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**Dispositifs pour le piégeage passif
des particules fines de l'air extérieur**

**Devices for passive trapping of fine
particulate matters in outdoor air**

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Những sự cố gắng, tình yêu thương và lòng biết ơn xin dành cho:

Ông nội, bà nội, ông ngoại, bà ngoại, bố, mẹ, luôn tin tưởng và yêu thương con, luôn dõi theo và đồng hành cùng con.

<3 Bố, Mẹ, Anh, Khoai <3

"Quây nhau lạy trước phật đài
Tái sinh trần tạ, lòng người từ bi"*
Đời người được có mấy khi,
Cày sâu cuốc bẫm, chi sang mấy ngày?
Cây đều, xanh tốt, thẳng ngay,
Rồi cũng khô héo như là lá đa
Rừng vàng, biển bạc là nhà
Đất là sinh khí cho cây nảy mầm.
Nước nguồn hoà vào nước sông
Là nơi ngựa uống, lòng người chớ quên.
Chẳng ai nhớ mặt, thuộc tên,
Nên hoà đất đá, ôm ghì núi sông.
Trời cao, biển rộng mênh mông,
Ở trong ánh mắt, nụ cười em thơ.

*: trích câu 2283 Truyện Kiều,
Nguyễn Du

Before, far beyond once upon a time,
We live in the dark, fire is a prime
But we don't know, oh we never know
The darkest moment is before dawn
And do you see, in the brightest moment,
That small dot of little dark spawns.

Kings rise and fall as autumn leaves
Lovers meet, separate, union, leave
Where is our soul's destination?
Why dates so sweet and not the lemon?
How long was I stay still at the train station?
When the oceans become mountains?
What are we doing?
Between the stars, we are dancing!

"We only live once!" No, that's not!
We dance in the light, and missing the dot
We run for dawn, forgot the crawling dark
We can see upon the sky and wish others luck
Please sometimes check under our beds,
The unfortunate ground is going to crack!

*Re-salut,
Tu es la personne que j'ai rencontrée hier
Ta sublime sourire, avec ton regard fier
Tout le monde se tourne la tête après toi
On t'écoute, t'admire, et te respecte.
Tu possèdes cet univers entier, sauf moi!
Surement tu es une personne merveilleuse
Des bonhommes rêvent de ta main amoureuse
Maladroit, je voudrais te dire une fois,
Nul n'est parfait, ni toi, ni moi, ni des rois.
J'aimerais connaître tes lumières et ténèbres
Je serai ton obscurité pour que tu brilles,
Et du soleil qui allume tes jours sombres.
J'aimerais te montrer aussi mes bonheurs,
Mes délires, mes efforts, et mes douleurs
si, et seulement si tu en veux.
Juste excuses-moi,
Qui-es-tu?*

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RESUME - ABSTRACT



DISPOSITIFS POUR LA FILTRATION PASSIVE DES PARTICULES FINES EN MILIEU URBAIN ET PERIURBAIN À STRASBOURG, FRANCE

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Résumé

Le trafic routier contribue à une part importante de l'émission des particules fines (PM) dans l'air extérieur au niveau des zones urbaines. Ce projet consiste au développement d'un système de piégeage passif des particules fines dans l'air extérieur par un support enduit d'une couche de revêtement à base d'huile végétale. Deux profils de PM ont été dressés en se basant sur les variations du lieu d'implantation des deux prototypes, des types de conduites et des conditions de trafic. Le système a la capacité de capter et retenir jusqu'à $84 \pm 6 \text{ g.m}^{-2}$ de PM total par surface de filtre dans le cas d'une voie rapide (périphérique) et $50 \pm 8 \text{ g.m}^{-2}$ dans le cas d'une avenue entourée par des bâtiments résidentiels (rue canyon). Le prototype à proximité de la voie rapide (RM35) a collecté principalement des particules issues de la dégradation de pneus et de la route, tandis que les particules métalliques émises par les systèmes de freinage et d'embrayage ont principalement été détectées sous forme de traces dans le cas du prototype localisé dans la zone résidentielle (ADR). Les particules métalliques ont été aussi détectées au prototype RM35, due au freinage occasionnelle à grande vitesse. La structure du support est lavable et régénérable, et conserve sa capacité de captage après plusieurs cycles de régénération. Ce système de filtration a des potentiels d'application dans les établissements sensibles tels que les hôpitaux et écoles, ainsi que dans des milieux semi-confinés tels que les parkings et gares souterraines.

Mots-clés : Trafic urbain, Particules fines, Captation passive, Piège à enduction d'huile, Régénérable

I. Introduction

Les particules fines (PM), sous forme solide et noyau solide enrobé par une couche liquide, contribuent activement à la pollution de l'air ambiant (air extérieur). Ces PM, classées selon leurs diamètres, se retrouvent généralement dans trois catégories : $PM_{10} < 10 \mu m$, $PM_{2.5} < 2,5 \mu m$ et $PM_1 < 1 \mu m$. Les $PM_{2.5}$ et PM_1 (comprenant également les nanoparticules de plus petites tailles) sont les plus nocives pour la santé. En effet, en raison de leur petite taille, ces particules peuvent pénétrer profondément dans le système respiratoire, puis dans le sang, pouvant alors notamment créer des problèmes inflammatoires (Cheriyen et al., 2021; Peters et al., 2004). Chaque année, la dégradation de la qualité de l'air extérieur par les particules fines est responsable de plus de 48 000 décès en France et autour de 4 millions à l'échelle mondiale (Burnett et al., 2018; Pascal et al., 2016). En termes d'économie, 3,55 milliards USD\$ de frais médicaux et de sécurité sociale, ainsi que 143 milliards USD\$ de valeur de main-d'œuvre liés d'une manière directe ou indirecte à la pollution de l'air (extérieur et intérieur) sont dépensés chaque année (The World Bank, 2016, 2020). D'après l'Organisation mondiale de la santé (OMS) (WHO, 2021), l'amélioration de la qualité de l'air par la réduction des concentrations en particules fines est primordiale pour les villes, représentant également l'une des priorités dans les politiques environnementales de nombreux pays. La compréhension et la réduction des PM font partie des objectifs stratégiques et projets d'études de plus en plus nombreux de par le monde (K. Li et al., 2019; Wang et al., 2022), ceci dans le but d'améliorer la qualité de vie et la santé des habitants, notamment en ville.

Les émissions de particules fines proviennent de différentes sources, avec des concentrations variables en fonction des facteurs d'émission naturels ou anthropiques (Thunis, 2018), et dont le devenir est fortement dépendant de facteurs de diffusion directement liés à la météo (Reiminger & Jurado, 2024). Les sources naturelles de PM sont originaires de l'altération des roches et sédiments qui sont transportés, déposés, ou remis en suspension par le vent, des émissions saisonnières des pollens et des spores ainsi que des émissions liées à des événements naturels comme les feux de forêt ou encore les éruptions volcaniques. (Kuhlbusch et al., 2009). Ces événements peuvent déclencher des épisodes de pollution de l'air lointains par rapport à la source d'émission, entraînant alors des déclenchements de mécanismes d'allergie chronique chez les personnes sensibles (Sénéchal et al., 2015). La prévention de la pollution par les PM naturelles est souvent rendue possible par des systèmes de détection (par exemple LIDAR), et peut être inclus dans les plans de réaction contre des

désastres naturels. Les sources non naturelles sont quant à elles originaires d'activités anthropiques comme notamment la combustion de biomasses et d'énergies fossiles (trafic routier, chauffage urbain et résidentiel ...), l'agriculture (engrais, pesticides), la construction, etc. Ces sources anthropiques sont les plus importantes sources de pollution aérienne par les PM, d'autant plus dans les villes ou à proximité des axes routiers (Zhang et al., 2015).

En plus de la suie retrouvée en sortie d'échappement des véhicules à moteur thermique, une quantité très importante de PM est également émise hors échappement. Ces sources de PM, originaires de la dégradation des freins et pneus des véhicules, mais aussi de la chaussée, représentent également une quantité significative de PM rejetées dans l'atmosphère (Piscitello et al., 2021). Quel que soit le véhicule, thermique ou électrique, les PM issues du trafic routier sont la cause principale des pics de pollutions dans les villes, particulièrement pendant les heures de pointe ainsi que durant des jours de faibles vents (Kobayashi et al., 2013; Martín et al., 2024). En outre, cette pollution dite « primaire » peut également s'associer à d'autres polluants comme les oxydes d'azote (NO_x), les oxydes de soufre (SO_x), ainsi que d'autres polluants atmosphériques gazeux pour former des polluants secondaires de type particules fines (Guo et al., 2014). Actuellement, plusieurs mesures ont été proposées et appliquées dans les grandes villes françaises afin de baisser les impacts de la pollution de l'air liée au trafic routier, telles que l'interdiction des poids lourds dans certaines sections de la ville et/ou durant les heures de forte affluence, la réduction de la vitesse maximale sur les axes routiers importants, l'application du système de certificat de l'air Crit'air, la mise en place de zones à faible émission, etc. (Host et al., 2020; Ku Donggyun et al., 2020). La combinaison de ces méthodes pourrait contribuer à la lutte contre la pollution de l'air par les PM issues du trafic routier (EMS, 2024; Pascal et al., 2016).

En parallèle des efforts pour réduire les PM à la source, il existe également des mesures afin de réduire la concentration de PM dans les villes et/ou de capter des particules avant leur dispersion dans la nature. Comme le trafic routier est une des principales sources d'émission de particules fines dans les villes, de fortes concentrations de PM sont souvent observées à proximité des axes routiers. Certaines études ont montré que la mise en place de végétation à proximité d'axes routiers ou dans les quartiers résidentiels semble être une bonne mesure pour lutter contre la pollution atmosphérique (Tang, 2023). En complément des bénéfices classiques, mais importants des végétaux (approvisionnement en oxygène, retardement des ruissellements, réduction de la chaleur environnante, etc.), ces derniers sont aussi considérés comme des filtres naturels de PM, passifs, et autolavables par la pluie (Kwak et al., 2023). Il

est toutefois important de garder à l'esprit que les PM lavées par la pluie peuvent alors se retrouver dans les eaux fluviales, rejoignant alors le petit et le grand cycle de l'eau, aggravant la présence de micropolluants dans les cours d'eau et, finalement, les océans (Kole et al., 2017; Sommer et al., 2018). En absence de méthodes de captation et traitement adaptées, les PM peuvent donc être remises en suspension après avoir été captées par dépôt sec sur les feuilles. En plus de solutions passives comme l'implantation de végétation et la construction de murs végétalisés, l'intérêt de la mise en place de stations pour filtrer l'air dans les espaces publics a été également étudié et des solutions ont été commercialisées (Bächler et al., 2021; Splittgerber, 2015). Le principe de ces stations est d'aspirer l'air mécaniquement (fonctionnement actif), puis de filtrer les particules fines se trouvant dans le flux d'air grâce à des matériaux présentant une bonne efficacité en filtration. Il s'agit notamment de filtres à matrice de micro ou nano fibres de verre ou polymère créées par électrospinning (Russo et al., 2022), de structures de carbone activé et de nanotubes de carbone (Jung et al., 2018) ou encore de fibres électrostatiques qui fixent des particules par stimulation électrique (Gao et al., 2022). Ces solutions montrent des potentiels importants pour la purification de l'air extérieur et peuvent permettre de réduire les concentrations locales en particules fines dans certaines zones, tout en restant dépendant de l'échelle de fonctionnement des stations de filtration. En effet, une des contraintes de ces stations de filtration dites « active » est leur besoin d'une source d'électricité à proximité pour fonctionner. Cette limite peut donc poser des problèmes pour leur installation (par exemple dans des lieux avec restrictions liées au risque incendie ou encore dans des espaces réduits), tout en engendrant des surcoûts de fonctionnement et de maintenance. La pollution sonore associée à ce type de filtre peut également poser des problèmes pour les riverains.

Le présent projet vise à tester une nouvelle méthode de filtration des particules fines en milieu urbain extérieur à l'aide de dispositifs de filtration passifs qui ont été installés à proximité d'axes routiers à fort trafic au niveau la ville de Strasbourg, en France. Le système de filtration est constitué d'une matrice de support en fibre polymère de grande porosité et de faible perte de charge recouverte par une fine couche d'huile végétale. Cette couche joue un rôle indispensable en atténuant l'impact des particules tout en les retenant sur les fibres, comme démontré dans diverses études (Agranovski, 2010; Müller et al., 2014; Pyankov et al., 2008). Deux différents profils de PM ont pu être établis et comparés en analysant la quantité de PM captées, leurs profils granulométriques ainsi que leur composition chimique, tout en utilisant un minimum de matériaux et sans aucun apport d'énergie externe pour leur

fonctionnement. Les différences entre les deux profils de PM sont expliquées par les données météorologiques locales, par les concentrations en PM mesurées dans l'air à proximité des sites d'études ainsi que par le trafic observé au niveau des axes routiers proches.

II. Matériels et méthodes

II.1. Matériaux

Le caisson contenant les dispositifs de piégeage est sous forme d'un bloc rectangulaire équipé de ventelles inclinées afin d'éviter l'entrée d'eau de pluie ainsi que d'éventuels petits animaux. Le caisson est orienté perpendiculairement au sens de circulation des véhicules (Fig. 1A). Le prototype de l'Avenue du Rhin (prototype AdR) a été installé sur le terre-plein central d'une section de route affectée par deux sens de circulation avec des feux rouges à proximité, et dont la vitesse est limitée à 50 km.h⁻¹ (Flèche bleu en bas de la Fig. 1A). Le prototype de la voie rapide RM35 (prototype RM35) se situe à quelques mètres de la bande d'arrêt d'urgence, avec une vitesse de circulation limitée à 70 km.h⁻¹ (Flèche bleu en haut à gauche du Fig. 1A).

