Mobile Air Purifiers

- How good are they?

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2. Background

Air pollution is the third largest cause of mortality in Denmark. We spend 90% of our time indoors and good air quality is, therefore, of great importance. Smoke and particles from food, candles, or wood stoves, and degassing from other relevant sources are affecting the indoor air quality and removing these sources would lead to an improvement. Outside sources, such as heavy traffic and emissions from nearby factories, can have a negative impact on the indoor climate and natural ventilation is, therefore, not always the best solution. One long-term solution would be to simply avoid/remove the pollution sources; however, this is not always an option. One short-term solution is to insert mechanical ventilation and/or regular airing. Although, this is in some cases not sufficient or feasible. For this reason, many families and public institutions are looking to mobile air purifiers as a solution to ensure cleaner indoor air.

The market for air purifiers is rapidly expanding, and novel technologies are emerging. Currently, there are no harmonized standards or regulations for the efficiency and endorsement of air purifiers in Europe. The claim of efficiency for these products is reported in numerous incomparable ways and needs to be balanced concerning price, noise, and power consumption.

For this reason, the market is incomprehensible, and the real-life effect in private homes is unclear. Further studies are necessary, to set the ground for these lacking standards and regulations and to guide consumers towards a sound basis for decision.

3. Project scope

In this project, products claiming the ability to improve indoor air quality in private homes, are thoroughly investigated in a controlled environment using well-established methodologies. Ultimately, the project delivers guidance on the performance of clean air technologies present in the Danish market as well as evaluates relevant in-use characteristics (e.g., noise, power consumption, and by-product formation).

In total, 29 mobile air purifiers, comprising a representative section of the Danish market in terms of technology, price, and claimed cleaning capacity, are tested, and evaluated in detail. The efficiency of these products is tested towards the most common indoor air pollutants; particulate matter and harmful gaseous compounds in the form of so-called volatile organic compounds (VOCs), and viruses.

The performance test of all products is performed in a controlled laboratory setting at the Danish Technological Institute, as well as in real-life conditions in a private home for a smaller selection of the products.

As a surrogate for indoor air pollution, we have chosen cigarette smoke for the testing, due to its high reproducibility in total emission of particulate matter (including ultrafine particles) and VOCs. Cigarette smoke is, furthermore, the *de-facto* standard pollutant when testing mobile air purifiers.

In summary, the air purifiers are tested in the laboratory on the following parameters:

- Their performance towards particulate matter and VOCs using cigarette smoke.
- Emission of other pollution byproducts (ozone or VOCs).
- Power consumption and noise level.
- The reduction rate of airborne virus (tested on six representative mobile air purifiers).

The cleaning performance of the mobile air purifiers is presented as a Clean Air Delivery Rate value (CADR). The CADR-value expresses the amount of clean air delivered by the product per hour with respect to a specific air pollutant. It is independent of the room size and duration used for testing, which makes the CADR values directly comparable across products.

During the test in a private home, the real-life performance is evaluated with a focus on the reduction of exposure to air pollution, as well as comparing the performance to common options, such as mechanical ventilation, exhaust hood, and airing. This highlights the use scenarios where mobile air purifiers are highly applicable and scenarios where these products are more to be seen as a supplement or even unnecessary. Cooking and scented candles were used as pollutant sources for these tests.

Additionally, this project provides a critical evaluation of product claims and endorsements, emphasizing the need for harmonized standards and legislation in the area of mobile air purifiers.

4. Conclusion

Below we have listed a few selected conclusions from this project. All statements are elaborated on in detail in the results section.

- Mechanical filtration, such as HEPA filters (high-efficiency particulate air filters), showed the highest cleaning rate for particle pollution.
- All products, utilizing activated carbon, had the capability to reduce the concentration of total volatile organic compounds (TVOC). However, the range of reduction varied greatly.
- The removal of gaseous pollutants, such as TVOC, is more troublesome than the removal of particle pollution.
- Ozone generation was measured for 2 products. One ozone generator and one UV-C based device
- A large difference in noise levels was observed for products delivering approximately the same amount of clean air.
- There was no clear correlation between purchase cost and cleaning rate.
- HEPA-based devices showed the highest reduction rate of active virus.
- Our results highlight the need for harmonized standards for measuring efficiency and performance for mobile air purifiers, as well as product endorsements such as suggested maximum room size.

In addition, conclusions from testing mobile air purifiers in a private home can be found here (link to report) and detailed evaluation of all products can be found on the Danish Consumer Counsel website (link to evaluation)

5. Danish Summary:

Luftforurening er en af de væsentligste årsager til for tidlig død i Danmark. Den største eksponering til sundhedsskadelig luftforurening sker indendørs, da vi befinder os størstedelen af tiden her og omgives tæt af kilder til forurening, såsom madlavning, stearinlys og brændeovne, samt rengøringsartikler og afgasning fra boliginventar. Denne luftforurening kan afhjælpes med udluftning, men den udendørs luftkvalitet kan ligeledes være skadelig grundet tung trafik, industri, allergener eller naborøg, hvilket ikke altid gør udluftning og mekanisk ventilation til den bedste løsning. Derfor vælger flere og flere at bruge mobile luftrensere med ønske om at forbedre indeklimaet. Markedet for mobile luftrensere er vokset eksplosivt over de seneste år, grundet øget fokus på luftkvalitet og sundt indeklima. Det har medført mange nye aktører og produkter på markedet, samt flere typer af teknologier, som anvendes til at rense luften. For nuværende findes ingen harmoniseret standard eller lovkrav til test af effektiviteten for mobile luftrensere. Dette medfører at produkter anprises på måder, som er usammenlignelige og til tider misledende, ligesom sammenhængen mellem effektivitet, støj, strømforbrug og pris er meget ugennemsigtig for forbrugerne.

I dette projekt undersøger vi mobile luftrensere henvendt til forbrugerne på det danske marked. I alt er der udvalgt 29 produkter, som repræsenterer markedet i form af forskellige prisklasser, typer af renseteknologi og anprist renseevne. Disse produkter har undergået detaljerede undersøgelser under kontrollerede forhold ved Teknologisk Institut med fokus på renseevne overfor partikler, skadelige gasarter og luftbårne vira, samt støj, strøm og ozondannelse. Konklusionerne fra denne undersøgelse er præsenteret i denne rapport. Herudover er der i projektet undersøgt den oplevede effekt i private hjem under virkelige forhold (Link til rapport), samt udarbejdet en detaljeret evaluering og anbefaling til forbrugerne (Link til TÆNKs evaluering!).

De væsentligste konklusioner fra undersøgelsen under kontrollerede forhold er:

- Mobile luftrensere, som anvender mekanisk filtrering, såsom HEPA- og EPA-filtre, blev målt til at have den højeste renseevne overfor partikler (både *fine* og *ultrafine* partikler).
- Andre former for teknologier (UV-C lys, ionisering, ikke-termisk plasma, luftvasker, ozongenerator og olielampe) blev målt til at have markant lavere renseevne overfor partikler. I flere tilfælde ingen evne overhovedet.
- Alle produkter, som anvender filtre med aktivt kul, blev målt til at kunne fjerne skadelige gasarter, i form af flygtige organiske forbindelser (*VOC*). Dog varierede renseevnen markant.
- Renseevnen overfor partikler var generelt markant større end for skadelige gasarter.
- Ozondannelse blev målt for 2 produkter; en ozongenerator og et produkt med UV-C lys.
- En relativ stor forskel i støj (op til 10 dB) blev målt for produkter med cirka samme renseevne.
- Der blev ikke målt en sammenhæng mellem produkternes indkøbspris og deres evne til at fjerne partikler og/eller skadelige gasarter.
- Produkter, som anvender et HEPA-filter, blev målt til at have den største reduktionsrate af virus i luften.
- Resultaterne fra dette projekt viser tydeligt, at der er behov for en harmoniseret standard og lovgivning vedrørende dokumentation af renseevne for mobile luftrensere samt produktanprisninger (f.eks. anbefalet maksimal rum størrelse, hvor produktet er effektivt).

6. Results

The overall results from the air cleaning performance are presented in the table below.

Table 1: Summarized results for all 29 products, categorized according to their primary clean air technology.

Technology		CADR [m³/hour]		Reduction TVOC
		Fine particulate matter (PM2.5)	Ultrafine particles (UFP)	
Mechanical Filtration	HEPA (1 device)	304	255	35 %
	HEPA + Activated Carbon Filter + Other technologies* (14 devices)	92 – 741 (avg. 308)	77 – 723 (avg. 268)	15 – 83 % (avg. 42 %)
	HEPA + Other technologies* (1 device)	79	58	6 %
	EPA + Activated Carbon Filter + Other technologies* (4 devices)	212 – 471 (avg. 313)	182 – 409 (avg. 270)	4 – 67 % (avg. 43 %)
	EPA + Other technologies* (1 devices)	330	286	4 %
UV-C (2 devices)		0	0	6 – 9 %
Non-thermal Plasma (1 device)		12	6	10 %
Ionizer (1 device)		41	39	0 %
Other	Activated carbon in bag (1 device)	0	0	0 %
	Air Washer (1 device)	0	0	33 %
	Ozone generator (1 device)	0	0	8 %
	Oil lamp (1 device)	0	5	Generates VOCs

* Other technologies indicate one or more of the following: Photocatalytic Oxidation (PCO), Ionization, and/or UV-C.

Air pollution

The CADR-values for all mobile air purifiers are presented in Figure 1. Overall, it was found that products utilizing **mechanical filtration**, such as HEPA filters (high-efficiency particulate air filters), **showed the highest cleaning rate for particle pollution**. Interestingly, it was found that lower-class mechanical filters, such as EPA, on average showed the same cleaning rate for particles. Other technologies, such as UV-C, non-thermal plasma, and ionizers, did only show little or no effect on particle pollution.
The CADR-values measured for PM2.5 were in all cases larger than the CADR-values measured for ultrafine particles. The difference was within 25 %.

