives concentrations ranging from averages of 21 to 34 µg/m^3. For the blank values, the calculated values in this study are a little below 30 µg/m^3. This small difference could be due to several factors, such as the outdoor concentration that were used as well as the removal rate that were determined in a stainless-steel chamber with few obstacles. In a real room furniture and curtains etc. could lead to a higher removal rate and corresponding lower concentrations. More detailed measurements and calculations would be needed to obtain a more accurate estimate of the effect of the systems in real conditions.

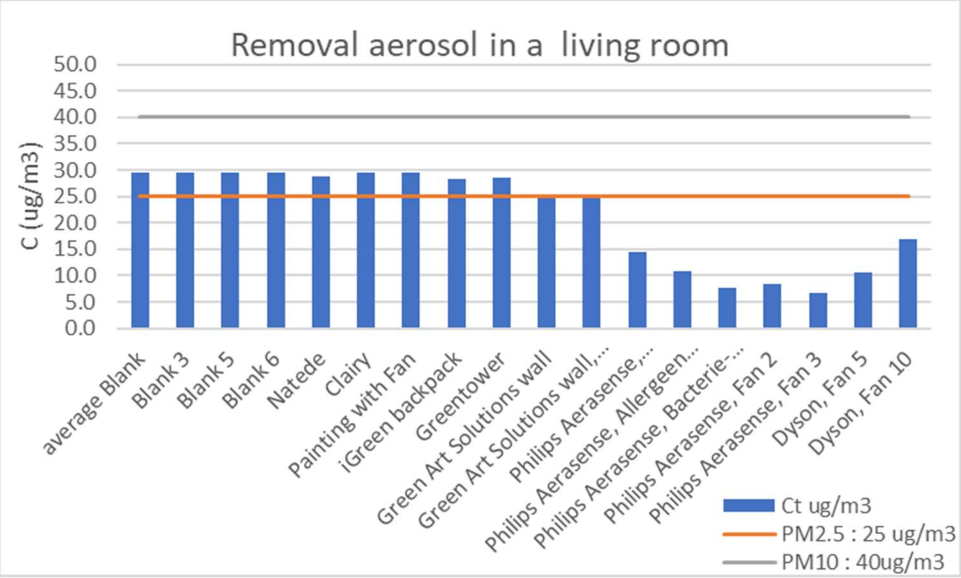

Figure 28 Equilibrium aerosol concentration for all tested systems, when starting with 50 µg/m^3 aerosol.

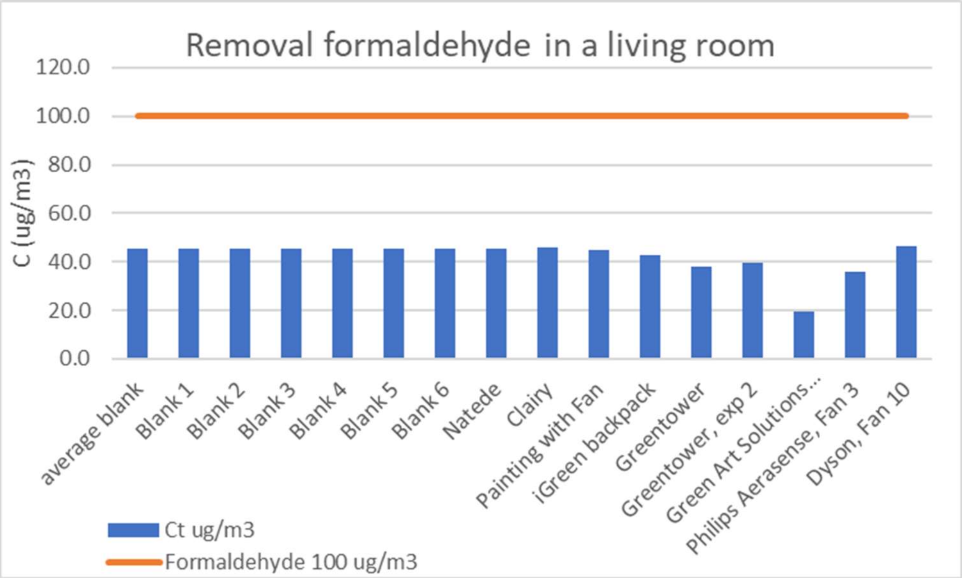

Figure 29 Equilibrium formaldehyde concentration for all tested systems, when starting with 60 µg/m^3 formaldehyde.