Chaque dispositif contient vingt filtres, de dimension 220 mm x 220 mm, fixés dans leurs cadres métalliques, ainsi que divers capteurs pour l'enregistrement de différents paramètres météorologiques (vitesse du vent, pression, humidité, etc.). Une photo représentant l'intérieur du dispositif de filtration est présentée sur la Fig. 1B. Le média filtrant est composé de matrices fibreuses en polyester structurées pour offrir une large surface d'exposition, maximisant ainsi le contact entre l'air pollué et les fibres (Fig. 1C), tout en facilitant le passage d'air avec une faible perte de charge.

La capacité de rétention des PM peut être considérablement améliorée par le dépôt d'une couche d'huile végétale sur la totalité de la surface du substrat d'accueil (Fig. 1D). Cette couche d'huile sélectionnée pour sa stabilité en viscosité permet de capturer et retenir des particules sur le support (adsorption) pendant une période relativement longue, allant jusqu'à quelques semaines. Le piégeage des PM est réalisé par simple contact entre les particules en suspension dans l'air avec la surface des fibres, ce processus dépendant principalement du débit d'air extérieur traversant le média filtrant, sans avoir besoin de ventilation active pour aspirer l'air. Les particules piégées peuvent ainsi varier de quelques nanomètres à plusieurs centaines de micromètres, voire millimètres.

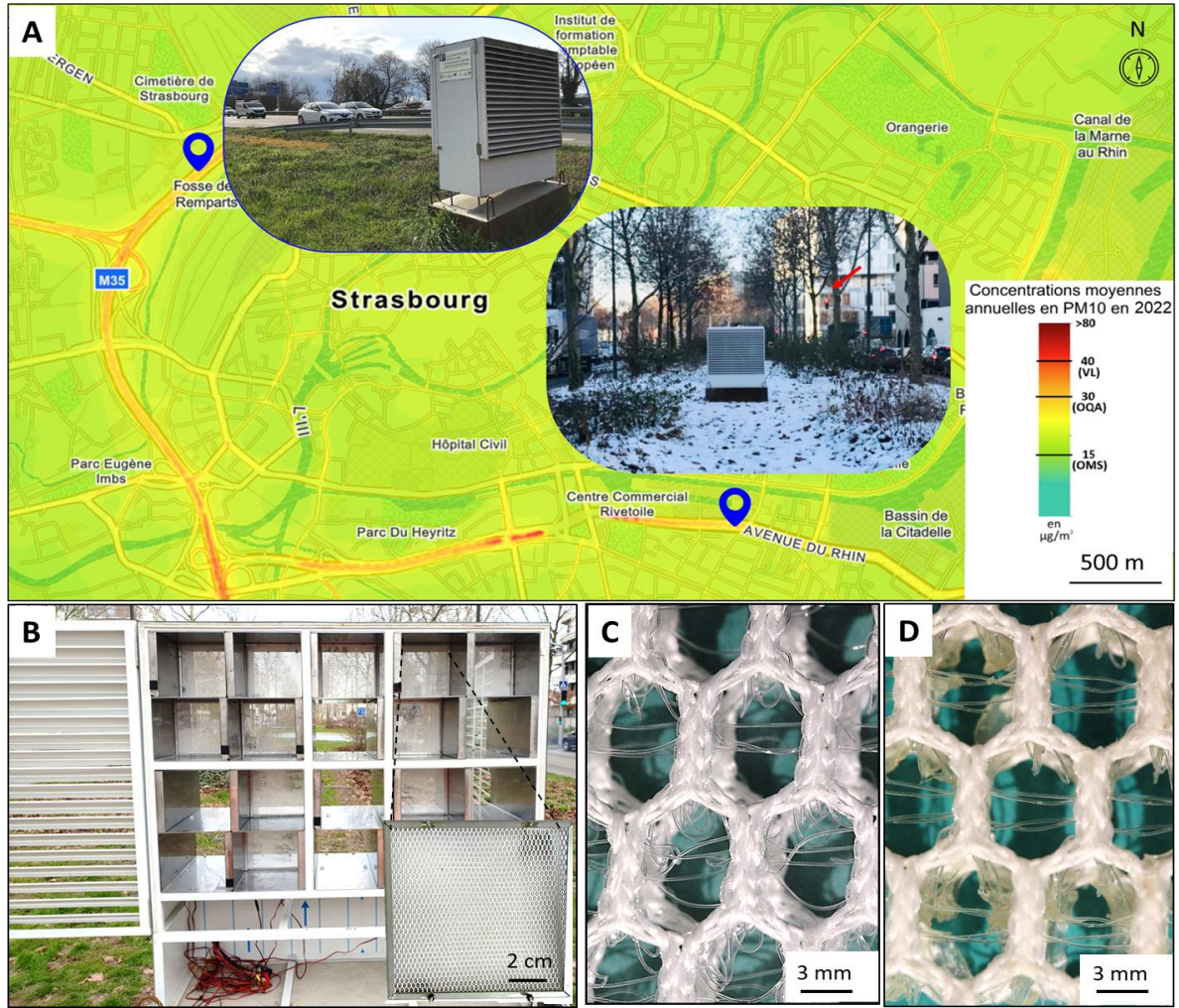


Figure 1 : (A) Cartographie de la ville de Strasbourg pour la concentration moyenne annuelle de PM₁₀ en 2022 (Source: ATMO Grand Est). Inlet photos: prototype d'AdR (droite) et prototype de la RM35 (gauche). Légende: OMS: Recommandé par L'OMS; OQA: Objectif qualité de l'air UE; VL: Valeur limite. (B) Photo digitale du prototype avec 20 casiers de 220 mm x 220 mm. Insert : image d'un échantillon de filtre dans son cadre métallique avant d'être installé. (C) Agrandissement des mailles du matériel de support sans huile. (D) Échantillon infiltré par une couche d'huile végétale.

II.2. Techniques de caractérisation

Les échantillons sont exposés pour des périodes allant de 2 à 18 semaines et sont prélevés toutes les deux semaines pour être caractérisés. Les échantillons équivalents dans chaque prototype (même dates et durée d'exposition et occupant la même position dans le dispositif) sont analysés et les résultats sont comparés afin de déterminer les influences des conditions d'exposition et de la pollution spécifique à chaque site d'exposition. Après leur prélèvement, les échantillons ont été caractérisés au laboratoire par différentes techniques afin d'analyser

les propriétés du média, la quantité, la nature et la distribution granulométrique des particules piégées. Plus de détails techniques sont aussi présentés dans (Trinh et al., 2024).

II.2.1. Mesure de la perte de charge

Les mesures ont été réalisées à l'aide d'un tube vertical, de 80 cm de hauteur et 4 cm de diamètre interne. L'échantillon d'épaisseur 6 mm était placé au centre du dispositif et maintenu en position par les anneaux pour garantir sa stabilité à haute pression. La vitesse de l'air a été mesurée par un anémomètre Testo 435-1. La perte de charge entre l'amont et l'aval du matériel a été mesurée par un capteur de pression différentielle (Digital Manometer Ehdis CR410), en faisant varier la vitesse entrante de l'air entre 0 et 10 m. s⁻¹ en variant le débit d'entrée d'air.

II.2.2. Protocole de caractérisation de la viscosité

La viscosité de l'huile a été analysée par un rhéomètre TA Instrument DHR3 équipé d'un disque Pelletier. Pour chaque échantillon, 0,6 ml de liquide a été prélevé pour réaliser deux tests : l'un mesurant la viscosité en fonction de la température et l'autre en fonction du taux de cisaillement. Pour le premier test, les viscosités des huiles ont été mesurées à une vitesse fixe de 10 rpm (tours par minute) pendant 20 minutes, avec une plage de température variant de -15 °C à 80 °C. Cependant, dans le deuxième test, la température a été maintenue constante à 40 °C, le taux de cisaillement augmentait progressivement (vitesse variant de 3 à 50 rpm pendant 5 minutes). Avant chaque test, l'échantillon a été conditionné pendant 2 minutes afin d'assurer une bonne homogénéité en température et en densité, évitant ainsi la formation de bulles d'air susceptibles de fausser les mesures. Entre deux analyses consécutives, le disque Pelletier a été nettoyé avec de l'éthanol et de l'acétone.

II.2.3. Microscopie électronique à balayage (MEB) et microscopie électronique en transmission (MET)

L'observation d'un prélèvement de dimensions 10 mm × 10 mm × 6 mm d'un échantillon a été fait avec un microscope ZEISS 2600F doté d'une résolution de 5 nm. Avant l'analyse, l'échantillon a été séché au four à 60 °C pendant une nuit afin de réduire l'épaisseur de la couche d'huile, qui pourrait gêner l'observation détaillée des particules piégées. L'échantillon a ensuite été fixé sur un ruban adhésif en graphite double face pour éviter les effets de charge électrostatique pendant l'analyse. Une analyse statistique à différentes échelles de grossissement a été effectuée sur au moins quatre zones par échantillon afin de fournir une

répartition globale des particules piégées. Les résultats statistiques du MEB ont également été utilisés pour mesurer la distribution du diamètre des particules, et ces résultats ont été comparés avec ceux obtenus par le granulomètre laser.

Les analyses MET ont été réalisées avec un microscope JEOL ARM-200F fonctionnant à une tension accélératrice de 200 kV, équipé d'un correcteur de sonde pour les aberrations sphériques, et offrant une résolution point-à-point de 0,2 nm. L'échantillon a été dispersé par ultrasons dans une solution d'éthanol pendant 5 min, puis une goutte de cette solution a été déposée sur une grille en cuivre recouverte d'une membrane de carbone perforée pour l'observation. Les analyses MEB et MET sont également couplées avec une spectroscopie de rayons X à dispersion d'énergie (EDX) pour caractériser des éléments chimiques et cartographier des zones de l'échantillon.

II.2.4. Analyse granulométrique par granulomètre à diffraction laser

Une suspension de 5 mL d'échantillon a été prélevée dans le mélange homogénéisé de la solution de lavage pour une analyse granulométrique. Les analyses ont été effectuées avec un granulomètre MALVERN Mastersizer 3000 utilisant de l'eau comme solvant, sans ajout d'additifs. La suspension a été passée aux ultrasons pendant 2 minutes avant l'analyse. L'analyse a été réalisée avec une vitesse d'agitation et de pompage réglée à 50 %, permettant de mesurer les particules dans une plage dimensionnelle de 0,01 à 2000 μm .

II.2.5. Lavage et réutilisation des médias

Le média usagé a été traité avec une solution contenant 10 mL de détergent (Alcool C9-C11 éthoxylé, KOH) mélangée avec 1 L de l'eau distillée, agitée à 80 °C, suivie d'une ultrasonication pendant 15 minutes. Le cycle de lavage peut être répété jusqu'à ce que plus aucune particule ne soit visible sur le filtre. Après l'étape de lavage, le filtre est séché à l'étuve à 60 °C pendant une nuit avant d'être réutilisé. Une nouvelle couche d'huile est ensuite infiltrée sur le support lavé et séché avant d'être installée à nouveau au prototype. Cette étude a pour but de vérifier la réutilisation des systèmes filtrants afin de réduire les impacts environnementaux du procédé.

III. Résultats et discussion

III.1. Évolution du piégeage des particules

Les résultats concernant la sélection du matériel de référence, sa régénération (par lavage) et sa réutilisation, ainsi que le choix d'huile de revêtement ont été publiés dans TRINH et al. [2024]. En général, les résultats obtenus sur les deux prototypes présentent la même tendance, mais avec des valeurs différentes (Fig. 2A). La quantité de PM totales piégées par les prototypes augmente régulièrement jusqu'à 12-14 semaines d'exposition, atteignant ensuite une phase de stabilisation, voire de saturation et relargage une fois que le temps d'exposition a dépassé ce seuil. La quantité de PM captée dépend d'une manière significative du trafic routier du milieu exposé. En effet, $84 \pm 6 \text{ g.m}^{-2}$ de PM ont été captés après 14 semaines d'exposition sur le prototype RM35, contre $50 \pm 8 \text{ g.m}^{-2}$ pour celui d'ADR. La formation dans le temps et la diffusion des PM semblent se différencier d'une manière relativement importante entre les deux lieux d'exposition. Même si la variation spatiale n'était pas significative, ces différences sont dépendantes de l'aménagement de la route, du mode de circulation des véhicules, et aussi de la vitesse (W. Li et al., 2023). Dans notre cas, le prototype RM35 se distingue du prototype ADR, non seulement par la limitation de la vitesse du trafic routier, mais aussi de l'affluence du trafic et des types de véhicules qui y circulent. Sur la voie rapide RM35, le trafic est fluide, les véhicules circulent à grande vitesse dans un seul sens, freinant peu, ce qui explique une concentration élevée en PM pendant les heures de pointe où le nombre de véhicules devient important. La plupart des échantillons prélevés sur la RM35 sont deux fois plus chargés que ceux de l'ADR, où le prototype est situé dans une rue canyon avec deux voies de circulation, des feux tricolores, et des bâtiments environnants. En 2022, le SIRAC (Service d'Information et De Régulation Automatique de la Circulation) a décompté en moyenne annuelle, environ 75000 véhicules circulant par jour sur la RM35 (uniquement dans le sens Colmar-Strasbourg qui passe à côté du prototype) et 38000 véhicules par jour à l'ADR (deux sens confondus, le piège étant placé entre les deux axes de circulation). Les données du capteur TEOM d'ATMO Grand Est situé à proximité du prototype RM35 ont montré de fortes concentrations en PM durant et après les heures de pointe. Différentes études, utilisant des capteurs au niveau du sol comme TEOM, ou de télédétection par image satellite, ont certifié le trafic comme une des sources importantes de PM, spécialement dans les grandes villes avec fortes affluences aux heures de pointe (Finkelstein et al., 2004; Zhang et al., 2015).