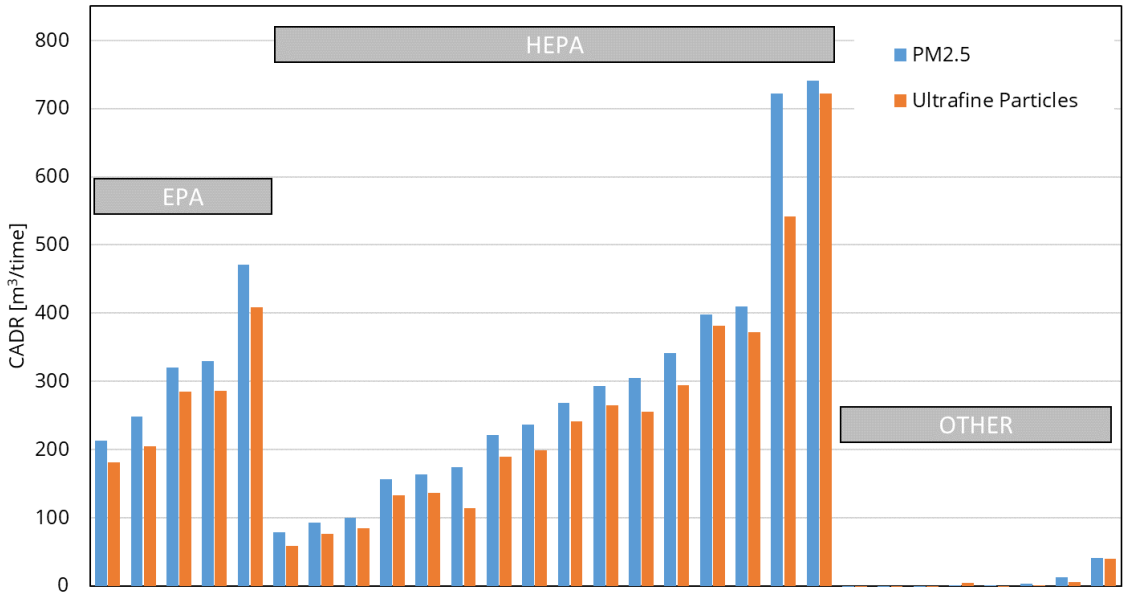

Figure 1: Overview of CADR-value (PM2.5 in blue and ultrafine particles in orange) for all products grouped into EPA, HEPA and other (UV-C, Non-thermal plasma, Ionizer, Activated Carbon in bag, air washer, ozone generator and oil lamp)

The results do not provide any clear conclusions on TVOC removal. **Products utilizing activated carbon filters** (18 in total) **all had the capability to reduce the concentration of TVOC** (see Figure 2). However, the range of reduction varied greatly, from 4 % for the worst to 83 % for the best. Thus, activated carbon filters do not ensure an efficient TVOC removal. Furthermore, it was not evident whether additional TVOC cleaning technologies (e.g., photocatalytic oxidation (PCO) or ionization) improved the efficiency. Products, with a combination of mechanical filtration and activated carbon filter, showed a higher average TVOC reduction, than products combining mechanical filtration, activated carbon filter, and additional technology. Other technologies such as UV-C and non-thermal plasma showed a small reduction of TVOC, 6 – 9 %, and 10 %, respectively. Noticeably, the air washer showed relatively high TVOC reduction, compared to the non-filter-based technologies.

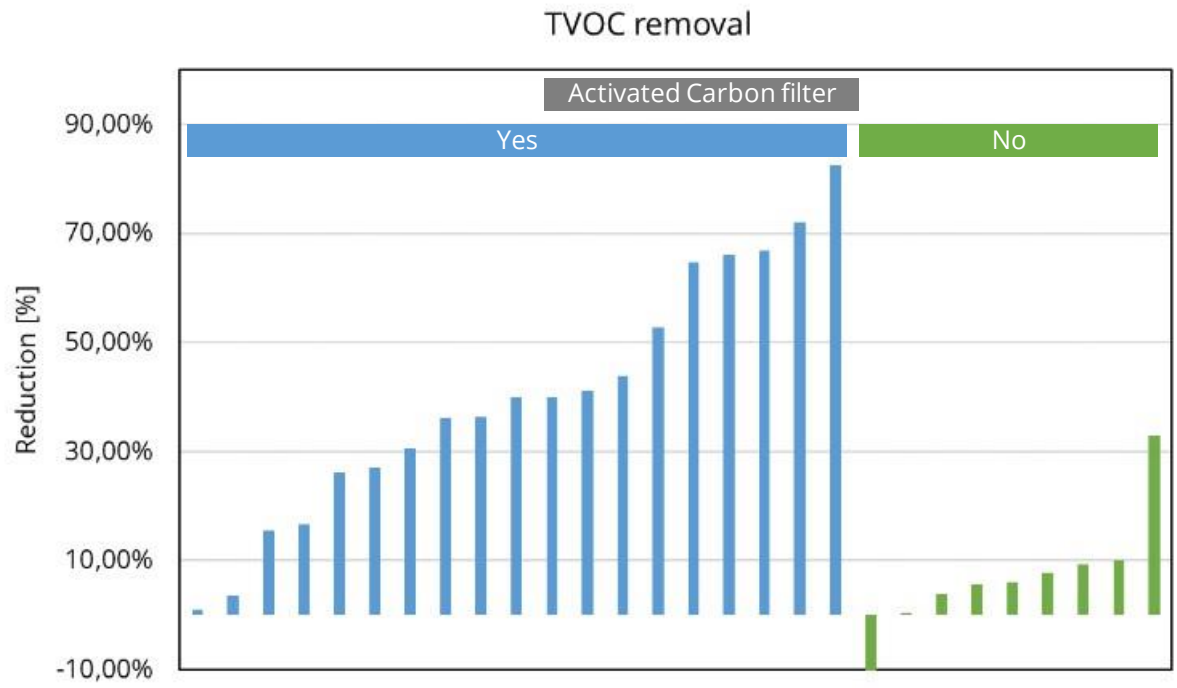

Figure 2: Overview of TVOC removal for all products grouped into with (blue) and without (green) activated carbon filter

It was clear from these measurements that **the removal of gaseous pollutants, such as TVOC, is more troublesome than the removal of particle pollution**. This can clearly be seen by the highest TVOC reduction of 83 %, as compared to 16 devices reducing the particle concentration with more than 97 % during the 30-minute test period.

When evaluating mobile air purifiers, a key aspect is the cleaning capacity or efficiency as described above, however, one also must take the noise, power consumption, and cost into consideration to fully evaluate the product and technologies. These "trade-off"-parameters are discussed below. Additional "trade-offs" out of scope for this project include maintenance, e.g., lifetime of vital parts, replacement of filters, and potential formation of by-products, e.g., conversion of typical gaseous compounds into harmful VOCs (except for ozone).

Ozone

Ozone is a harmful gaseous compound, that can Inflame and damage the airways, as well as make the lungs more susceptible to infection, even at relatively low levels. WHO air quality guidelines for ozone recommend exposure limits at 0.05 ppm (8 hour mean).

Ozone generation can potentially be generated from clean air technologies using electricity, e.g., UV-C light, plasma, photocatalytic oxidation, and ionizers. Thus, mobile air purifiers can produce ozone intentionally as a "cleaning agent" or unintentionally as a by-product

The generation of ozone was investigated in detail for all products, as this is a common and well-established concern regarding these air purifiers. In total, **ozone generation was measured for 2 products**: the ozone generator and a UV-C device.

Noise

Noise is the most notable nuisance from these products, as the movement of air by a fan always will cause noise to some degree. Ultimately, a product should be able to deliver as much clean air as possible with as little noise as possible. In Figure 3 below, we present this relationship for all 29 products.

A relatively large difference in noise levels can be observed for products delivering almost the same amount of clean air. For example, for product with a CADR-value around 250 m^3/hour, a difference of up to 10 dB is measured.

Another important fact is that noise is not a predictor of the cleaning rate. Hence, some products are able to deliver more clean air at lower noise levels than other products producing more noise and a lower amount of clean air.

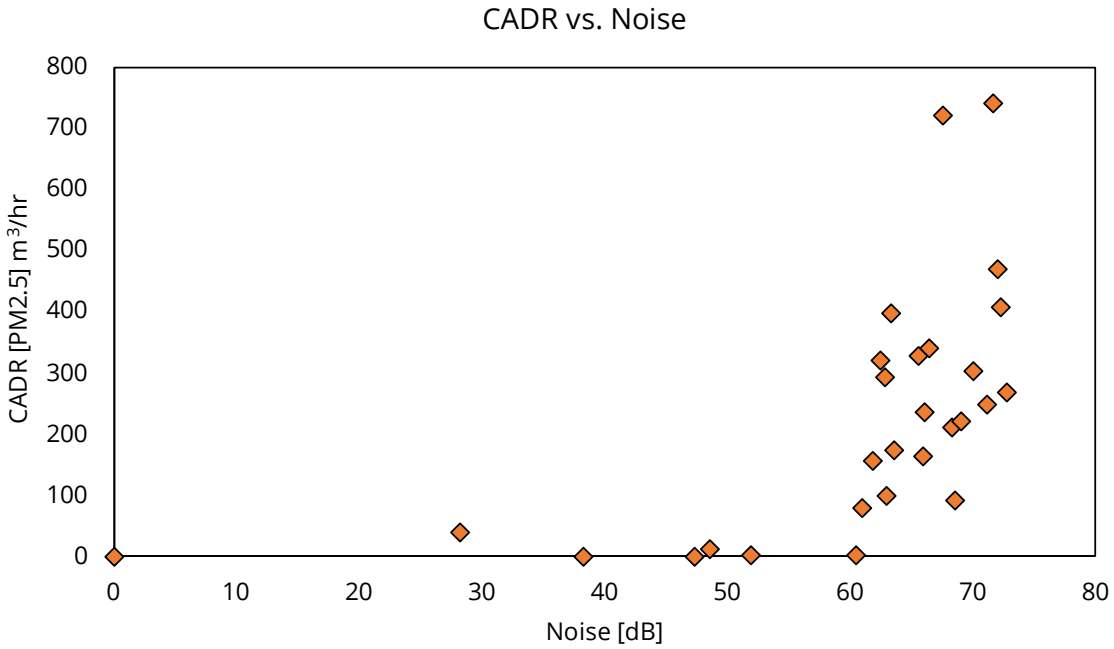

Figure 3: Overview of noise levels for all products in relation to cleaning rate (CADR)

Power

Another downside of mobile air purifiers is the power consumption. All test products use a fan for moving air (except the bag with activated carbon) which needs power, and most products also use electricity for their cleaning technologies (e.g., UV-C light or ionizer). In Figure 4, we present the relationship between CADR and power consumption.