Table 4 Equilibrium concentrations for aerosol starting with 50 µg/m^3 and for formaldehyde starting with 60 µg/m^3.

	C_0 = 50 µg/m^3	C_0 = 60 µg/m^3
Tested system	**aerosol**	**formaldehyde**
	C_t (µg/m^3)	C_t (µg/m^3)
average Blank	29.6	45.2
Natede	28.8	45.5
Clairy	29.6	46.0
Painting with Fan	29.6	45.1
iGreen backpack	28.2	42.5
Greentower	28.6	38.0
Greentower, exp. 2		39.8
Green Art Solutions wall	25.3	19.4
Green Art Solutions wall, exp. 2	25.1	
Philips Aerasense, Algemene Modus	14.4	
Philips Aerasense, Allergeen Modus	10.8	
Philips Aerasense, Bacterie- & Virus Modus	7.6	
Philips Aerasense, Fan 2	8.3	
Philips Aerasense, Fan 3	6.7	35.8
Dyson, Fan 5	10.5	
Dyson, Fan 10	17.0	46.6

4 Discussion and Conclusions

Six plant systems and two mechanical systems were tested in our climate chamber on the removal of aerosol and formaldehyde. The environmental conditions in this climate chamber were carefully controlled and realistic and representative environmental conditions (temperature, relative humidity) were chosen.
Air concentrations of aerosol and formaldehyde were chosen to represent realistic situations in the Netherlands. In our study formaldehyde is chosen as a representative for VOCs. This is a good choice in view its position in indoor air pollution.

The results of the climatic chamber were extrapolated to a living room with realistic dimensions, and where outdoor air is exchanged with a specific rate. The calculations were considered realistic at least compared to the limited number of concentration measurements of PM10 and PM2.5 for aerosol available in literature. No measurements for formaldehyde were found in literature.

Our calculations show that, in the absence of an air purifying system, the aerosol concentration in a house will reduce by 40%. The Natede, Clairy and Living Painting show comparable results, when considering the total aerosol removal only. With the iGreen backpack and the Green Tower, the removal rate increased slightly, and the Green Art Solutions wall performed best of all plant systems in terms of total aerosol removal. The mechanical systems show a much higher aerosol removal.

In the absence of an air purifying system, the formaldehyde concentration will reduce by 25%. The Natede, Clairy and Living Painting show comparable results, when only looking at the total formaldehyde removal. With the iGreen backpack and the Green Tower, de removal increased, and the Green Art Solutions wall performed best of all plant systems in terms of formaldehyde removal. The removal percentage of mechanical systems show that the Aerasense can remove formaldehyde comparable to the Green Tower and the Dyson is not capable of removing formaldehyde.

It was not the purpose of this study to investigate the differences in the systems and understand why some perform better than others. This would require additional investigations that are beyond the scope of this study. Some results are already obvious: systems containing large amounts of water will be better in taking up soluble VOCs such as formaldehyde. Also, systems containing classical filters show a relatively large effect. More research would be needed to improve the impact of the plant containing systems even further.

The setup and methods in this study are new and no comparable studies have been found in literature. The experiments were also limited in time, it is not clear how plant systems (where living plants form the base) perform in the longer term. More and longer experiments are needed to determine this. The extrapolation from a stainless-steel test chamber to a model living room should be considered indicative. In real life obstacles such as furniture and curtains will affect the removal rate as well.

Even with these limitations this simple and unique study show that plant systems can contribute to an improvement of the indoor air quality. This is concluded from experiments carried out under realistic conditions and extrapolated to a real life living room as an illustration. There seems to be considerable difference among the impact of the systems tested. Classical filter-based systems gave best results.

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6 Signature

Petten, 18-6.2019	TNO
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