Plus le trafic est dense, plus l'émission de PM est importante, dû à l'érosion des pneus sur la chaussée, l'émission des particules issues de la combustion dans le moteur, et, pour une faible proportion, aux freinages, d'où l'écart de masse totale de PM captée entre les deux prototypes (si on néglige les influences des différences de composition des PM, de sens de circulation, de la présence des végétaux, etc.). Par ailleurs, les fortes concentrations de PM₁₀ ont été observées tôt le matin, spécialement pendant des jours de température inférieure à 10°C en février, mars, et décembre 2022 (Fig. 2C). Cette observation pourrait être expliquée par l'émission de PM issue de la combustion de biomasse (chauffage urbain) ainsi que par le chauffage résidentiel qui font augmenter la pollution de fond en PM sur toute la ville (Hama et al., 2021; McDuffie et al., 2021). De plus, en l'absence de facteurs de dispersion tels que le vent ou la pluie, la formation de PM secondaires, ainsi que l'apparition de gouttelettes avec ou sans noyaux solides, dans des conditions météorologiques particulières comme une forte humidité relative et/ou une inversion de température (Guo et al., 2014; Tie et al., 2017)) pourrait entraîner des pics de pollution et fausser les mesures in situ.

La Figure 2C présente quelques paramètres météorologiques importants à Strasbourg pendant la période de test. Pour la concentration de PM₁₀, le capteur TEOM d'ATMO Grand Est à l'Avenue du Rhin se situe à proximité du prototype ADR, mais est séparé par un bâtiment (école Solange Fernex) : le capteur est situé dans la cour de l'école, derrière le bâtiment principal et à plusieurs mètres de hauteur. Ses données révèlent des concentrations en PM₁₀ très élevées pendant l'hiver, spécialement au début de la campagne en mars 2022. Dans cet article, seule la courbe d'évolution des concentrations journalières en PM₁₀ du prototype RM35 est présentée, car le capteur ATMO Grand Est présent à proximité de la voie rapide se trouve dans des conditions d'exposition au trafic et aux aléas météorologiques relativement similaires au prototype ADR. Bien que l'évolution de la quantité de PM captée en fonction du temps soit assez stable, la captation à court terme est fortement perturbée par les conditions météorologiques (Fig. 2A-C). En sachant que les flux de trafic à proximité des deux prototypes sont assez stables pendant l'année (réduction à environ 75 % du flux normal pendant les week-ends et 50 % pendant les vacances d'été), les autres paramètres météorologiques (température, l'humidité, vitesse du vent, pression atmosphérique, etc.) pourraient apporter des perturbations sur la captation de PM, au profit d'une augmentation, mais aussi d'une diminution des quantités captées.

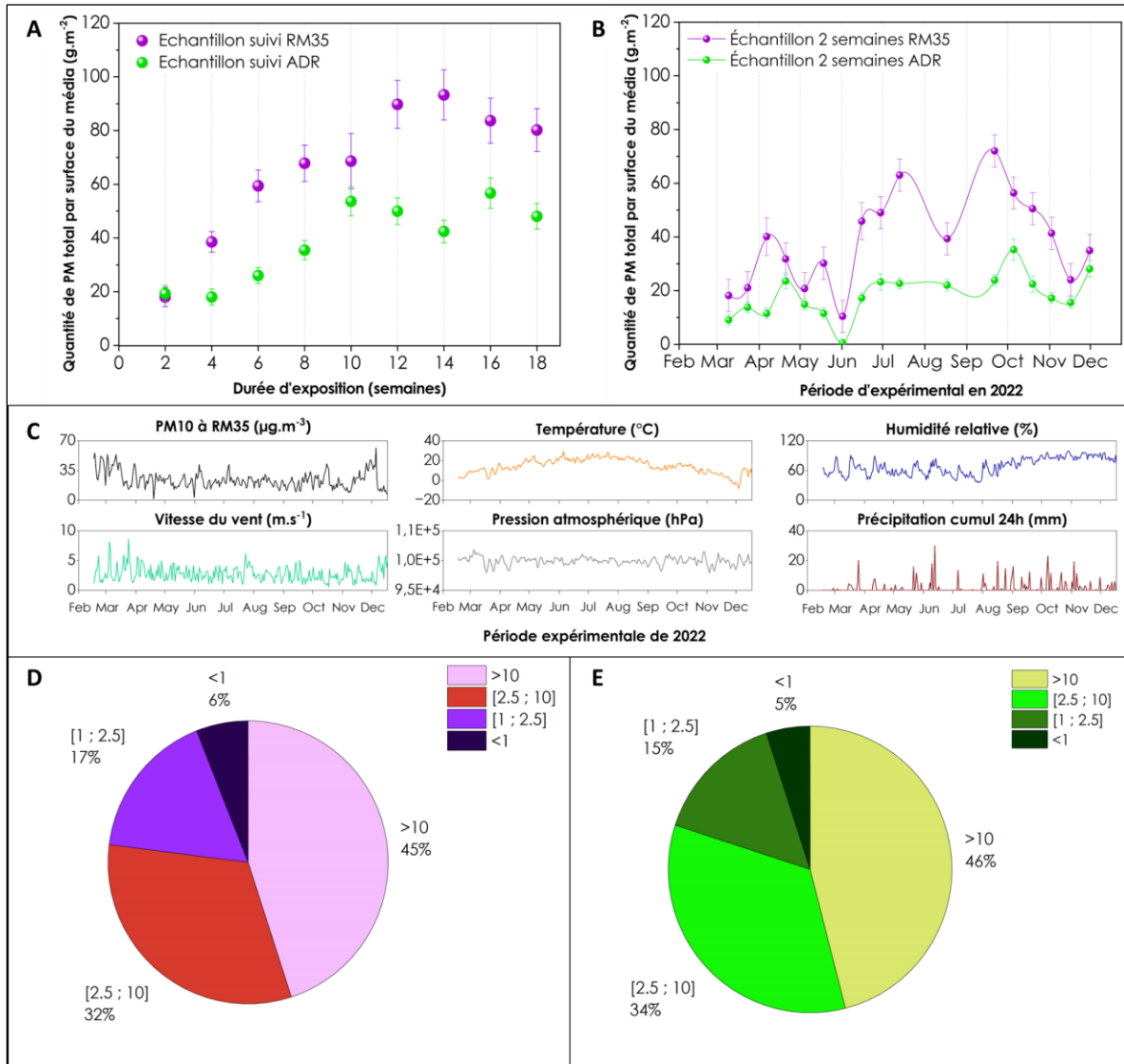


Figure 2 : (A) Evolution de quantité de PM total captée sur les deux prototypes en fonction de leur durée d'exposition. (B) Evolution de quantité de PM total captée après 2 semaine d'exposition en fonction de la période de l'année. (C) Moyenne journalière des données météorologiques à Strasbourg pendant la période d'expérience de Mars à Décembre 2022. (D) Résultats des analyses granulométriques du volume des particules captées au prototype RM35 (toutes durées confondues). Unité des intervalles de diamètres de particules est en μm . (E) Moyenne des résultats d'analyses granulométriques du volume des particules captées au prototype ADR (toutes échantillons confondues).

La quantité des PM captées est directement liée aux conditions météorologiques et la pluie et le vent sont les premiers facteurs de dispersion de PM (Fameli et al., 2023; Martín et al., 2024). En effet, la faible concentration de PM_{10} mesurée, ainsi que le déficit en quantité de PM total captées durant les périodes Mai-Juin et Octobre-Novembre 2022 sont probablement liés à la présence de hautes fréquences de pluie qui induisent une forte réduction

de concentration de PM_{10} dans l'air (Fig. 2C). L'inégalité en masse totale de PM captées entre les deux prototypes se reproduit avec des échantillons prélevés par l'intervalle fixe de 2 semaines (Fig. 2B). Cette expérience sert non seulement à comparer ces deux prototypes, mais permet également d'évaluer l'impact de la météo à court terme (2 semaines) sur la quantité de PM captées. Exception faite de la principale différence en source d'émission (flux de trafic routier), les positions des prototypes pourraient aussi expliquer la différence de captage de PM. Comme le prototype RM35 se situe dans l'axe SO-NE, qui est aussi l'axe des vents prépondérants à Strasbourg, et qu'il n'y a quasiment pas d'obstacle à proximité (Fig. 1A), ce prototype a des conditions d'essais optimales pour un contact direct entre source de pollution et média filtrant. En outre, le prototype ADR se situe dans l'axe E-O, au milieu du terre-plein central d'une rue canyon entourée par des bâtiments d'environ 10 à 20 m de hauteur, ainsi que de végétation qui représentent des obstacles à la diffusion des polluants atmosphériques. Ces éléments peuvent significativement décélérer la vitesse du vent, bloquer ainsi la ventilation dans la rue et donc, la circulation des pollutions avant d'arriver au contact avec le prototype. Les autres paramètres météorologiques comme la température, l'humidité relative, et la pression, en plus de leur rôle dans la formation des PM secondaires, jouent également un rôle sur les concentrations en PM observées dans l'air ainsi que sur le dépôt solide (Banks et al., 2022). Une hypothèse émergente est la baisse de l'efficacité de captage du piège en fonction de la température. Les tests de viscosité dans notre étude précédente (Trinh et al., 2024), ont montré une augmentation de la viscosité de l'huile à basse température, pouvant ainsi réduire l'adhésion des particules sur la couche d'huile. Ceci pourrait expliquer la baisse de la quantité de PM captées pendant les mois où la température est basse (mars, novembre, décembre) par rapport au reste de l'année.

Les analyses granulométriques des échantillons de suivi météorologique (2 et 4 semaines) des deux prototypes ont montré des résultats très variés pour la distribution granulométrique des PM captées sur les pièges. D'une manière globale, plus de 90 % des PM (en nombre des particules captées) sont constituées par des $PM_{2.5}$ et PM_1 , et ce, quel que soit l'endroit. L'origine de ces particules fines et ultrafines pourrait être liée aux rejets des gaz d'échappement émis par les véhicules à moteur thermique (Piscitello et al., 2021), ou encore au freinage qui est la source principale du $PM_{2.5}$ dans des émissions de PM hors échappement (Timmers & Achten, 2016). En raison de leur petite taille, l'exposition à ces particules pourrait causer des effets néfastes sur la santé des riverains. Concernant la distribution des particules, on constate une similarité entre la moyenne granulométrique des échantillons des

prototypes RM35 et ADR (Fig. 2D et 2E). Plus de la moitié du volume des particules captées sur les deux prototypes correspond à des PM_{10} (y compris $PM_{2.5}$ – environ 15 % et PM_1 – autour 5 % du volume total). Ces résultats granulométriques démontrent l'aptitude du dispositif à capter et retenir sur les fibres des particules de diamètre inférieures à $1\ \mu m$ qui sont les plus néfastes pour la santé publique et qui sont également les plus difficiles à capter.

III.2. Observations microscopiques et analyses chimiques des particules captées

Dans le concept de filtration classique, afin d'améliorer l'efficacité de filtration, les fibres des matériaux filtrants sont généralement arrangées de manière très rapprochées l'une de l'autre, ce qui entraîne une faible porosité dans le filtre, associée à une forte augmentation des pertes de charge ainsi qu'à une réduction de la durée de vie du filtre à cause des problèmes de colmatage (Callé et al., 2002). Ceci peut provoquer une hausse de la consommation énergétique au niveau du pompage afin de maintenir la circulation du flux d'air. Au contraire, le substrat de filtration passif étudié ici est constitué par des fibres de polyesters tissées en forme de nid d'abeille avec une forte porosité macroscopique (Fig. 1D et 1E). Cette structure très poreuse permet d'avoir une très faible perte de charge, même après avoir été enduite par une couche d'huile végétale, et, de ce fait, n'induit pas de problème qui peuvent engendrer la circulation des flux d'air lors de la filtration passive. En effet, le mécanisme de captage repose sur l'effet d'adhésion des particules, présentes dans l'air circulant au travers des fibres, sur la fine couche d'huile enrobant le support (Corn, 1961; Larsen, 1958). Lorsque les particules entrent en contact avec le film d'huile, l'adhésion est réalisée de manière instantanée et les particules restent attachées au filtre. On dit dans ce cas de figure que la force d'inertie des particules est plus élevée que la combinaison des forces de mouvement et gravitationnelles, avec comme conséquence, le piégeage de ces particules sur le support filtrant. En d'autres termes, la couche d'huile agit comme une surface adhésive retenant les particules (Agranovski & Braddock, 1998; Boskovic et al., 2007; Mullins et al., 2007; Pyankov et al., 2008).

Les échantillons ainsi récupérés sont analysés par microscopie électronique à balayage (MEB) et les résultats sont présentés sur la Fig. 3. Les fibres du support, recouvertes de particules de différentes tailles, sont clairement visibles (Fig. 3A-3H). Les images des échantillons après 4 et 8 semaines d'exposition (Fig. 3C, 3D, 3E, 3F) montrent des fibres plus chargées en PM sur le prototype RM35 que les fibres exposées sur le prototype ADR.