There is no clear correlation between power consumption and CADR value. There is measured a broad span in power for the middle-range air purifiers (CADR 200 – 300 m^3/hour). Thus, one needs to have attention to the power consumption in addition to the cleaning rate.

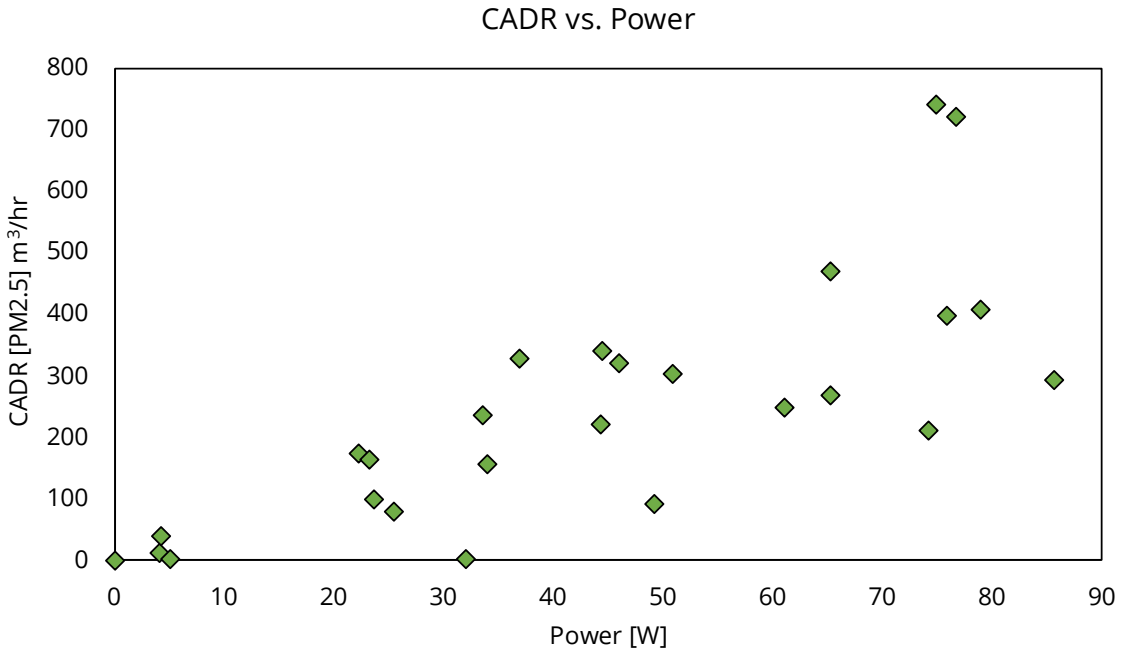

Figure 4: Overview of power for all products in relation to cleaning rate (CADR). The ozone generator is emitted from this plot, as it operated non-continuously.

Cost effectiveness

Lastly, we have evaluated the cost-effectiveness of the 29 products, as it might be speculated that price is a precise indicator for cleaning rate. This is, however, not the case, as witnessed in Figure 5. Even though the product with the highest CADR is also the one with the highest purchase cost, the correlation is more or less random. Some of the products with the highest CADR is found among the cheapest products, whereas some products with high purchase cost have relatively low CADR values.

Moreover, we have evaluated the "amount of clean air per 1 DKK" for all products (Figure 6), based on the purchase cost of the product. The most cost-effective products delivered approximately 0.30 m^3 of clean air per 1 DKK, whereas the less cost-effective only delivered 0.01 m^3 of clean air per 1 DKK. Interestingly, EPA-based devices were on average more cost-effective than HEPA-based devices.

When evaluating the cost-effectiveness of TVOC removal (Figure 7) it was found that products utilizing activated carbon filters were the most cost-effective. However, a few products without activated carbon filters, utilizing other technologies, were found to be more cost-effective than most of the products with activated carbon filters.

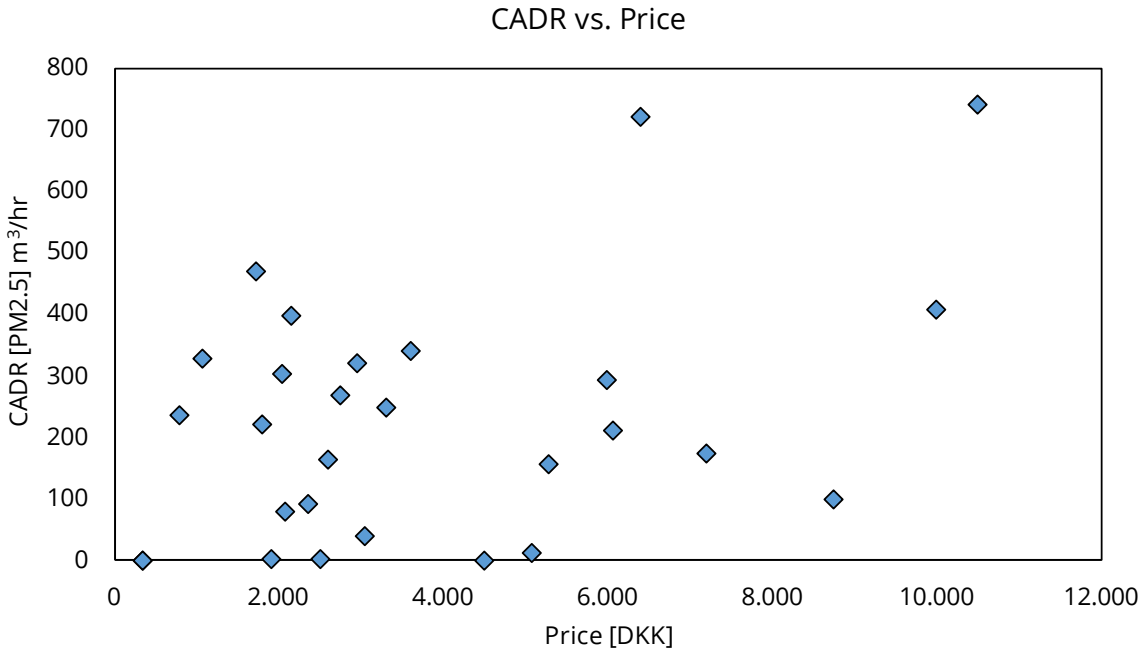

Figure 5: Overview of purchase cost for all products in relation to cleaning rate (CADR)

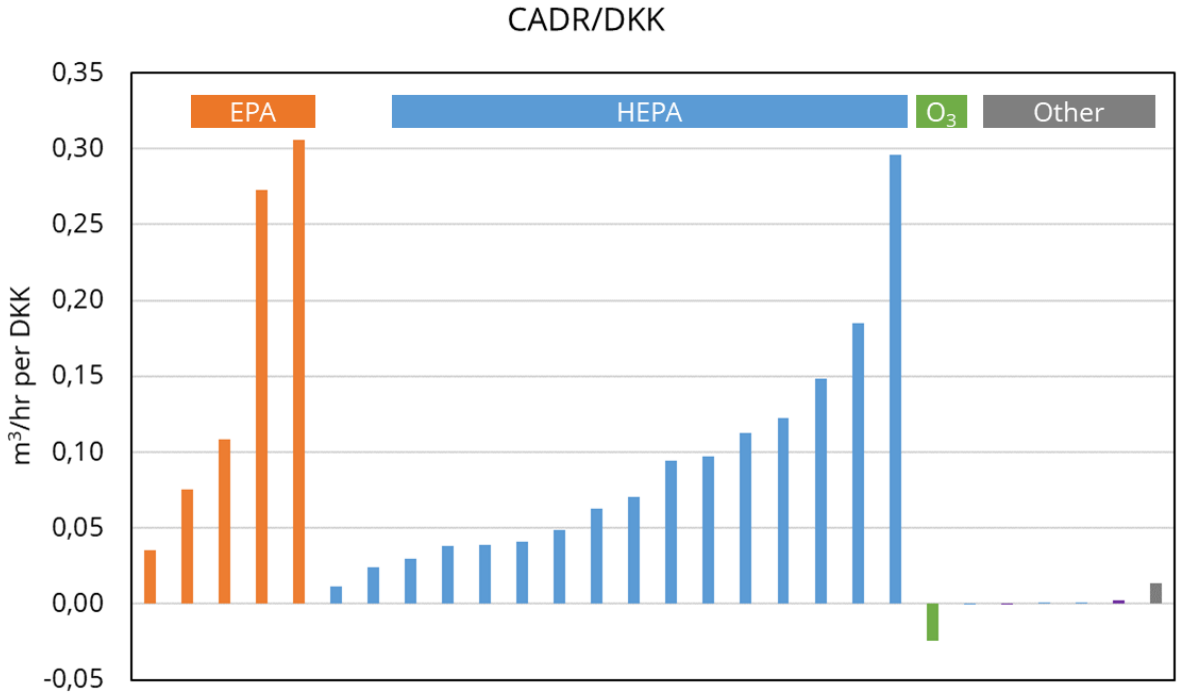

Figure 6: Overview over the cost-effectiveness of all products, calculated as amount of clean air per 1 DKK (CADR [PM2.5] / purchase cost)