L'évolution du dépôt des particules sur la surface du média en fonction du temps se distingue entre les deux prototypes. Dès 2 semaines (Fig. 1A et 1B), des nodules et accumulations de PM sont déjà visibles sur les fibres d'échantillon du prototype RM35, tandis que les particules captées au niveau du prototype ADR sont mieux distribuées avec moins d'agrégats. Ceci est probablement dû à une concentration moindre des particules dans l'air circulant à travers les pièges de l'ADR par rapport à celle se trouvant à proximité de la RM35. Après 8 semaines d'exposition (Fig. 3E et 3F), les particules couvrent la plupart des fibres, et celles retrouvées dans le prototype ADR ont toujours une meilleure distribution que celles du prototype RM35. Grâce à la couche d'huile, les particules sont bien conservées sur la surface de fibre qui continue de capter et d'accumuler de nouvelles particules. Après 14 semaines, le revêtement d'huile sèche ce qui entraîne la saturation du filtre ainsi qu'un équilibre entre dépôt et relargage, entraînant un seuil de captation relativement stable (Fig. 2A). Ces différences en termes de dépôt de PM pourraient aussi être expliquées par la configuration des deux prototypes. Celui de la RM35 (Fig. 3, côté gauche) se trouve quasiment sur un terrain dénudé d'obstacles avec une densité de véhicules plus élevée permettant de recevoir une grande partie des rejets particulaires à partir de la source de pollution. Les particules, pour cette raison, se déposent sur le filtre avec des impacts plus forts compte tenu du fait qu'elles ne sont pas déviées par d'autres obstacles avant d'arriver sur le dispositif de filtration. Une autre possibilité est que les particules à haute concentration (c.-à-d. pendant des heures de pointe) se déplacent dans un courant d'air turbulent et pourraient s'agglomérer avant de se déposer sur le filtre. Concernant le prototype ADR (Fig. 3, côté droit), la limitation de vitesse et la présence de feux tricolores réduisent la fluidité du trafic, tandis que la végétation environnante agit comme un obstacle supplémentaire, modérant la dynamique des flux d'air. Cette configuration du prototype ADR favorise un transport plus lent des particules, conduisant à un dépôt plus homogène et structuré sur les fibres. Les obstacles alentour, jouant également le rôle de déflecteurs, réduisent artificiellement la concentration des particules émises à partir des sources d'émission.

Des particules d'origine végétale ont également été observées sur la surface des médias des deux prototypes, rendant l'analyse microscopique plus difficile. Ces débris de végétaux, légers et facilement transportés par le vent, flottent également dans l'eau et sont en grande partie éliminés lors du lavage, sauf pour les pollens ou particules de petites tailles qui sont confondus avec des PM. La diffusion des pollens dans le vent fait partie d'une source naturelle de PM. L'exposition à ces particules pourrait provoquer des réactions allergiques chez des

personnes sensibles au pollen (Sénéchal et al., 2015). Cela démontre un autre intérêt d'installer de tels types de filtres de particules dans les milieux urbains afin de protéger des publics ciblés, comme des personnes âgées ou immunodéprimées. Il est à noter cependant que l'installation des systèmes de filtration passifs, telles que la plantation des arbres et le déploiement des filtres de particules, sur des échelles plus larges nécessitent des études méticuleuses en amont afin d'optimiser des bienfaits pour la santé publique, tout en minimisant les coûts d'installation et d'entretien. L'une des solutions très efficace pour cela est la modélisation numérique type CFD (Computational Fluid Dynamic) qui permet de simuler différents scénarios en se basant sur des conditions réelles et des lois physiques (Mirzaei, 2021; Reiminger, Jurado, Vazquez, Wemmert, Blond, Dufresne, et al., 2020). Cela aide les chercheurs et les décideurs à établir des hypothèses et prévisions sur l'aménagement urbain, à partir d'un nombre limité de résultats expérimentaux.

L'observation des échantillons à l'échelle microscopique nous donne aussi l'information sur l'évolution de la couche d'huile jouant le rôle de couche d'accroche. Pour une exposition jusqu'à 8 semaines (Fig. 3A-3F), la couche d'huile est encore relativement fraîche et remplit bien son rôle de couche d'accroche, comme indique le dépôt des particules plus ou moins homogène sur la surface des fibres. A partir de 10 semaines, et plus visible sur des photos prises sur les échantillons exposés pendant 14 semaines (Fig. 3G et 3H), la couche d'huile sèche et perd sa capacité à capter de nouvelles particules par la filtration en profondeur comme les semaines précédentes. Sur ces images on ne voit plus des particules affleurant la surface de la couche d'accroche mais une structure plus ou moins compacte résultant de la solidification de l'huile en surface. A 14 semaines (Fig. 3G), le séchage d'huile se combine avec l'agglomération des particules solides et liquides, formant des plaques qui réduisent l'espace entre des fibres. Cela évoque le mode de filtration sur gâteau où une couche dense de particules se forment à la surface plutôt que de se répartir dans l'épaisseur du filtre (Frising et al., 2005; Tian et al., 2023). Suite à la formation de la couche de gâteau, la perte de charge est considérablement augmentée, bloquant la circulation du flux d'air. A ce stade, le filtre n'est plus opérationnel et devrait être désinstallé, nettoyé et remplacé par un filtre régénéré avec une couche de revêtement fraîche.

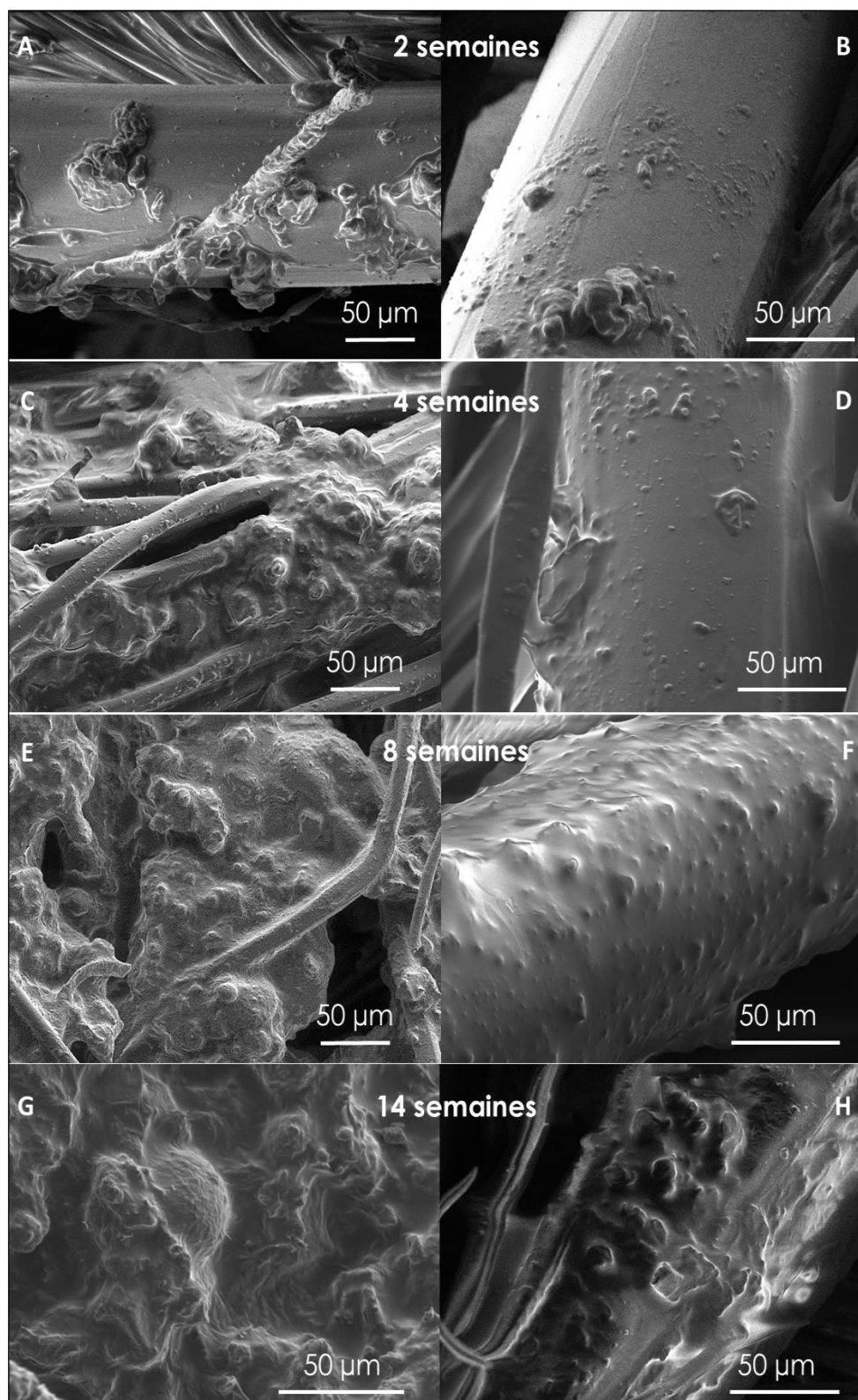


Figure 3 : Images par microscopies de la surface des fibres du média filtrant après exposition dans les prototypes. A gauche (**A-C-E-G**) pour les échantillons du prototype RM35, à droite (**B-D-F-H**) pour ceux du prototype ADR, après 2, 4, 8 et 14 semaines d'exposition, respectivement.

Quant au prototype ADR, la densité du dépôt des particules n'est pas suffisante pour couvrir toute la surface des fibres. Même à 14 semaines (Fig. 3H), plusieurs nodules et agglomération de PMs ont été formés, mais certaines zones sur la fibre restent sans particules. Même si ces zones vides sont toujours revêtues par l'huile qui est séchée, les fibres n'arrivent plus à capter et retenir des nouvelles particules. Dans ce cas, il est recommandé de remplacer le filtre même s'il n'est pas encore atteint l'encrassement total, car les fibres ne captent plus de nouvelles particules, et les PMs captées risquent d'être relarguées dans l'air après le séchage de la couche d'huile.

La cartographie MEB-EDX et l'analyse TEM des échantillons de la RM35 (Fig. 4A) montrent une concentration en carbone nettement plus élevée que pour les échantillons de l'AdR, avec des traces plus faibles de métaux (Fe, Ni, Co). Des particules carbonées de toutes tailles (de $< 1 \mu\text{m}$ à $> 10 \mu\text{m}$) ont également été observées par le TEM (Fig. 4B). En outre, les analyses MEB-EDX sur les échantillons d'ADR (Fig. 4C) révèlent une prédominance des éléments à base de C et O, accompagnés de traces de N, Si, S et de métaux tels que Fe, Al, Ni. Bien que leur proportion soit faible, les particules métalliques fines ($\text{PM}_{2.5}$) et ultrafines (PM_1) ont été détectées dans les particules récoltées dans les eaux de lavages des médias (Fig. 4D) par le microscope TEM.

En effet, le carbone est un élément très abondant sur Terre qui se présente dans toutes les matières organiques et aussi dans certaines structures inorganiques (Fischer et al., 2020), incluant des PMs. Dans notre étude, les deux prototypes se situent à l'extérieur à proximité d'axes routiers. Donc l'origine des PMs pourrait être de multiples sources naturelles (dépôt éolienne de sable, poussière, pollen, etc.) ou anthropiques (trafic, construction, combustion de biomasse ou déchets, etc.). Mais vu la position des deux prototypes, et en projetant avec des études similaires (Amato et al., 2011; Cunha-Lopes et al., 2023; Weerakkody et al., 2018), le carbone dans les particules captées dans nos échantillons sont majoritairement issues des émissions issues du trafic. Les PM issues du trafic routier se divisent en deux catégories : particules d'échappement et particules hors échappement. Les particules d'échappement, résultant de la combustion incomplète des carburants, sont mises en suspension dans l'air et contiennent des hydrocarbures aromatiques polycycliques (HAPs) cancérogènes et mutagènes (Degrendele et al., 2021). Ces particules sont en partie filtrées par les systèmes embarqués des véhicules, dont l'efficacité dépend du type, de l'année et de l'entretien. Les tests en laboratoire n'ont pas détecté de quantités significatives de HAPs dans les échantillons. Les particules hors échappement CAPTATUS (Salah Khaldi et al., 2018) proviennent de l'usure des freins, des

pneus ou de la chaussée. Ce phénomène concerne également les véhicules électriques, alourdis par leurs batteries. Avec les récentes mesures prises par les autorités locales, la qualité de l'air de la ville s'est progressivement améliorée après l'interdiction de la circulation des poids lourds sur certains secteurs et l'application du système de vignette Crit-air (EMS, 2024). Ces efforts en additionnant la conversion de nouveaux véhicules à moteurs thermiques à d'autres alternatives (hybrides, électriques) pourraient aider à réduire des particules issues des pots échappements, mais pas des PMs hors-échappements tels que les usures des freins, pneus, chaussées, etc.

Sur la voie rapide RM35, où la limitation de vitesse est de 70 km.h^{-1} et où la circulation est souvent fluide, les particules fines (PM) proviennent principalement de l'usure des pneus en contact avec la surface de la route. La présence de soufre (S) provient du soufre utilisé lors de l'étape de vulcanisation du caoutchouc (Wik & Dave, 2006). Le transport de ces particules issues de l'abrasion des pneus (non digestibles par les organismes marins) via les eaux usées dans les systèmes fluviaux constitue une source majeure de microparticules, aggravant ainsi la pollution microplastique des océans (Sommer et al., 2018). Cependant, l'analyse élémentaire des PM piégées sur la RM35 révèle également la présence de nombreux éléments métalliques tels que le Ti, l'Al, le Fe, pouvant être attribués à la dégradation des freins. En effet, le freinage existe même s'il n'est pas fréquent sur ce tronçon routier. Cependant, le freinage à 70 km.h^{-1} entraîne une usure plus importante des plaquettes de frein et génère ainsi davantage de particules issues des éléments constituant lesdites plaquettes. Le prototype ADR est situé sur une route urbaine avec feux de signalisation (freinages plus fréquents) et une limitation de vitesse de 50 km.h^{-1} , d'où la présence de PM métalliques attribuées à l'usure des freins et de l'embrayage est observée sur le filtre (Fig. 4C et 4D). L'action de freinage est assurée par le frottement du disque de frein avec les roues du véhicule, qui possède une inertie importante en raison de sa masse.