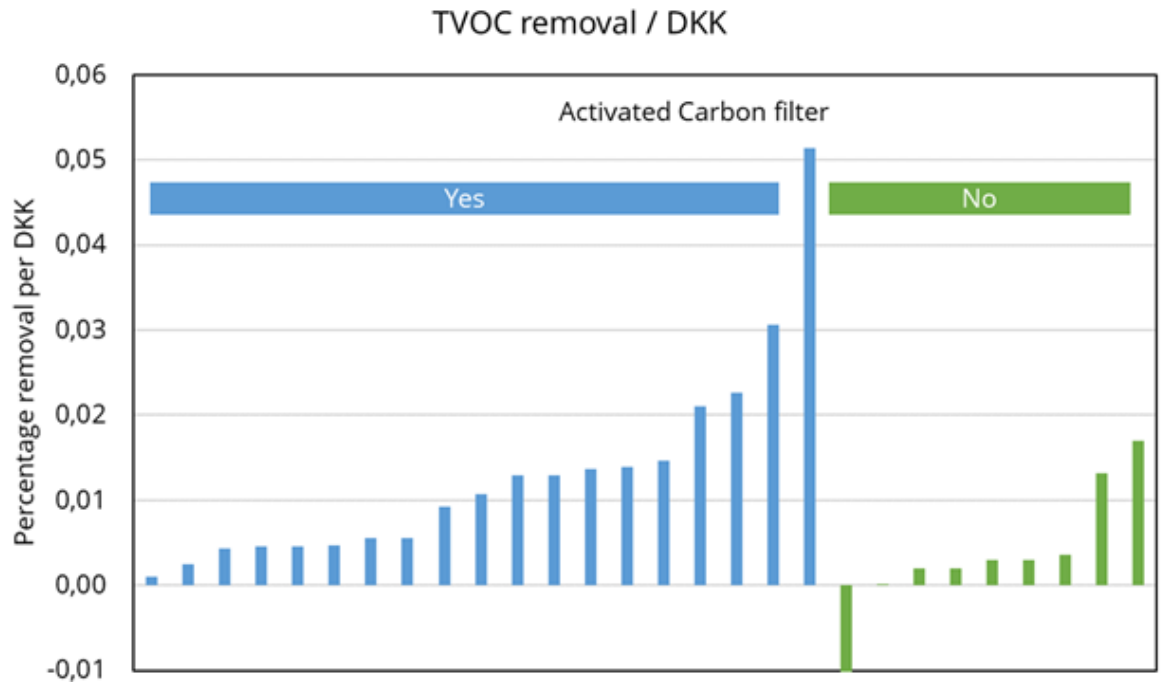

Figure 7 Overview over the cost-effectiveness of all products, calculated as amount of clean air per 1 DKK (TVOC removal [%] / purchase cost)

Airborne Viruses

Another key aspect of mobile air purifiers is the ability to remove or inactivate airborne viruses. In this project, a representative part of the various technologies used for mobile air purifiers were tested (six products in total). Results can be found in Table 2. The result is presented as *reduction rate*, a term that indicates how much the air purifier improves the reduction of active virus compared to the natural decay.

Generally, the HEPA-based devices showed the highest reduction rate of active virus from the chamber (at least 99 % or more after 30 minutes).

The EPA-based device also had a +99% reduction rate during the 30-minute test period.

The UV-C technology has been heavily marketed during the pandemic, however, the reduction rate measured for this device (51.16%) was significantly lower than for HEPA devices. Since UV-C is a technology that varies from product to product, the tested UV-C device is not necessarily representative of all UV-C air purifiers.

The air purifier with ionization technology had the lowest reduction rate, at 28.73%.

The small difference between the three HEPA-based devices (Air Purifier 2, 3, and 6) does not indicate that the additional clean air technologies utilized in Air Purifier 2 and 3 give rise to higher reduction rates. Rather, the difference can be related to the airflow for each air purifier. The airflow has a huge impact on how much air is moved inside the chamber and thus how much air is passing through the air purifier. This means that two air purifiers with the same technology can have different reduction rates because of the amount of air the products "treats". Airflow has not been measured since the efficiency experiments are enough for the evaluation of the air purifier.

Furthermore, it should be noted that the relatively little difference in reduction rate in percentage translates to a rather big difference in absolute concentration. E.g., Air Purifier 2 and 6 have a reduction rate of 99.68 % and 99.93 %, respectively. This corresponds to more than 615.000 active virus aerosols per cubic meter (m^3) after 30 minutes of cleaning for Air Purifier 2, and less than 10.000 virus aerosols per m^3 for Air Purifier 6. The starting concentration of viruses before switching the air purifiers on was on average 610,000,000 per m^3.

Table 2. Summary of test with airborne virus (MS2). AC = activated carbon

Air Purifier no.	1	2	3	4	5	6
Technology	Ionizer	HEPA, AC, TiO2, UV-C	HEPA, AC	EPA	UV-C	HEPA
Reduction rate (20 m^3, 30 min.)	28.73% ±16%	99.68% ±0.12%	99.89% ±0.03%	99.57% ±0.44%	51.16% ±13%	99.93% ± 0.05%
Remaining concentration (30 min) [#/m^3]	70,000,000	616,000	81,000	171,100	16,100,000	10,000

Note, that the predominant mode of transmission of most respiratory viruses, incl. *SARS-CoV-2*, is not fully agreed upon[1, 2]. Airborne transmission through aerosols is a potential mode of transmission in addition to contact and droplet transmission. Thus, the test report is not to be used as evidence for virucidal (ability to inactivate viruses) activity on *SARS-CoV-2*. Thus, this test report only concludes on the efficiency to reduce the concentration of aerosols containing active virus, and not on mitigation of the spread of infectious agents.

7. Outlook

In this project, the test results are furthermore compared with endorsements from the product providers, especially with regards to CADR and suggested maximum room size. Concerning the CADR value, it was found that the test results were as low as 59 % of the value stated by the company. On the other hand, some of the products have stated a CADR value below what was measured in our test. This clearly highlights the need for a harmonized standard for measuring the efficiency and performance of mobile air purifiers. This will ensure that consumers can compare products on equal terms.

Another benchmark value often observed in marketing material, is *suggested maximum room size*. As for the CADR value, there is no harmonized standard for calculating this. By calculating the maximum suggested room size as described in ANSI/AHAM AC-1-2015 using the CADR value found in this test, the test results can be compared with the product endorsement stated by the companies. Out of the 29 products, only three products have similar suggested maximum room size in this test and their product endorsement. For 15 products, the calculated suggested maximum room size is only 50 % or lower than what is stated by the companies.

The ANSI/AHAM AC-1-2015 standard uses a conversion factor between CADR and a suggested maximum room size of 0.086, which is adopted in this project. When calculating a similar conversion factor from the stated CADR and room size, it was found that companies use values up to 4 times higher. This can result in under-dimensioned products applied in rooms, where they will not effectively clean

[1] CDC.gov *"Science Brief: SARS-CoV-2 and Potential Airborne Transmission" (updated October. 05 2020)*
[2] WHO.int *"Transmission of SARS-CoV-2: implications for infection prevention precautions" (updated July 09 2020)*

the air. This also clearly highlights a need for a harmonized standard for product endorsements regarding suggested room size.

A fast-growing trend in the market for mobile air purifiers, is the use of air quality sensors, which are embedded in the product to control the fan speed from a direct measurement of air quality, typically particle pollution (PM2.5). 16 out of 29 products had this feature. It is well-established that these so-called low-cost sensors can have issues regarding accuracy and reliability, which would induce the automated control of these products to be somewhat unreliable.

Moreover, these low-cost sensors might be "blind" to ultrafine particles and harmful gaseous compounds, which would entail that these products might lower their cleaning rate, as the air is experienced as clean when in fact, it is not. We did not investigate this topic in detail in this project, however, it was found that there was a significant difference in PM2.5-concentration at the point where the mobile air purifiers switched fan speed automatically. One product turned down the fan speed already at 1.5 mg/m^3, whereas another product only turned down the fan speed at 0.06 mg/m^3. This might not be a direct consequence of the accuracy of the low-cost sensor, but also the underlying algorithm. Nevertheless, it points towards an area of interest and further investigation.

8. Methodology

Testing in the laboratory

The protocol used for testing all 29 mobile air purifiers in a systematic and controlled setting in the laboratory is based on the standard ANSI/AHAM AC-1-2015 *"Method for Measuring Performance of Portable Household Electric Room Air Cleaners"*. The test is performed in a 20 m^3 test chamber specially designed to test clean air technologies.

In Figure 8, an overview of the protocol is shown. Prior to testing, the test chamber is thoroughly ventilated until specified background concentration levels are reached. Three cigarettes are "smoked" simultaneously in the chamber, and to obtain adequate concentrations of particulate matter and VOCs, the duration of smoking is approximately 7 minutes. Following this so-called smoking phase, the air in the test chamber is highly polluted with both particulate matter and VOCs, and to ensure homogenized pollution a 5-minute mixing period is initialized. Finally, the air purifier is turned on and allowed to operate for 30 minutes.

In addition, a reference test similar to the protocol above is performed, but without switching on the air purifier in order to determine the natural decay and sedimentation during the test period. This contribution is accounted for when reporting the performance of the mobile air purifiers.

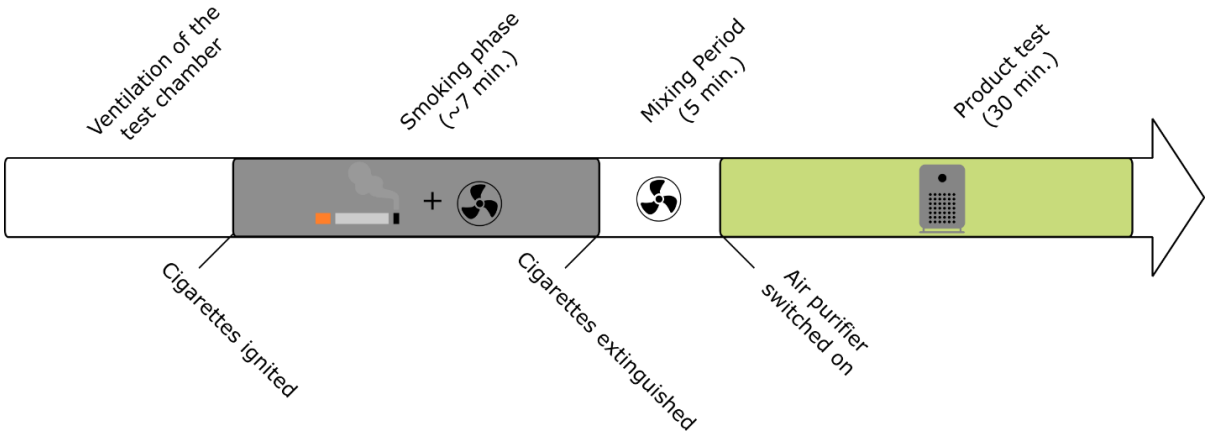

Figure 8. Schematic overview of the protocol for testing the efficiency of the air purifiers to remove cigarette smoke.