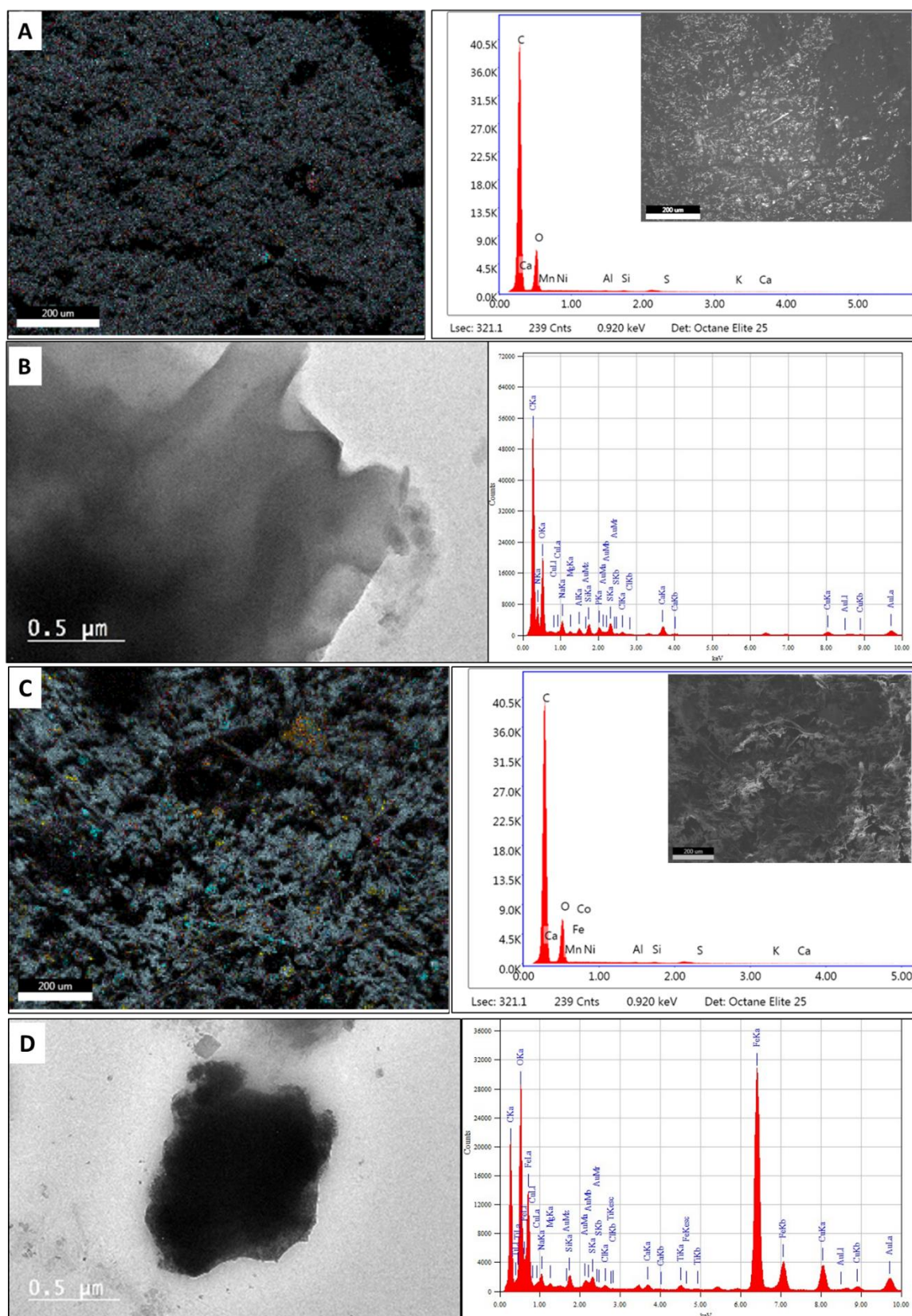


Figure 4 : Cartographie de SEM-EDX et micrographie de TEM des particules captées sur le prototype RM35 (A et B) et au prototype ADR (C et D). Les observations sont celles des échantillons après 4 semaines d'exposition (du 02/03/2022 à 30/03/2022).

Cependant, les éléments pouvant être attribués au système de freinage restent faibles parmi les particules piégées, comparés à ceux observés sur la RM35 (Fig. 4A et 4B). Une telle différence pourrait être attribuée à la différence de limitation de vitesse, soit 50 km.h^{-1} contre 70 km.h^{-1} . En effet, en fonction de la vitesse du véhicule, la force de freinage doit être élevée, car elle est proportionnelle à la vitesse, ce qui explique la présence d'une quantité relativement importante de particules émises par le disque de frein en zone périurbaine par rapport aux zones urbaines (Beji et al., 2020). En dehors des particules métalliques, un niveau élevé de C représente l'usure des pneus et de la chaussée, comme observé sur le prototype RM35. Il convient de noter que l'élément S est quasiment absent sur la portion ADR. De tels résultats pourraient être attribués à la faible vitesse des véhicules, ce qui réduit la dispersion des particules issues de l'abrasion des pneus dans le milieu environnant, contrairement à ce qui est observé sur la RM35 où la vitesse élevée contribue à une dispersion significative des particules. Quant à l'élément azote (N), il constitue également un indicateur de pollution atmosphérique présent dans les émissions de NO_x liées au trafic. Les NO_x peuvent être adsorbés sur des particules primaires, principalement carbonées, et se retrouvent piégés sur les filtres sous forme de particules secondaires. En l'absence de solutions adéquates et de facteurs de dispersion tels que la pluie ou le vent, ces polluants solides et gazeux peuvent stagner au niveau du sol, engendrant des risques sanitaires problématiques pour les riverains.

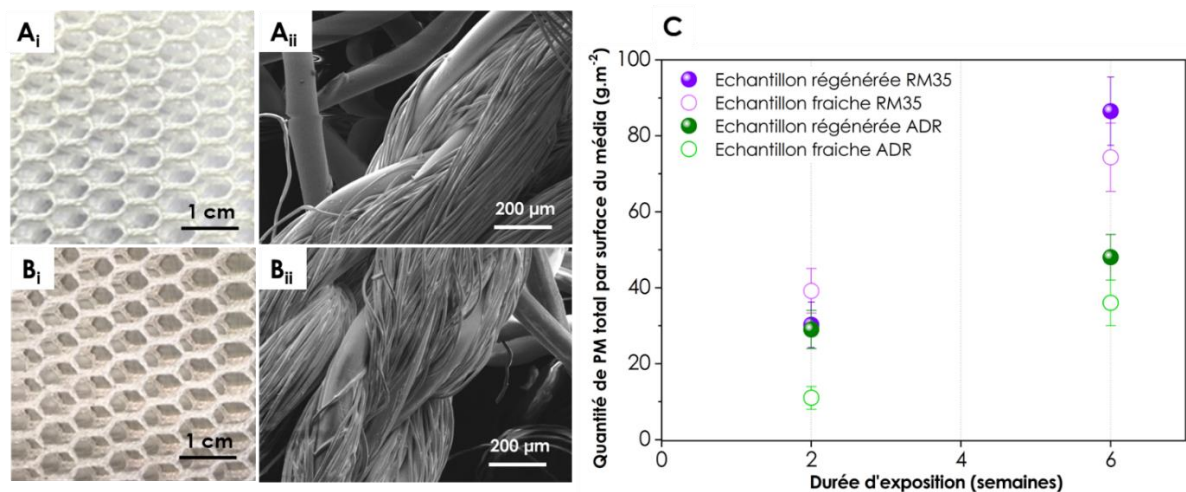


Figure 5 : (A_i et A_{ii}) Photo digitale (gauche) et image microscopique (droite) du structure support avant d'infiltration d'huile. (B_i et B_{ii}) Photo digitale (gauche) et image microscopique (droite) du structure support d'un échantillon exposé 4 semaines à l'ADR après l'étape de lavage. (C) Evolution de la quantité de PM captée sur l'échantillon fraîche et régénérée au prototype RM35 (violet) et ADR (vert).

La lavabilité et le recyclage des filtres à particules sont des critères très importants dans la procédure de réduction des impacts environnementaux. La procédure de lavage pouvait enlever 85 % de quantité d'huile référence pour un échantillon frais, ainsi que la plupart des particules accrochées sur les structures de support (c.f Fig. 5A et 5B). L'eau de lavage qui contient de l'huile, du surfactant et des particules fines serait collecté et traité par les procédures industrielles afin de réduire des impacts environnementaux (Melián et al., 2023; Mohammadi et al., 2022). Dans le cadre du planning d'augmentation en échelle, une station de lavage pourrait être envisagée afin de traiter des filtres de dimensions et/ou en quantité plus importante. Après cette étape, la structure du filtre est séchée et re-enduite d'huile. La performance des échantillons régénérées est équivalente ou même un peu meilleur que des échantillons fraîches (Fig. 5C). La raison pourrait provenir de la quantité d'huile résiduelle après l'étape de lavage qui fait augmenter la quantité d'huile sur la structure support.

IV. Conclusion

Cette étude a testé sur deux prototypes expérimentaux une nouvelle méthode pour filtrer passivement les particules fines dans l'air extérieur grâce à un matériel lavable, enduit d'une couche d'huile végétale.

D'une part, le substrat et l'huile de revêtement, présélectionnés par des tests au laboratoire, montrent une bonne capacité de captage des particules fines dans l'air extérieur. La quantité de PM captées augmente régulièrement lors des premières semaines d'exposition puis se stabilise autour de 12 semaines en raison du vieillissement de la couche d'huile. La variation des paramètres météorologiques a une forte influence sur la concentration de PM dans l'air, et aussi sur le captage des particules. Bien que les précipitations et les vents forts favorisent la dispersion des particules atmosphériques (Fameli et al., 2023), des températures élevées ainsi qu'une forte humidité relative peuvent, quant à elles, favoriser la formation de particules secondaires et améliorer les performances de captation et de rétention des dispositifs de filtration (Banks et al., 2022b; Corn, 1961). La couche d'huile joue un rôle clé dans le piégeage des particules, alors que le substrat fibreux retient des particules dans sa matrice poreuse en assurant un bon passage de l'air. Après la saturation du média et/ou séchage de la couche d'huile, le média filtrant peut être déposé, lavé, et réutilisé comme nouveau substrat après avoir été enduit par une nouvelle couche d'huile.

D'autre part, deux prototypes de filtrations d'air extérieur situées au niveau de deux axes routiers très fréquentés de Strasbourg nous ont permis d'établir deux profils de pollutions de particules fines. Le prototype RM35 qui se situe à côté d'une voie rapide limitée à 70 km.h⁻¹ sans beaucoup de freinages, émet principalement des particules contenant carbone, oxygène et soufre, provenant de l'usure des pneus et du bitume. Les particules métalliques se présentent parfois avec la taille plus grandes que celles à l'ADR, preuve du freinage à grande vitesse. En outre, le prototype ADR se trouve dans la circulation périphérique du centre-ville où la vitesse se limite à 50 km.h⁻¹ avec beaucoup de feux tricolores qui engendrent une haute fréquence de freinage et redémarrage des véhicules. D'où l'existence des particules métalliques Fe, Ni, Co en plus du carbone et de l'oxygène, expliqué par l'usure des plaquettes de frein et de l'embrayage. L'accumulation de PM total avant saturation de piège ainsi que le suivie de captation sur la RM35 sont supérieurs à ceux observés sur l'ADR, l'écart allant jusqu'à un facteur 2 sur certaines périodes. Ces différences pourraient être expliquées par le moindre trafic journalier et la présence de végétaux autour du prototype ADR. En addition aux écarts entre sources d'émission et terrain, les variations spatio-temporaires et météorologiques à petites échelles pourraient aussi engendrer des décalages en comparant les résultats des deux prototypes.

Avec ces résultats expérimentaux ainsi que les données collectées provenant de sources multiples, des études de simulations CFD pourraient être réalisées afin de construire de nouveaux modèles capable d'estimer l'impact positif de ce type de solution de filtration à plus grande échelle. Ces travaux permettent d'extrapoler des résultats acquis, optimiser des conditions de captage des PMs tout au long du cycle d'utilisation du média. En évaluant ces modèles CFD, les investigateurs et aménagements urbains pourraient avoir des perspectives au déploiement de prototypes similaires, d'inclusion des filtres dans les murs anti-bruits, d'installation des filtres dans les autres espaces ouverts ou semi-ouverts comme des gares souterraines ou des parkings. Par ailleurs, des études approfondies et quantitatives en caractérisant des facteurs d'émissions et/ou diffusions des particules pourraient émettre de nouvelles perspectives. Cela permettrait d'appliquer une modélisation encore plus précise pour affiner les performances du système. Enfin, différentes alternatives de support de filtration et liquide de revêtement pourraient être testées et appliquées dans différentes conditions afin de s'adapter aux conditions météorologiques et d'optimiser la performance de piégeage, tout en respectant des normes de sécurité du lieu ainsi que l'environnement.