When testing in the laboratory, the air purifier had to abide by the following conditions:

- The air purifier is tested as new.
- The air purifier is tested with all standard filters that came with the appliance and no additional filters were bought or inserted that did not come with the appliance.
- The air purifier is tested with all available purification technologies switched on.
- If auto-mode is available, the device is tested on auto, as it is most likely that consumers will use the auto function. Otherwise, the air purifier is tested at the highest level of air intake.
- The air purifier is placed on the floor in the middle of the test chamber unless otherwise clearly stated in the manual.
- The manual is read and followed as is expected a regular consumer would do.

Clean Air Delivery Rate (CADR) - Smoke

No harmonized standard, certification, or legislation for measuring and reporting the performance of mobile air purifiers exists in Denmark or European Union. One of the most widespread methodologies for measuring performance originates from the standard ANSI/AHAM AC-1-2015 "*Method for Measuring Performance Of Portable Household Electric Room Air Cleaners*", which also introduces the term Clean Air Delivery Rate (CADR). The CADR value is calculated from the concentration profile of a specific pollutant, namely the decay rate (labeled *k*) obtained from an exponential fit. The CADR value describes the volume (m^3) of clean air delivered by the product per hour and accounts for the natural decay.

$$CADR = V(k_{air\ purifier} - k_{reference})$$

The CADR value is independent of the duration of the test as well as the test chamber volume (*V*). Thus, CADR values are directly comparable across air purifiers despite slightly different test conditions. We have chosen to adopt the CADR-term and a modified version of the protocol for reporting results in this project.

Additionally, we report the percentage-wise reduction of each of the pollutant parameters, as this might be more comprehensible for non-professionals. However, it should be clearly noted that this result is true only in the exact setup used in this project and is not comparable to other types of tests or cannot be as comparable as the CADR value.

Particle mass concentration

The particle mass concentration of fine particulate matter, namely particles with a diameter of 2.5 µm or below (PM2.5) is measured continuously with a DustTrak DRX (model 8533, TSI Inc.) to visualize and determine the efficiency. PM2.5 is chosen as a pollutant parameter as it is ubiquitous and due to its well-established negative health effects.

In Figure 9, an example of an air purifier test is shown. The blue curves indicate the concentration of PM2.5 during the experiment and the black line shows a fitted line where the slope relates to the decay rate. The grey curves show the span in reference experiments (explained in detail below), where no air purifier is operated during testing. The time scale is defined from the point of switching on the air purifier (Time = 0 min). The smoking phase and mixing period are prior to this. It is clearly observed that the PM2.5 concentration decreases rapidly and is significantly different than the reference experiments (grey). The test is concluded after 30 minutes of operating the air purifier.

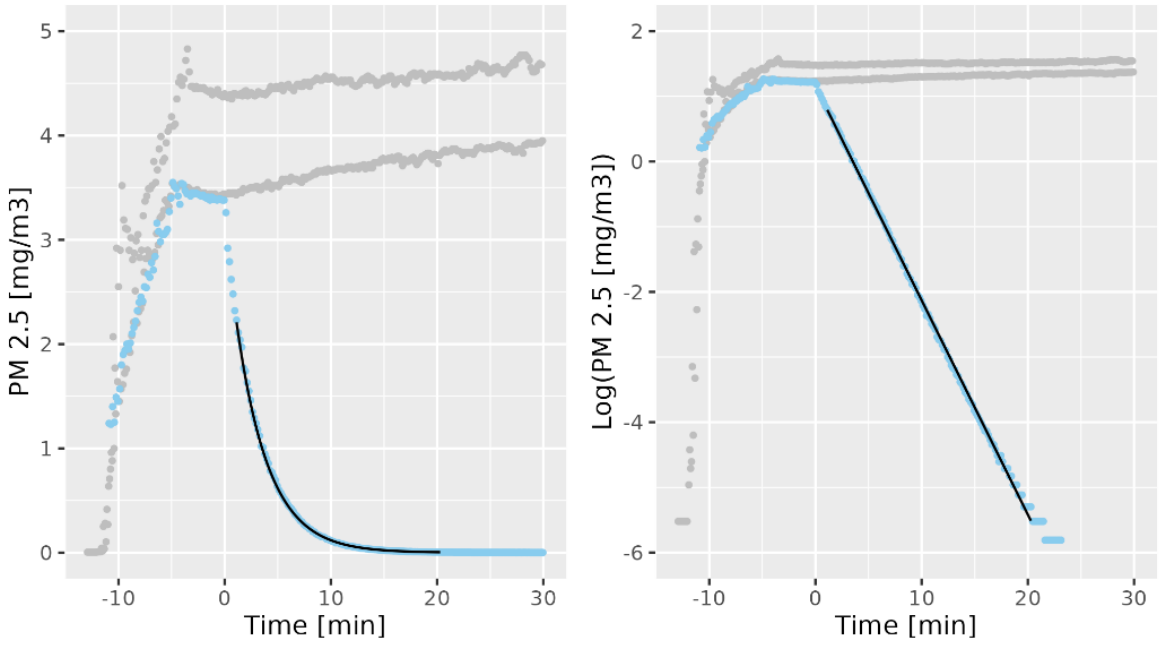

Figure 9. Visualization of the development in particle mass concentration (PM2.5) over time. At time=0, the air purifier is turned on. The two grey lines show the span of the reference measurements (no air purifier inserted in the chamber). The blue line is the air purifier, and the black line is the fitted line to the data.

In Figure 10, the particle mass concentration (PM2.5) is visualized during the reference experiments (no air purifier). The figure visualizes the natural decay and sedimentation of particles from smoking three cigarettes when no outside disturbances are present. In the figure, the concentration increases after Time = 0 min, which is attributed to the agglomeration of smaller particles into larger particles. Hence, the particles obtain a diameter that is detectable to the measurement instrument. As can be seen in the figure, the maximum concentration reached at Time=0 varies across experiments. This is attributed to the uncertainty in handling the smoking process (ignition, duration of smoking, and physically removing cigarette butts), as well as the deviation between cigarettes.

In this project, the CADR value is calculated using a reference that is the average decay rate of all reference experiments shown in Figure 10. This ensures that all air purifiers can be compared under the same conditions.

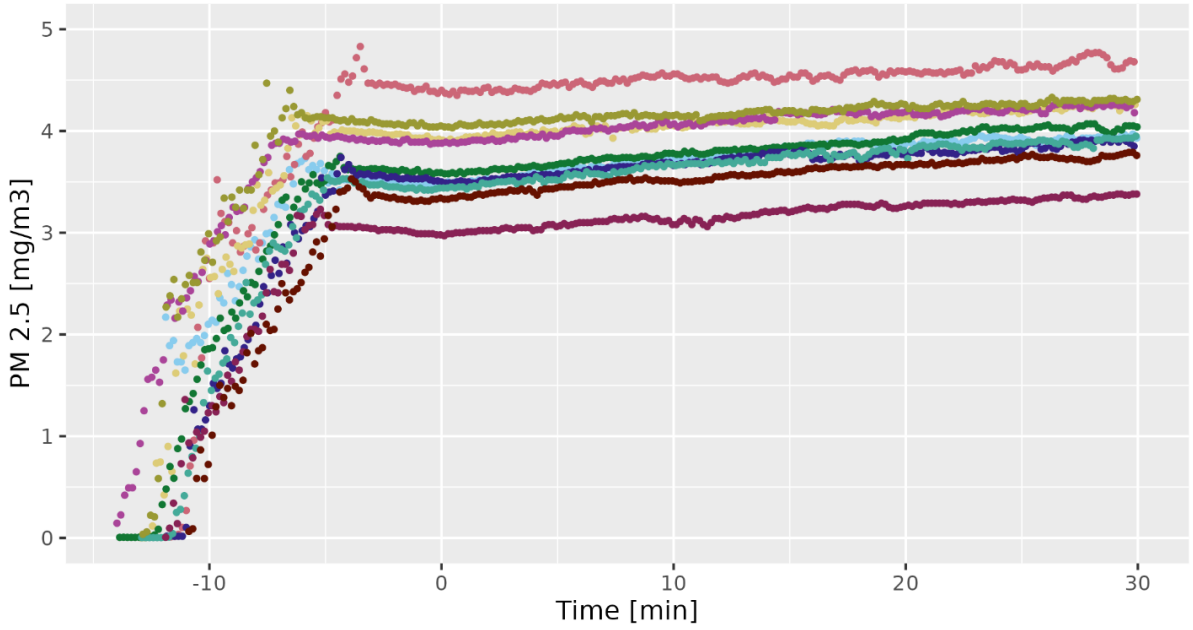

Figure 10. Visualization of 10 reference experiments performed with the DustTrak.

Products with auto-function

The "auto" function denotes an automated control of the fan speed, hence airflow, of the device based on a direct input on the concentration of a specific air pollutant (most commonly PM2.5) by an internal sensor.

The air purifier was set to "auto" if this setting was available, otherwise, the device was set to run with maximum speed. The auto-mode is deemed the most likely way of operating the device by consumers in private homes. Thus, the auto-mode will give the most realistic picture of how the air purifier will perform in a private home.

A test with an air purifier running in auto-mode is shown in Figure 11. At Time=0 the air purifier is turned on and the cleaning phase is initiated. During the cleaning phase, it was observed that the auto-mode switched to lower fan speeds as the particle concentration reduced. This is witnessed by the kinks in the graph decrease in slope, as compared to the linear graph in the logarithmic plot in the figure.

The decay rates for different fan speeds are found by fitting the various sections of the graph and finding the slope. In the figure, we can see three different fitted lines (the black lines), and this represents different fan speeds that the air purifier operates. The reported CADR value, which is calculated from the decay rate, is found from the initial period where the particle concentration is high, and where it is assumed the air purifier is running at maximum speed. The same is done when calculating the CADR value of ultrafine particles and VOCs (see next sections).

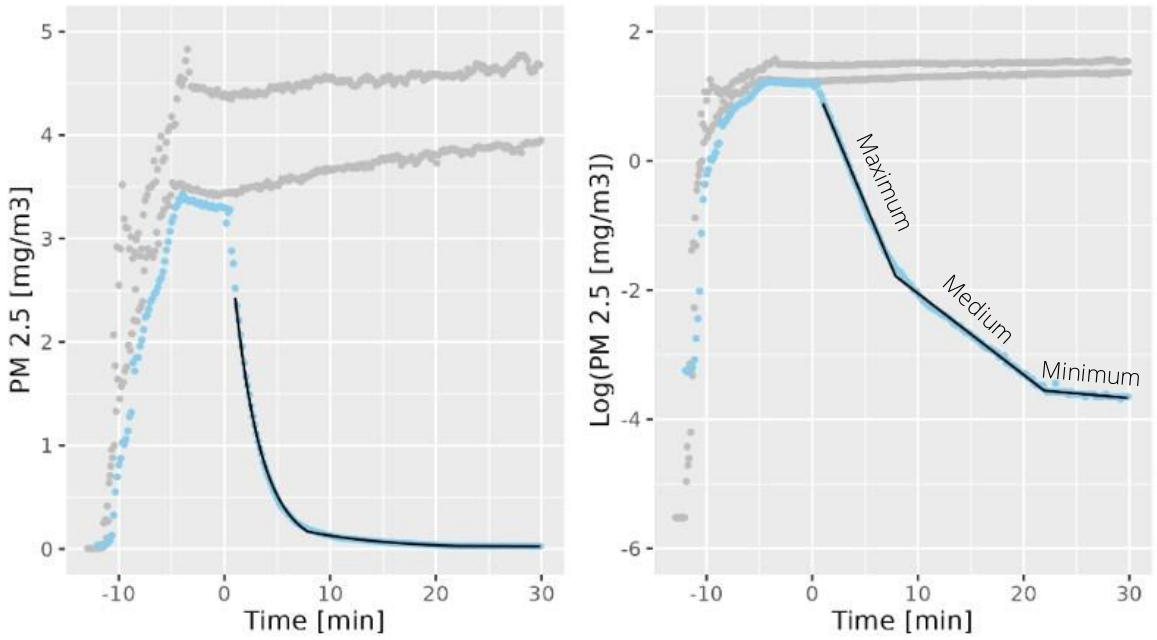

Figure 11. Visualization of the development in particle mass concentration (PM2.5) over time with an air purifier set on "auto". At Time= 0 the air purifier is turned on. The two grey lines show the two references (no air purifier inserted in the chamber). The blue line is the air purifier, and the black line is the fitted line to the data.

Particle number concentration

The concentration of particle number is measured continuously using the SMPS Nanoparticle Sizer (TSI NANOSCAN 3910). The instrument counts particles in the size range of 10-420 nanometers (nm) (0.01-0.42 µm) with a time solution of 60 seconds. The particle number concentration is investigated, in addition to PM2.5, as the majority of particles from cigarette smoke are in the size range of 50-150 nm (Figure 13). Thus, the particle size distribution is dominated by ultrafine particles, which are expected to have severe negative health effects. It should be noted that ultrafine particles typically are defined as particles with a size smaller than 100 nm. For the purpose of clarity, we do not distinguish between particle sizes and summaries the findings as ultrafine particles for the entire size range.
In Figure 12, the total particle number concentration from the reference experiments is shown. At Time=-5 the mixing period begins, and we can see that the concentration is at its highest. Hereafter, the concentration slowly decreases as the particles decay due to sedimentation and accumulation.

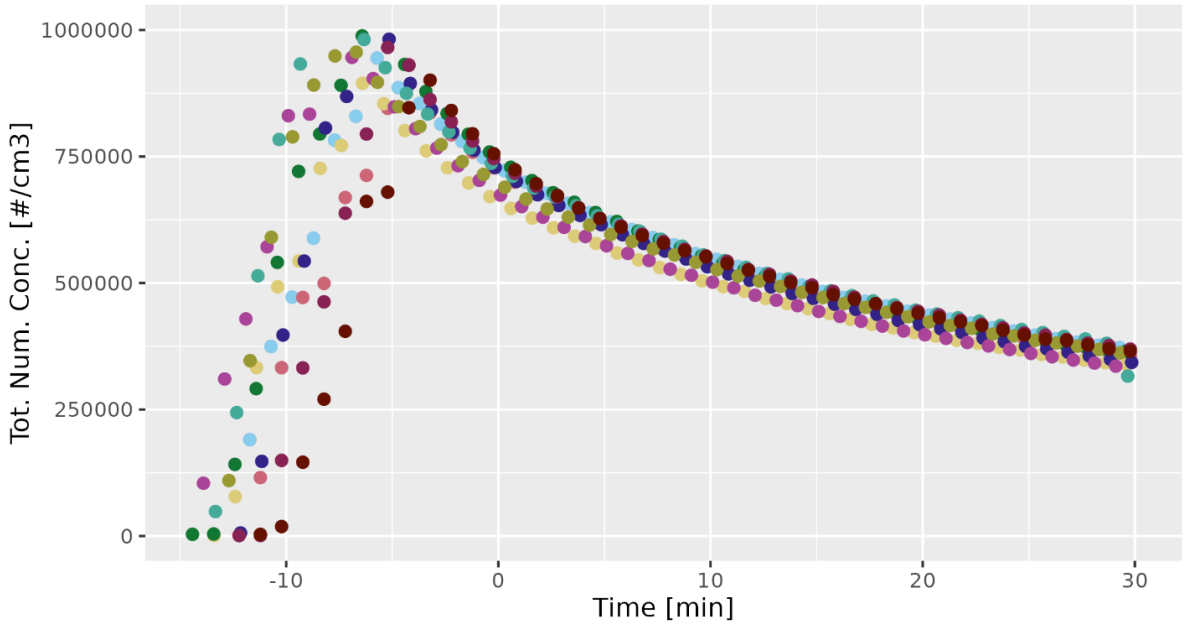

Figure 12. The evolution of particle number concentration from the reference experiments.

In Figure 13, the particle number concentration is visualized according to the size (nm) of the particles. The figure shows the reference experiments at the initial period (Time = 0 min) and the final period (Time = 30 min). From this figure, we see the agglomeration of the particles (smaller particles clustering together into larger particles), as the number concentration of particles with a size of 200 nm increases between time = 0 min (solid line, circular points) and time = 30 min (dashed line, triangular points), whereas all other particle sizes decrease in concentration.

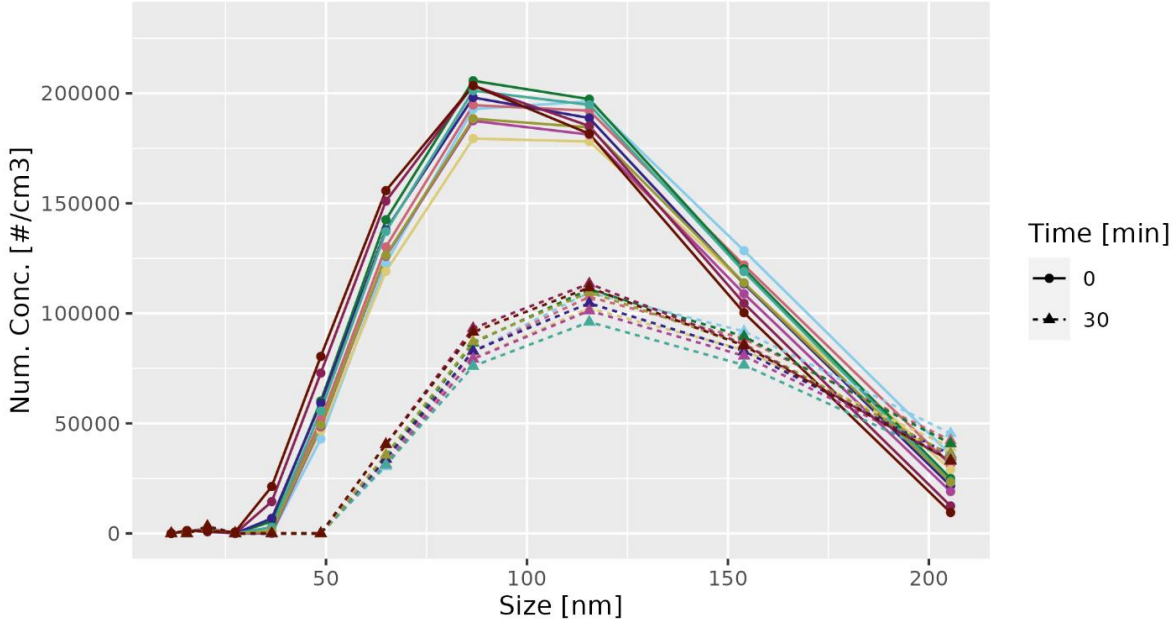

Figure 13. The number concentration size distribution from the reference experiments. For each reference, there is a point where the time=0 min (where the air purifier is switched on if present) and a point with time=30 min where the experiments are complete.

In Figure 14, we present the particle number concentration measured during a test of an air purifier (blue dots) in addition to a reference measurement for comparison (grey dots). The time scale is defined from the point of switching the air purifier on (Time = 0 min). It is clearly seen that the particle number concentration is reduced upon switching on the air purifier and is significantly different from the reference experiments. As already mentioned, the performance of the tested air purifier is reported as a CADR value found by the difference in decay rate between the product and the reference measurement.