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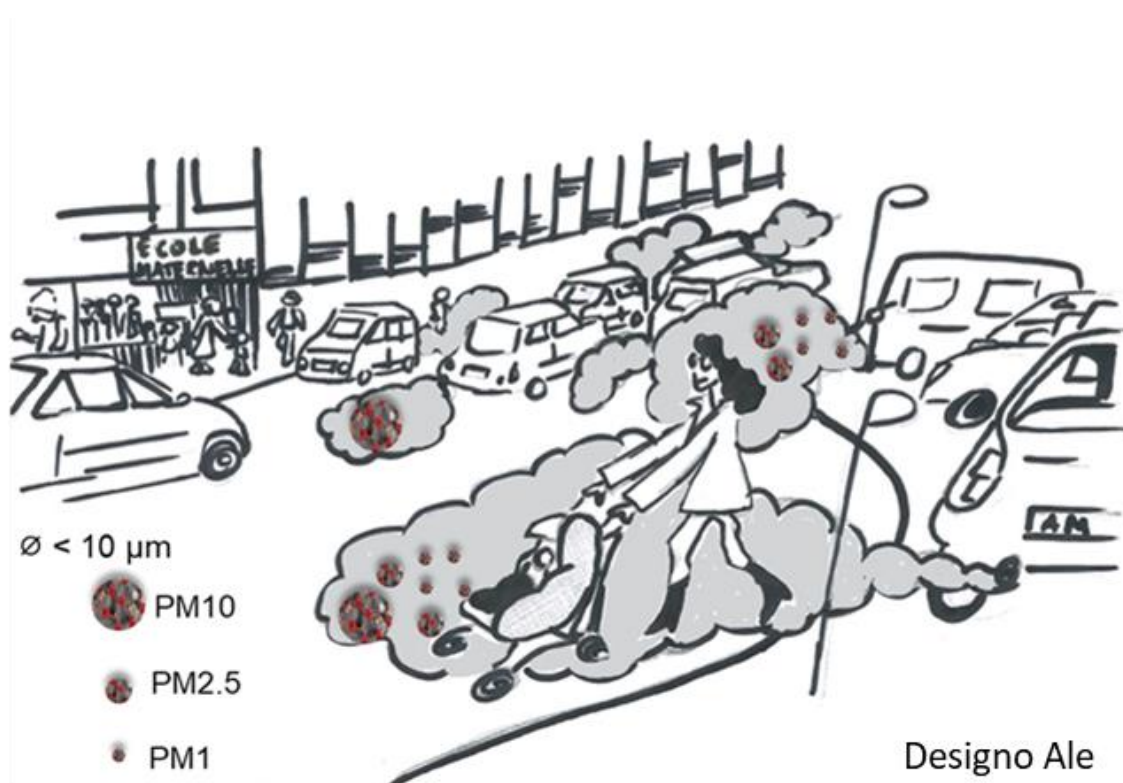
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CHAPTER 1

STATE OF THE ART



Filtration systems for particulate matter reduction in outdoor air: a review

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Abstract

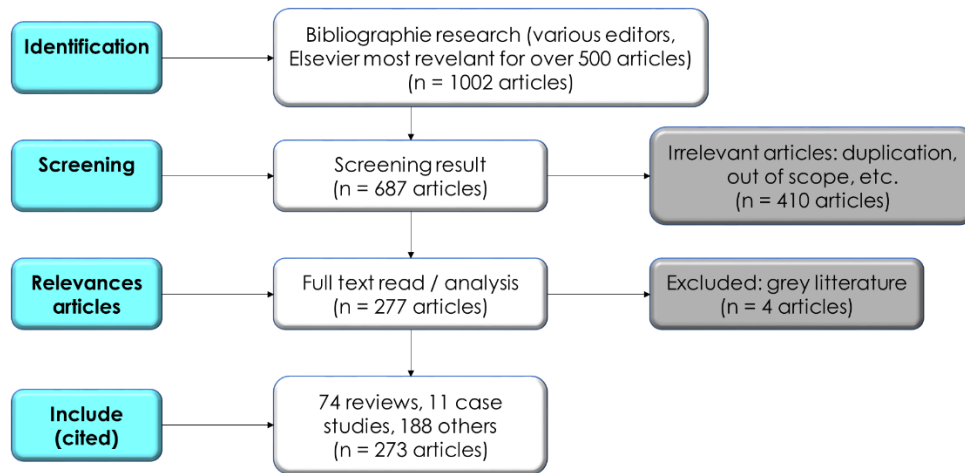
Outdoor particulate matter (PM) pollution poses a critical socio-economic and public health challenge worldwide. This review systematically evaluates over 250 studies on PM sources, health impacts, and outdoor filtration strategies, with a focus on both active and passive approaches. Our objectives were to (i) categorize major PM emission sources: transport, industry/ construction, agriculture, and natural sources; (ii) assess the performance and operating costs also possibility of recycling, regeneration of leading active outdoor filtration systems (e.g., SMOG Free Tower, Mann+Hummel filter cube, electrostatic filters, etc.); (iii) examine passive methods such as urban green walls, passive outdoor filters, passive house air regulation. In the current trending, numerical modeling (CFD) emerges as indispensable for optimizing large-scale deployment, with the possibility of integration with artificial intelligent to predict the outcome results. We conclude that integrating targeted active units with passive methods offers a great cost-effective benefice for PM mitigation plan, potentially applicable in the same time for short- and long-term strategies in urban management.

Highlights

- Particulate matters (PM) sources, risks, current solutions to reduce PM in outdoor air.
- Revision of general fibrous filtration history, mechanisms, and material development.
- Active filtration systems have high efficiency, but also higher costs and requirements.
- Passive filtration is more sustainable, but demand strategies and urban management.
- Numerical modeling can be applied for computing fluid dynamics (CFD) application in air filtration, and simulating different scenarios based on smaller scale data.

Keywords: PM; Outdoor air; Air filtration; Active and Passive methods; CFD modeling

Method



We conducted a structured, PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) inspired bibliographic workflow in four stages: Identification, Screening, Full-Text Relevance Assessment, and Inclusion in order to assemble 273 studies on PM origin, health and economic impacts, and PM filtration / air pollution regulation. In the identification step, broad keywords (e.g., PM pollution, outdoor air filtration, active filter, passive air filter, etc.) searches across Elsevier, Springer, Wiley, and other platforms yielded 1,002 records. During the screening step, title/abstract review and deduplication removed 410 out of scope or non-peer reviewed items, leaving 687 articles. In the Full-Text Assessment stage, strict criteria like outdoor context, concrete filtration methods, and methodological transparency were applied for the articles selection, excluding four gray-literature reports, and reach 277 articles. Finally, we included 273 unique works (74 reviews, 11 case studies, 188 original research articles), each coded for technology type, performance metrics, and context.

I. Introduction

I.1. Outdoor PM pollution situation

Industrial development in many countries leads to a sharp increase in production plants and in the increase in the number of road transport, including passenger cars and heavy trucks. Such relentless industrialization is at the origin of the emission of fine particulate matters (PMs), which are harmful to the environment (micro-inorganic matter dispersion), but especially to the health of populations living nearby. In the case of transport, cars and trucks generate PMs of varying sizes which remain concentrated around major roads and which have a strong impact on the health of populations living in large cities. Pollution by PMs is also present in underground stations where metal fine particles, generated from brakes and friction with rails, reach relatively high values compared to the threshold set by the World Health Organization (WHO). Various air pollutants can stay in the atmosphere for minutes, even years, depending on their weight and interactions with the surrounding environment. For example, PM as water dissolution, nucleation, oxidation, adsorption on other host substrates, and, could pose health problems to every scale of local, national, regional, or global due to the presence of natural vectors such as temperature, rainfall, or wind (W. Li et al., 2023). For now, PMs are mostly categorized by three main categories based on the average size of the particles constituting, i.e., PM_1 (ultrafine), $PM_{2.5}$ (fine) and PM_{10} (coarse), which refer to particle sizes below 1, 2.5 and 10 μm , respectively. PM_1 and $PM_{2.5}$ pollution are particularly harmful since such pollutants can penetrate human bronchi and lungs owing to the small particle size (Chan et al., 1980; Pope, 2002). The most alarming fact concerns the dispersion of microplastic issued from the abrasion of tires into different water sources and, finally, could end-up in the food chain or drinking water (De Souza Machado et al., 2018; Sommer et al., 2018).

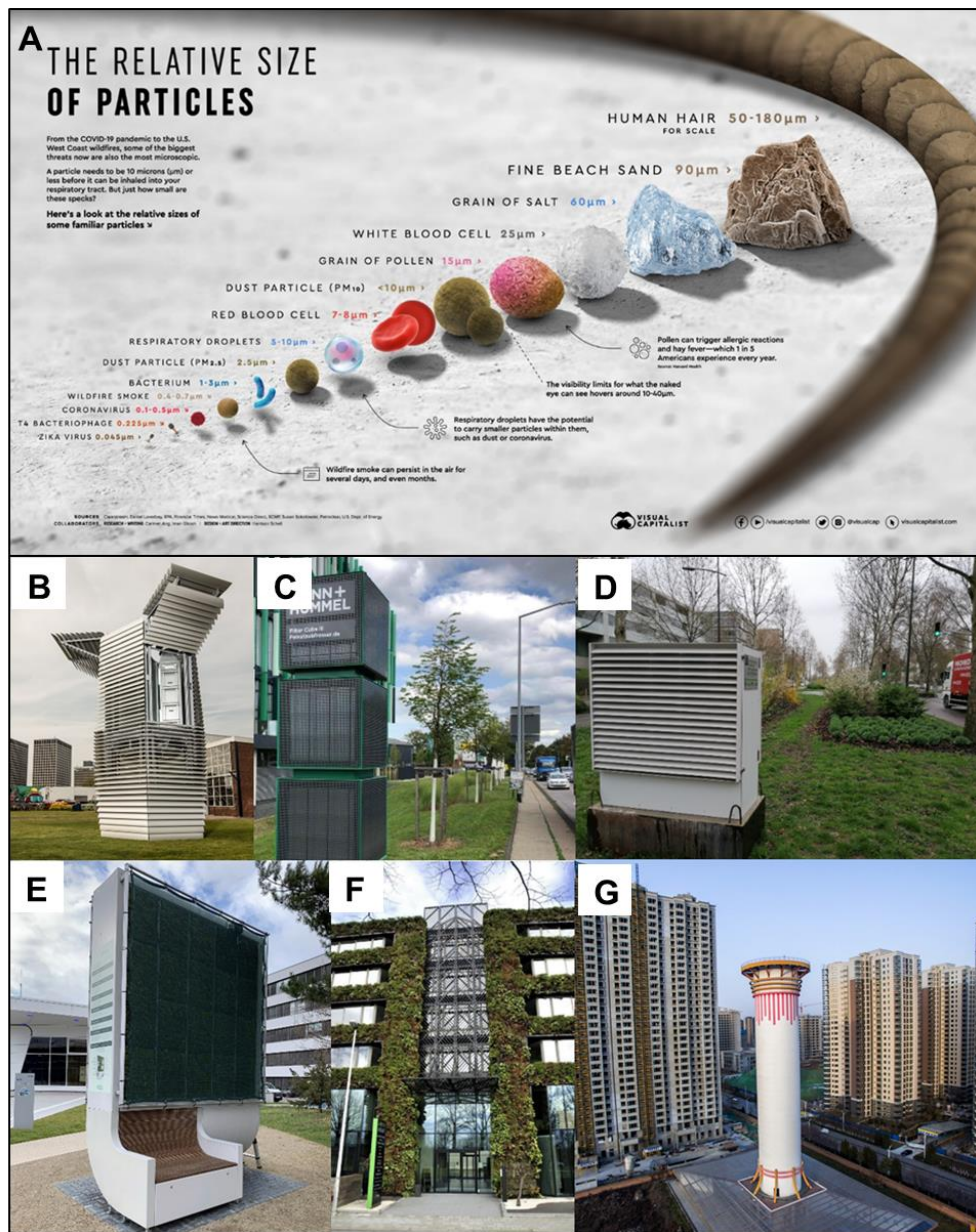


Figure 1 | **A.** Illustration of PM size with different objects. Image credit: Visual capitalist, designed by Harrison Schnell. | **B.** SMOG free tower – an active outdoor air filtration that reduces PM by electrostatic filters. Image source: (studio roosegaarde, 2025). | **C.** Mann+Hummel active outdoor filter ventilates air through the filter cubes and collect PM by glass fibers. Image source: ((Brake) MANN+HUMMEL, 2025). | **D.** TrapAparT passive outdoor filter, PM are captured passively by natural wind near high traffic emission source. (Trinh et al., 2024) – Copyright with Elsevier license number 5966430045511. | **E.** Green panels on urban streets, accompanied by an active ventilation for PM reduction (Donateo et al., 2021) – Copyright with Elsevier license number 5966420108278. | **F.** Green wall integrated with infrastructure as potential mitigation of PM concentration and heat reduction (Ysebaert et al., 2021) – Copyright with Elsevier license number 5966420316217. | **G.** Xian's SMOG tower in Shaanxi province of China. Image source: (Intelligent Living, 2019).

The scheme presented in Fig. 1A displays the relative size of the different particles including bacteria and viruses in relation to the PMs' sizes as discussed above. As schematized in the figure, PM₁ with relatively small aerodynamic size, can be easily ingested by humans through breathing, thus entering the body and induce diseases. In addition, due to their small size, these particles could stay in suspension long time in air, or be transported by different mechanisms, such as wind-driven advection diffusion or rainfall (Csizmazia & Nagyné Polyák, 2001; R. Zhang et al., 2015). It is thus of high interest to develop filtration systems which could trap PMs in outdoor environment, as close as to their emission source, in order to reduce their harmful effect on human health and environment.