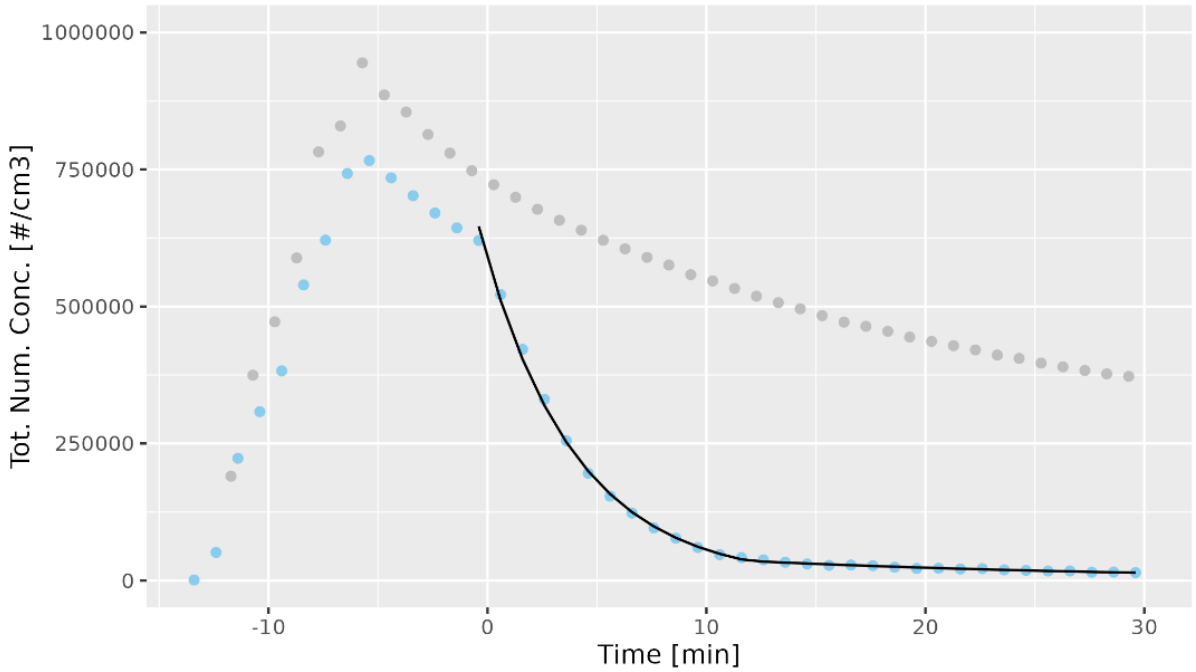

Figure 14. Example of the particle number concentration over time. At time=0 the air purifier is turned on. The grey is a reference where no air purifier is present, and the blue dots are the air purifier. The black line indicates the fitted parameter used for finding the decay rate.

In Figure 15, the size distribution is shown for the test with an air purifier. The blue curve (Time = 0) and red curve (Time=30) represent the size distribution prior to switching on the air purifier and after 30 minutes of operation, respectively. A significant reduction of particle concentration across the entire size range is observed for this specific air purifier. The reduction is partly credited to the natural decay, as witnessed in Figure 13, but mainly due to the effect of the air purifier.

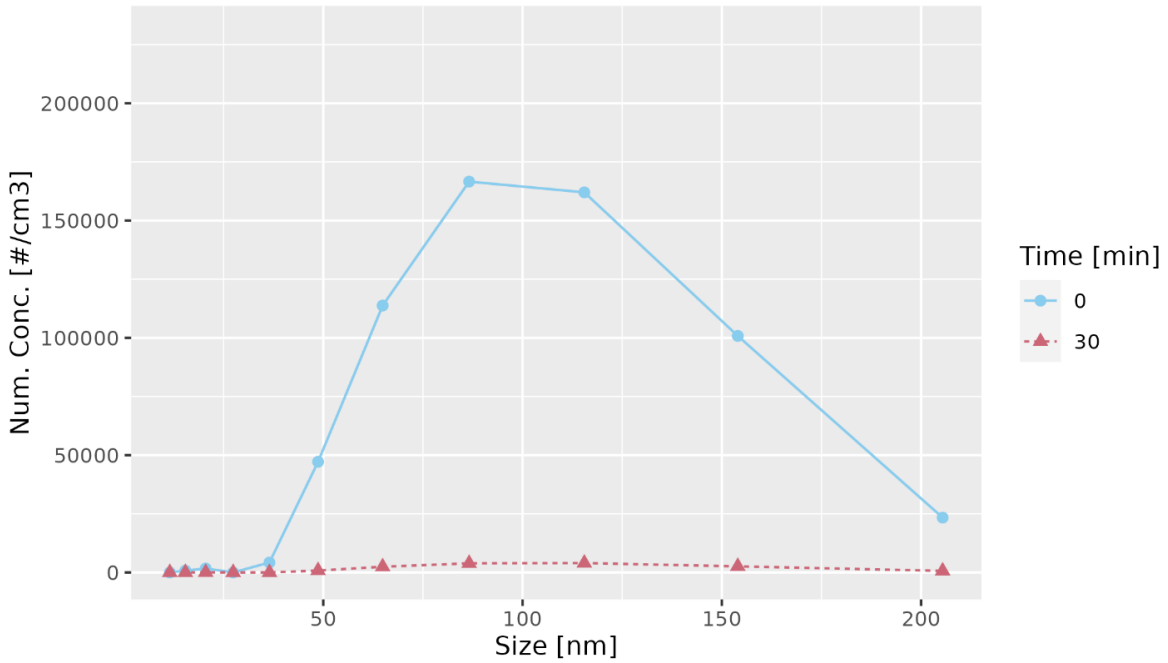

Figure 15. The number concentration of the different particle sizes (diameter) for the same air purifier as above. The blue line is the concentration at time=0 and the red line is the concentration at time=30.

Volatile Organic Compounds (VOCs)

Harmful gaseous pollutants from cigarette smoke mainly consist of volatile organic compounds (VOCs). VOC is a general term for organic chemical compounds which evaporate easily and can be found in various concentrations in ambient air. Cigarette smoke is known to contain countless harmful VOCs (e.g., formaldehyde, benzene, toluene, and styrene[3]) which are associated with respiratory and cardiovascular diseases. Additionally, odors associated with smoking are also caused by VOCs. The total concentration of all these gases is called total VOC or simply TVOC. In this project, we do not distinguish which types of VOCs are present in the chamber, but we monitor and report the total concentration of *all* VOCs.

One rarely talks about the "size" of VOCs, as these are gases consisting of molecules, each of which is significantly smaller than even ultrafine particles. Thus, VOCs are measured using a different technique than for particles, namely a photoionization detector (TIGER VOC detector from ION Science).

A significant difference between VOCs and particles is that VOCs to a larger degree remain in the air until the air is replaced or removed, whereas larger particles slowly will fall to the ground on their own over time. However, both types of pollutants can also settle on e.g., clothes and furniture, and thus, be “removed” from the air.

An example of a TVOC measurement from a test with an air purifier switched on is shown in Figure 16. Here, the TVOC concentration is shown on the y-axis, and the time duration is shown on the x-axis. At time = 0 the air purifier is switched on. The grey line shows one of the reference experiments (detailed description below). From this figure, we can see that the air purifier successfully reduces the VOC concentration. However, the concentration is not reduced exponentially, as seen for particles. This causes the calculated CADR value for TVOC to be somewhat uncertain.

[3] Mainstream Smoke Levels of Volatile Organic Compounds in 50 US Domestic Cigarette Brands Smoked with the ISO and Canadian Intense Protocols - PMC (nih.gov)

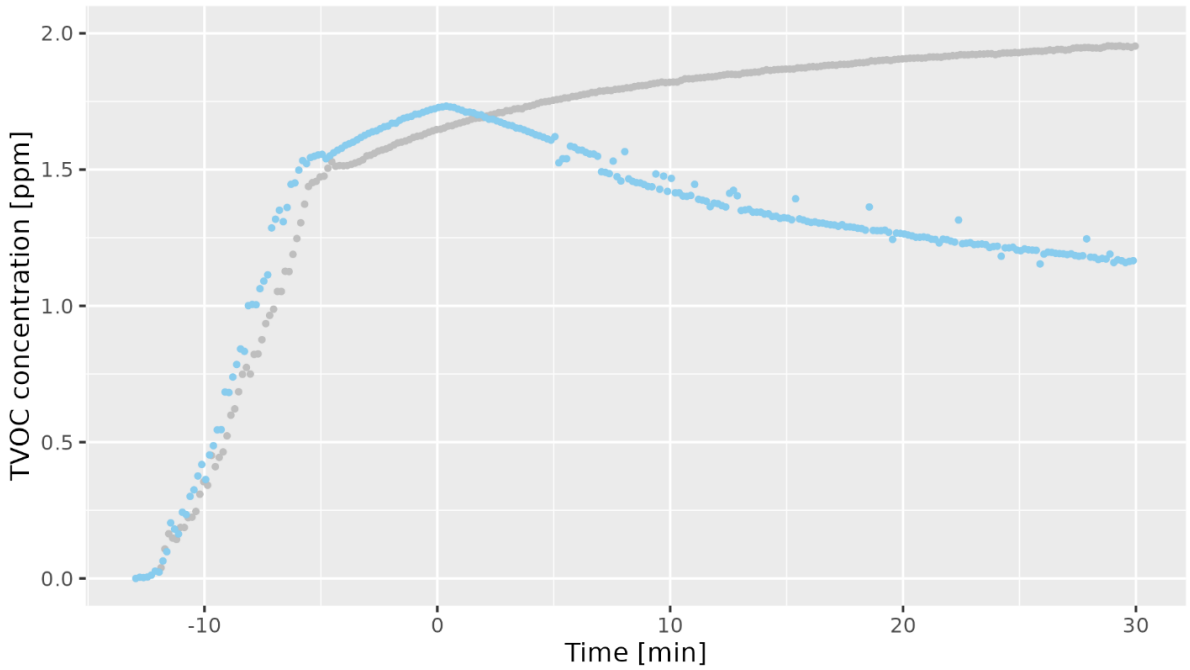

Figure 16. The concentration of VOCs (ppm) over the experiment for a given air purifier which reduces the VOC concentration. The grey is a reference, and the blue is the air purifier.

Figure 17 shows the reference experiments carried out during the experiments. On average, the TVOC concentration reached after the smoking phase was ~1.5 ppm and a small difference from day to day was observed.

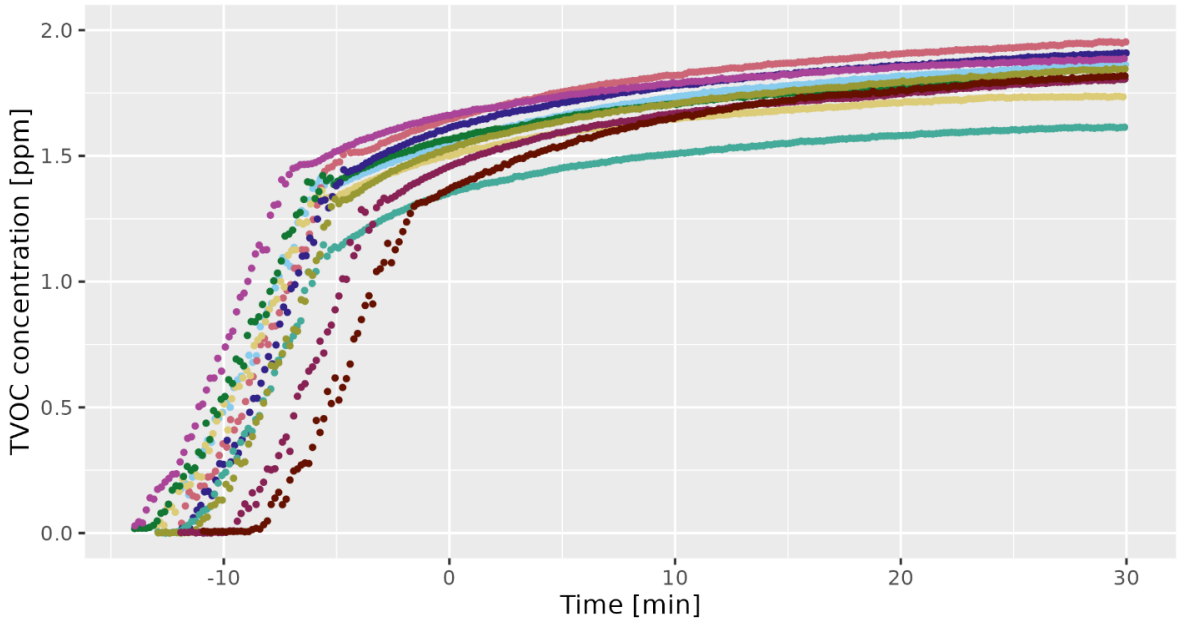

Figure 17. All 10 reference experiments from the laboratory of Volatile Organic Compounds (VOCs).

Ozone

Ozone is a harmful gaseous compound, that can inflame and damage the airways, as well as make the lungs more susceptible to infection, even at relatively low levels. WHO air quality guidelines for ozone recommend exposure limits at 0.05 ppm (8-hour mean). Ozone generation can potentially be generated from clean air technologies using electricity.

Because of the high risk of ozone production from air purifiers and the harmful nature of ozone, we have tested all products for ozone emission. For this test, Dräger Short-term tubes are used. This technique is well-proven and reliable, and it is widely used for quantifying ozone concentration, e.g., chemical work environment assessment. The utilized tubes have a standard measuring range of 0.05 to 0.7 ppm, with a standard deviation of ± 10-15 %. Air samples are taken directly from the outgoing air coming from the device.

Noise

The noise level was examined as it has a huge impact on the experience of the air purifier. A family will most likely not have an air purifier turned on if the noise is disturbing. Therefore, it is important to investigate and establish the noise on two levels: lowest/sleep and maximum/turbo. If the air purifier only had one level, the value was stated as maximum. The noise was measured with an NTi Audio XL2 handheld audio and acoustic analyzer together with a NTi Audio M2230 Microphone

Together with the measured value of noise, a subjective evaluation of the noise is performed. This is to establish whether the noise is a buzzing, a humming, or a shrieking noise. The lowest level is evaluated under the condition of whether a person could sleep from it (if the lowest was in sleep mode) or just whether you could hear it. The highest level was evaluated after how interrupting it was, and in most cases, it was hard to not notice the appliance. It is presumed, that a family most likely will use the appliance under auto function, however, the two outer cases will provide a representative picture of the noise levels the air purifier delivers.

Almost all product suppliers state a noise range that their appliance runs in, and they are compared with the measurements from our laboratory. Some precautions for the direct measurements need to be settled. Firstly, because of the conditions in our chamber, the values we measure will overestimate the actual value. Secondly, the value is an average over a period of 60 seconds.

Power

Measurements of the power consumption have been performed with a SparOmeter from Elma instruments. The power was measured for the appliance when on standby (plugged in but switched off), at minimum speed, and at maximum speed. The measured values are only a guiding evaluation and some precautions to the direct value must be taken into consideration.

Airborne Virus

The market for mobile air purifiers has grown significantly during the Covid-19 pandemic, both in terms of new technologies as well as companies associated with air cleaning. As of today, no harmonized standard for measuring performance exists, and neither does any legislation or certification for product endorsements. Thus, product claims are incomparable and may be misleading.

In this project, we have adopted and modified the standard ISO 16000-36:2018 "*Standard method for assessing the reduction rate of culturable airborne bacteria by air purifiers using a test chamber*" to determine the efficiency against airborne virus. The efficiency is reported as a "*reduction rate*", which indicates how much virus the air purifier removes/inactivates compared to the natural decay. The test duration was 30 minutes, and the room size was 20 m^3 (Figure 18).

The air purifiers are tested against a model virus named MS2 bacteriophage. MS2 is a well-recognized surrogate for a large variety of viruses. MS2 belongs to the virus family called non-enveloped, which usually are less susceptible to disinfectants such as UV-C light, etc., compared to the enveloped virus family, which includes the corona and influenza viruses. However, it should be noted that there is no unambiguous scientific correlation between the MS2 virus and the Sars-CoV-2 virus.

Testing of the efficiency of the air purifiers to inactivate/remove virus was performed on 6 representative products out of the 29 air purifiers. The aim of these experiments was to evaluate various technologies in terms of their ability to remove and/or inactivate virus. It is known that UV-C is one way of inactivating virus, and thus, the efficiency of an air purifier with this technology was tested. HEPA filters are also known to remove/inactivate virus and three air purifiers with this technology was tested, one solely with HEPA and two with HEPA and other technologies incorporated.

Prior to the test, the room was thoroughly cleaned and heavily ventilated. The relative humidity in the test chamber during testing was 50 ± 10 %RH and the temperature was 21.5 °C ± 1°C.
The sampling from the air was captured through 6 mm stainless steel tubes in the sidewall of the room using GilAir plus pump at 4.0 L/min.

For each timestamp, three air samples were extracted simultaneously at different locations in the test chamber. A total of 20 L was extracted per sample into an impinger with a 60 mL SM-buffer.
The timing of sampling was: 0 and 30 minutes after undertaking the aerosolization. The exact time for the sampling was defined at the beginning of the sampling time of about 5 minutes. The start of the first sample (Time = 0 min) is less than a minute after the nebulizer was stopped.

The procedure is the following:

- A suspension of MS2 in SM-buffer is prepared and the concentration is determined.
- A background sample is taken before the test and injection of aerosols.
- The reference test of the natural decay is carried out without the air purifier being turned on. The Palas nebulizer works at 2 bar pressure for a total time of 20 minutes before the reference test is initialized.
- The floor ventilator is switched off after the nebulization of the virus.
- Three samples are collected using impingers immediately after the nebulizer is conducted.
- Three samples are collected using impingers after 30 minutes.
- After the 30-minute test with the air purifier off, the room is flushed with clean air for 45 minutes.

- The same procedure is followed for subsequent air purifier tests. After injection of the MS2 containing aerosols and sampling of the time=0 minutes, the air purifying device is remotely switched on.
- The sampling is carried out 0 and 30 minutes after undertaking the aerosolization.
- The concentration of active MS2 virus is evaluated for each sample by mixing dilutions series with a fresh culture of the host bacteria, cultivation, and enumeration of plaque-forming unit (PFU) following incubation.

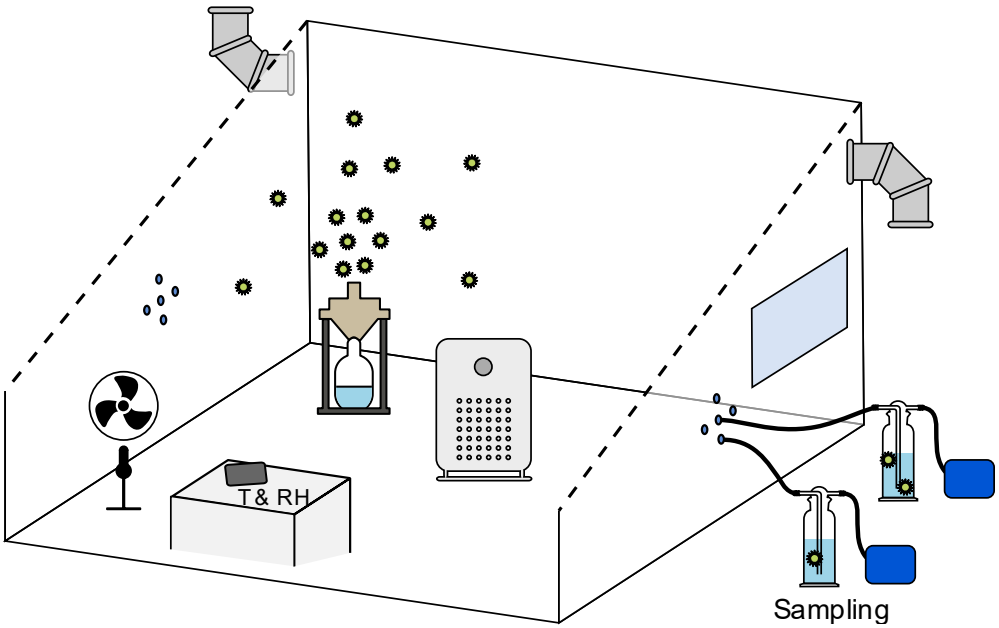

Figure 18: Schematic overview of test setup for virus tes

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