Some examples of filtration systems-passive and active ones-are presented in Fig. 1, for outdoor PM reduction, which are operated in different countries worldwide: SMOG free tower – an active outdoor air filtration which reduces PM by electrostatic filters (Fig. 1B), Mann+Hummel active outdoor filter ventilates air through the filter cubes and collect PMs by glass fibers (Fig. 1C), TrapAparT SAS passive outdoor filters, PMs are captured passively by natural wind near high traffic emission source (Fig. 1D), green panels on urban streets, accompanied by an active ventilation for PM reduction (Fig. 1E), green wall integrated with infrastructure as potential mitigation of PM concentration and heat reduction (Fig. 1F), Xian's SMOG tower in Shaanxi province of China (Fig. 1G). The examples clearly demonstrate that outdoor PM reduction is taken in a serious way in different industrialized countries as it represents a significant threat for both human and environment.

In addition, PMs can combine with other gaseous atmospheric pollutants, such as NO_x, SO_x, CO, VOCs, PAHs, O₃, etc., to generate secondary pollution, including acid rain, photochemical smog, and contaminants in run-off water (Le et al., 2020; Plasencia Sánchez et al., 2023; Raut et al., 2009; Ravindra et al., 2022). Such recombined secondary PMs also represent a more serious threat for humans due to the present of different harmful species in the same vector. Lacking adequate protection, PM particles pose a significant health risk due to their ability to penetrate deeply the respiratory system and organs, potentially leading to serious health problems (Balakrishnan et al., 2019; Gualtieri et al., 2010; Pope, 2002, 2007; Rajagopalan et al., 2018). Beside chronic diseases and average lifespan reduction (Fuller et al., 2022; Schwartz et al., 2021), PM exposure is also one of the main causes of premature death in both developed and developing countries (Burnett et al., 2018; Ostro et al., 2018). The WHO estimated to about 7 million the premature deaths annually, comprising 3 million

cases directly attributed to outdoors PM (World Health Organization, 2016). The World Bank estimated in their reports (The World Bank, 2016, 2020) that US\$ 143 billion labor income, and US\$ 3.55 trillion welfare losses every year worldwide were caused by exposure to PM. These studies (Dechezleprêtre et al., 2019; Kunzli et al., 2000; Rafique et al., 2022) show direct or indirect impacts of PM pollution to the healthcare system, and to socio-economic issues of modern societies. Hence, in parallel with reducing PM emission at the source, PM trapping is also important for establishing a healthy society. In the need of gathering more knowledge about the PM and how to capture them, this study highlights some existing methods of PM filtration with low energy consumption, and, limited process cost and secondary pollution through additional waste generation.

According to the brief summary of the problem presented above, one can clearly figure out the strong impact of air pollution by PMs on public health regardless the localization of their emission due to the fast transportation of the PM over large area through natural factors. In this review, we aim to report recent advances in PMs filtration technology using both active and passive filtration modes. First, the review will introduce some basic principles about the PM emission sources, its nature and possible recombination pathways with other inorganic or organic pollutants, its impact on the human health, and the solutions developed to reduce its concentration for both indoor and outdoor areas. In the second part of the review, we will discuss about the filtration mechanism, which can be applied for both active and passive filtration devices as well as the different filtration setups developed nowadays. The economic cost, including energy consumption, performance and regenerability, will be extensively discussed in a dedicated section. The next section deals with the discussion linked with numerical modeling, which could be of high interest for the implementation of the filtration systems, and for the planning of new construction with respect to the surrounding occupations in the area. Finally, a conclusion and future perspectives will be discussed and proposed based on the current technology development for the reduction of PM pollution in different areas. It is also expected that the ongoing electrification of different industrial sectors, through the extensive use of electricity to provide heat instead of gas burners via the development of renewable energy (RE), will contribute to a drastic decrease of the PM at the emitting sources.

I.2. PM sources and necessity to PM reduction

I.2.1. PM sources

Based on their various emission sources as well as their highly varying chemical composition, PMs can be divided into two categories: indoor and outdoor PMs. Indoor PMs emissions come mainly from human activities in closed space, but also from the outdoor environment through air exchange (C. Holman, 1999). Concentrations of PMs, VOCs (Volatile Organic Compounds) and PAHs (Polycyclic Aromatic Hydrocarbons) in indoor air can raise drastically within a short period of time by material combustion-including wood, charcoal heating, candle, incense burning, electronic and tobacco-containing cigarette smoking, etc. (Favez et al., 2009; Jiao et al., 2023; Lewtas, 2007; Saffari et al., 2014; Zgheib et al., 2023). In these studies (Abdullahi et al., 2013; Lachowicz et al., 2022; Militello-Hourigan & Miller, 2018) cooking represents one of the main sources of PM emissions, accompanied by volatile compounds and thermal degradation of fuels, foods and additives, especially in wood and charcoal cooking practice. In case of lack of extraction hood or sufficient aeration, PM concentrations could rise sharply and remain for a long time in the kitchen room or in the entire house. Moreover, skin, hair, solid or liquid excreta of animals and human bodies, fungus development and spore diffusion also take parts in bio-sources of PMs (Ferro et al., 2004; Gallon et al., 2020; Holme et al., 2020; Hospodsky et al., 2012; Z. Tan & Zhang, 2004; Yamamoto et al., 2015). The use of deodorant, cosmetic products, painting, cleaning and disinfecting agents, etc. could generate liquid droplets aerosols in indoor space (Lazaridis et al., 2015; Mata et al., 2022; Palmisani et al., 2021). These emission sources can also add a significant quantity of PM to indoor air pollution. According to (Chowdhury et al., 2023; Götschi et al., 2002; Grau-Bové & Strlič, 2013; Martins et al., 2020), indoor PMs are also supplied by particles from outdoor air via aeration, even transported by human clothes and accessories. The PM pollution for indoor area is the worst as most people stays a significant part of their time inside.

Outdoor PM could come from natural or anthropogenic sources or the mix between them, i.e., secondary PMs. Dust particles of all sizes could be produced by natural phenomena of volcanic eruptions, wildfires, airborne sand and pollen dispersion (Hama et al., 2021; Kobayashi et al., 2013; Kuhlbusch et al., 2009; Sénéchal et al., 2015). Their abruptly presence in air after one or a chain of PMs emission episodes may damage the balance of ecosystems

which may take many years or decades for resilience. These particles cause not only air quality degradation for the concerned zone, but could be transported by wind, up to thousands of kilometers further away (Csizmazia & Nagyné Polyák, 2001; W. Li et al., 2023; Plasencia Sánchez et al., 2023; Z. Wang et al., 2024; L. Zhang et al., 2021; R. Zhang et al., 2015). With the rising average of annual temperature and climate change, many countries around the world have to deal more and more with the growing in number and in the severity of natural disaster events, including natural PM emissions (i.e., wildfires in the United States and in Australia). Besides, the air pollution situation around the world is contributed by the PMs from anthropogenic activities including agriculture, transport, construction and industry. Agriculture emissions of PM originate from burning biomass and other sources like animals excretion, fertilizer and other artificial substances (Aneja et al., 2009; Hays et al., 2005; M. Cambra-López et al., 2011). Solid or liquid droplets of fertilizer and pesticide, herbicide or fungicide in suspension could be adsorbed on natural PM and transported to other sites (Clymo et al., 2005; Cooter & Hutzell, 2002; Kjær et al., 2011). The inhalation of these secondary PMs containing harmful chemical species can cause severe diseases for long-term exposition. Traffic-related (both exhaust and non-exhaust emissions) contributes up to 25% of the total ambient PM_{2.5} pollution in urban area (Karagulian et al., 2015). Many research groups (Catapano et al., 2019; Huang & Penning, 2014; C. T. Pham et al., 2013; J. Zhang et al., 2018; T. Zhao et al., 2020) studied soot particles from incomplete combustion procedures of fuel engines which are carcinogenic. Non-exhaust PM emission in both fossil fuel and electrical vehicles is linked to degradation of tires, brakes, and the road surface or the train wheels with rail tracks (Birmili et al., 2006; Garg et al., 2000; Grigoratos & Martini, 2015; Hulskotte et al., 2014; Liati et al., 2019; Silva & Kallon, 2019). As tramways and subway have become main daily transportation of a large number of urban and suburban population, this aspect should be considered more seriously for protecting passengers of public transports. Numerous studies (Beji et al., 2020; OECD, 2020; Piscitello et al., 2021; Timmers & Achten, 2016) estimated that 90% of PM from traffic-related sources are from non-exhaust emission, which is inevitable even for electrical vehicles. Furthermore, PM from road and building construction, as well as thermal power plant, is reported to have significant impacts in emerging countries (see fig. 4A) where the market has high demand in construction and industrialization but lack of measures for preventing PM emissions (Azarmi et al., 2016; Cheriyan et al., 2021; Guttikunda & Jawahar, 2014; Prasad et al., 2006). The PM could also adsorb viruses on its surface and through high dispersion vectorising the harms largely away

from the emitting zone rendering difficult for the control and eradication of the disease (Santurtún et al., 2022). The different points discussed above clearly pointed out the large impact of outdoor PM pollution, not only for emerging countries, i.e., China, India, just to cite a few, but also for developed ones, due to the high dispersion of such pollutants through secondary combination with other organic or living matters.

I.2.2. Necessity of PM reduction

For both indoor and outdoor air pollution mitigation, PM concentration needs to be controlled in order to reduce its impact on the human health. A report of Organisation for Economic Co-operation and Development - OECD (Dechezleprêtre et al., 2019) calculated that the gross domestic product (GDP) per capita of a country could decline about 0.8 % per $1 \mu\text{g. m}^{-3}$ of $\text{PM}_{2.5}$ annual concentration increment. As an alternative to regulating air quality and temperature comfort, mid to high-income individuals are exhibiting an inclination towards higher-quality air zones for their residences and favoring the use of indoor air filtration devices (B. Li et al., 2020; Reames & Bravo, 2019). The market size of air filters and air purifiers is estimated at \$US 15 billion in 2023 and could be growing between US\$ 25 billion and US\$ 30 billion in 2030 (Fortune Business Insights, 2023; Grand View Research, 2024). Regarding the need and local air quality, consumers and building managers have a large range of choices for their individual house or building HVAC system (heating, ventilation, air conditioning). For example, the High Efficiency Particulate Air (HEPA) filters for mechanical filtration; cartridge or baghouse filters for vacuum; dust collectors for industrial or individual use; advanced technologies such as activated carbon, electrostatic precipitators, ionic filters, UV lights (Eskelinen, 2015; P. Li et al., 2024; Robert & Nallathambi, 2020; Yit et al., 2020; Y. Zhang et al., 2011). Outdoor air quality control requires the synergy of different measures including environmental policies and smart technology application. For example, the Commission of the European Union (EU) (Commission Welcomes Provisional Agreement for Cleaner Air in the EU, 2024; WHO, 2021) accorded in 2024 new objectives and regulatory values on air pollution and PM reduction by 2030. Annual $\text{PM}_{2.5}$ concentration has been limited to $10 \mu\text{g. m}^{-3}$ instead of $25 \mu\text{g. m}^{-3}$, which is still 2 times higher than the air quality guideline level recommended by WHO in 2021.

I.3. Solutions to reduce PM concentration

In diverse investigations (Chapman & Keszthelyi, 2009; Headrick, 2020; Knight & Burningham, 2011; Middleton & Kang, 2017; Opp et al., 2021), humans have soon realized the existence and hazard of fine particles produced during natural disasters like sandstorms, volcanic ash eruptions, or wildfires. Prehistoric humans might seek natural shelters such as natural caves, rock formations, and lower grounds for avoiding these events. Then, simple shelters were constructed using raw materials such as branches, leaves, and animal hides. Clothes from hides and other materials were used, not only for temperature regulation, but also for covering the body from abrasive dust or hot ashes. Davies (Davies, 1974) mentioned the first appearance of clothes covering noses and mouths of Roman mining laborers. The history of face masks - earlier form of air filter, from the diseases in the 16th century, to the burping of air filtration technology during two World Wars, until modern face masks in COVID-19 outbreaks were presented in these studies (Ike et al., 2020; Matuschek et al., 2020; Selvaranjan et al., 2021; Torres & De-la-Torre, 2021). However, during the above-mentioned pandemic, in 2021, 3.4 billion single-use face masks and face shields were estimated to be distributed worldwide every day, which corresponds to 1.6 million tons of plastic wastes per day (Benson et al., 2021). Individual face masks might be an effective personal protection in the short term for preventing diseases and air pollution, however, it should not be considered as a sustainable method because it requires a cooperative of a large proportion of the population to wear it permanently, and an upcycling system to collect and handle the used materials (Dharmaraj et al., 2021). It is worthy to note that the incineration of the used facemasks could also be a new source of PM emission depending to the management of the incinerator exhaust stream. Beside face masks, high technology filters for vacuum cleaner, portable filters, or individual room air conditioner appeared in other reviews (Allen & Barn, 2020; Cheek et al., 2021; De Castro et al., 2020; Zhu et al., 2021). They will not be discussed in the current review, for the reason that these filters are primarily designed for local-scale applications. Despite the wide array of brands, models, and price ranges, their affordability remains limited, particularly for people in developing and emerging countries who are experiencing significant impacts from air pollution and climate change (Bruce et al., 2000; Y. Liu et al., 2021; Rafaj et al., 2018). Thus, new technologies are aiming to emphasize materials and air treatment mechanisms that could be affordable and applicable to common ventilation systems in building, parking, subway stations, outdoor and high-density public spaces. Current technologies provide various solutions to filter particulate matter in the outdoor

environment including devices that vacuum polluted air and retain PM on fiber, e.g., Mann+Hummel filter stations in Germany (Bächler et al., 2021), SMOG Tower in China, India (Arun et al., 2022; H. Zhang, Mao, et al., 2021), green panel of vegetation with mechanical ventilation as air quality and temperature regulation devices in urban streets (Donateo et al., 2021; Splittgerber, 2015), etc. However, there is no review yet providing a global overview of these different possibilities including pros and cons. The aim of this review is, therefore, to provide the different information gathered from literature reports about this topic. Although outdoor air quality degradation can affect the health of a large scale of population, not much of research discussed about application of technologies in outdoor air mitigation, especially when public interests in air quality still depend on living standard of each region (Bruce et al., 2000; H. Zhang, Mao, et al., 2021). Indeed, the concern for the quality of outdoor air, both as solid suspension (PMs) or volatile organic compounds (VOCs), is strongly developed in industrialized countries. The standard of living in these countries is relatively high, also for health preservation and prevention become an issue. While for emerging countries, the first concern is rather oriented towards the necessities, which are food and housing instead of health issues. The profit of the above-mentioned filters could vary as a function of air quality and weather conditions in the mentioned zone, but they demonstrated some undertaking policy measures for PM reducing in urban environment. In developing countries, the problem can be significantly reduced by introducing high standard and norms for combustion engines, i.e., cleaner fuel with sulfur and nitrogen impurities, high combustion efficiency, on-board PM filters for diesel engines, etc. However, PM release by friction, i.e., brakes, tires, roads, remaining underestimated and only some directives have been issued to tackle such problem. In addition, these small particles, mostly constituted by carbon-derived plastic particles, could be further degraded into microplastic particles which are easily dispersed in environment, especially in water medium, i.e., rivers and oceans, and finally, ending-up in the food chain and being ingested by human organisms. Filtration mechanisms, and sustainable methods of active and passive filtration will be discussed and evaluated by their filtration performance, energy consumption, reusability, cost benefice, and simulated models.

The map in Fig. 2A presents the annual PM_{2.5} worldwide pollution in the year of 2023. Not only the emerging countries, but also many developed countries have PM_{2.5} level surpassing the 5 µg. m⁻³ guidelines of the WHO. Among Asian cities that have poor air quality, pointed out by Gautam et al. (Gautam et al., 2016), Guttikunda et al. (Guttikunda et

al., 2023) observed the air quality of Delhi, India from 1990 to 2022 and concluded a very high level of outdoor PM_{2.5} pollution (Fig. 2B). In average, life expectancy of Indian people could extend 1.7 years more (estimation for 2017) if the pollution is controlled (Guttikunda & Jawahar, 2014). In order to archive a steady and long-term growth, air pollution mitigation is an important criterion to be included in every eco-friendly environmental policy. These authors (Kurmi et al., 2024; Rafaj et al., 2018) suggested innovative solutions and strategies for sustainable development in developing countries, which requires the synergy and close interactions between academia research, industry cooperation and development, government policy and norms. As the example of air pollution situation in China, many cities had very degraded air quality, by the reason of multisource emissions addition to inappropriate weather conditions (Gautam et al., 2019; Tao et al., 2014). The Air Pollution Prevention and Control Action Plan (APPCAP), which was promulgated by Chinese government in late 2013, represented a step-forward in the reduction of air pollution by PM and is summarized in reports (State Council of China, 2013; Zhong et al., 2021). Such plan aims to reduce the pollution at its sources on one hand, and to reduce the outdoor pollution through the installation of filtration systems in open areas. Such plan preconizes a reduction of PM_{2.5} concentration down to 35 $\mu\text{g. m}^{-3}$ by 2035. The observed annual mean of PM_{2.5} concentrations of a large number of cities show a steady decreasing trend from $65.7 \pm 27.3 \mu\text{g. m}^{-3}$ in 2013 to $36.8 \pm 12.0 \mu\text{g. m}^{-3}$ in 2019, which confirm the high efficiency of the process (L. Zhang, Zhang, et al., 2019; Zheng et al., 2017). Representative maps showing the change in terms of PM_{2.5} concentration from 2013 and the projection for 2035 are presented in Fig. 2C, which highlights the efficiency of the air pollution reduction initiated in 2013. The APPCAP also significantly contributes to the reduction of volatile organic compounds (VOCs) and secondary inorganic compounds from chemical plants according to the recent report by He et al. (L. He et al., 2024) on the regional pollution by the chemical industrial parks (CIPs) in China, especially in the Yangtze River Delta (YRD). However, the VOCs emission still remains high in the industrial area and becomes the subject of extensive research as VOCs serve as precursors for both O₃ and PM_{2.5}, which become the main source of air pollution in China (K. Li et al., 2019; J. Wang et al., 2020; Y. Wang et al., 2021).

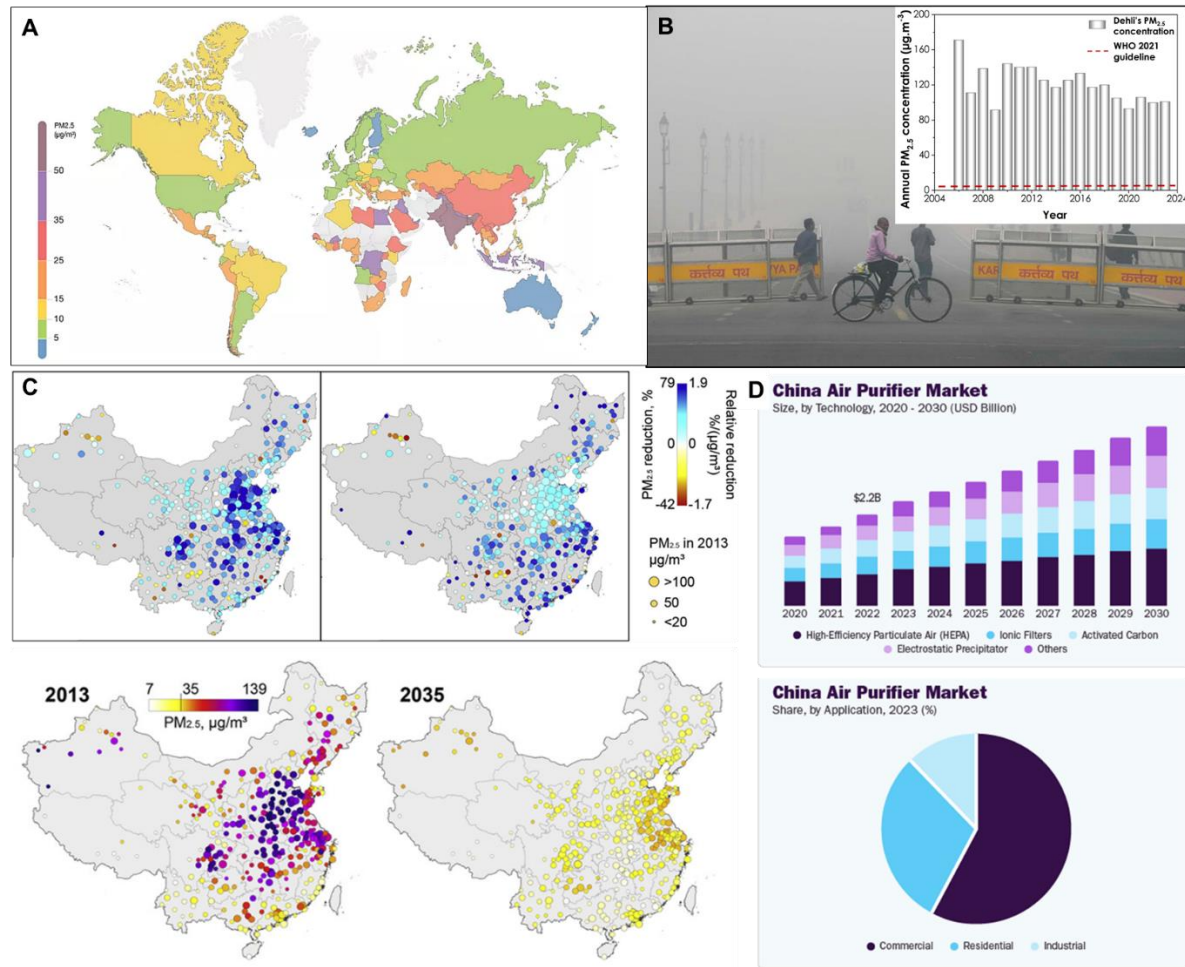


Figure 2 | **A.** Annual $PM_{2.5}$ concentration of countries around the world in the year of 2023, established by IQAir. The white color indicates that no data available trusted source available. Image source: (Angela Symons - IQAir, 2024). | **B.** A man cycles near the India Gate amid low visibility due to smog as air quality remains in “severe” category in New Delhi (India). Image source: (Staff, 2025). Inset: Graph of annual average $PM_{2.5}$ concentration in New Delhi from 2006 to 2023. The red line indicated the limited exposure annual value preconized by the WHO in 2021. Data retrieved from (Guttikunda et al., 2023). | **C.** Relative tendencies of $PM_{2.5}$ reduction in main Chinese cities (most polluted industries region are located in the east side) from 2013 to 2019 and projection to 2035. (Zhong et al., 2021) – Copyright with Elsevier license number 6027650304710. | **D.** Illustration of China air purifier market from 2020 to 2030 (Grand View Research, 2024).

Since air quality is an important index for evaluating life standard, air pollution situation can have influences on the housing prices and the migration flux between regions (B. Li et al., 2020). In the last few years, with the rising awareness of citizens and the Chinese government about these issues, many actions have been taken (definition high requirements for air quality standard, delocalization of industries, transition of polluted vehicles to greener or public transports, etc.) that positively ameliorated the air quality and public health (Pui et al., 2014; Xue et al., 2024). In developing countries, where long-term and large-scale solutions may not

yet be feasible, short- and medium-term measures can be implemented to control pollution and protect public health (i.e., the growing of air purifier market in China – Fig. 2D). Authors (Bruce et al., 2000) and (Blessy et al., 2023) have proposed innovative and practical approaches to improve indoor air quality, while Allen and Barn (Allen & Barn, 2020) emphasize the importance of wearing masks during exposure to outdoor air pollution. For agriculture emission such as particulate matter from straw burning in Vietnam (Dinh et al., 2024), source reduction and proper waste treatment are emerging as effective strategies for mitigating PM emissions directly at their origin.

II. Air filtration system

II.1. Filtration mechanisms

Fibrous filter is the most basic form and most studied subject of air filtration. From the beginning of human civilization, sieving materials such as fishing nets or colander have been used to filter objects bigger than the mesh opening. Common cloth filters of face masks can prevent gross particle size by sieving, but not the finer PMs which are more dangerous for human health as they can diffuse through the human body and to be vectored thorough the body's organs through the blood stream (Sembiring et al., 2021). Advanced air filtration technology is essential not only for maximizing the capture efficiency of PM, but also for maintaining the integrity of the airflow. This section builds on the fundamental principles of particle dynamics in a flow and their deposition on a single fiber surface. The random movement of solid particles in a gas or liquid was first described by Brown (R. Brown, 1828) and formulated by Einstein's molecular kinetic theory (Einstein, 1905), so-called Brown motion. By calculating the time-dependent average displacement, the pathway of each particle could be tracked and predicted. Reynolds (Reynolds, 1883) established the related physical laws for a fluid motion in a parallel channel, which is applicable for fluid or gas stream behaviors in a medium.

Table 1 | Important references of fiber filter mechanism and associated equations

Credit - Year - References	Related equation	Phase
Robert Brown - 1828 - (R. Brown, 1828; Einstein, 1905)	$r = \sqrt{2 \cdot D \cdot t}$ r : Average of distance travelled (m) ; t : time (s) D : Self-diffusion coefficient of material (m².s⁻¹)	Random movement trajectory of particles (particle - flow)
Osborn Reynolds - 1883 - (C N Davies, 1945; J. P. Holman & Bhattacharyya, 2011; Reynolds, 1883)	$Re = \frac{\rho_{flow} \cdot U \cdot L}{\eta_{flow}}$ Re : Reynolds number (-) ; ρ_{flow} : flow density (kg. m⁻³) ; U : flow velocity (m.s⁻¹) ; L : Characteristic length (m) ; η_{flow} : flow dynamic viscosity (kg. m⁻¹. s⁻¹)	Stream behavior could be laminar, turbulence, or transient (flow)
George Gabriel Stokes - 19 th century - (Davies, 1953; Raffel et al., 2017; C. Yang, 2012)	$Stk = \frac{\rho_p \cdot d_p^2 \cdot C_c \cdot U}{18 \cdot \eta_{flow} \cdot d_{fiber}}$ Stk : Stockes number (-) ; ρ_p : particle density (kg. m⁻³) ; d_p : particle diameter (m) ; d_{fiber} : fiber diameter (m) ; C_c : Cunningham correction factor (-)	Particle behavior in the flow (more or less follow the airstream lines) (particle - flow)
Jean Claude Eugène Péclet - 19 th century - (Hinds, 1999; Patankar, 2009)	$Pe = \frac{U \cdot d_{fiber}}{D}$ Pe : Peclet number (-)	Diffusion or advection behavior of particles in continuum flow (particle - flow)
Martin Knudsen - 1934 - (Knudsen & Partington, 1934)	$Kn = \frac{2 \cdot \lambda}{d_{fiber}}$ Kn : Knudsen number (-) ; λ : mean free path of a particle before collision with gas molecular or other particles (m)	Characterize the boundary condition (regime) of a flow (flow). (Fig. 3C)
Sinji Kuwabara - 1959 - (Kuwabara, 1959; K. W. Lee & Liu, 1982)	$Ku = -\frac{\ln(\alpha)}{2} + \alpha - \frac{\alpha^2}{4} - \frac{3}{4}$ With volume fraction of fiber $\alpha = \frac{10^{-3} \cdot G}{z \cdot \rho_{fiber}}$ (-) ; Ku : Kuwabara number (-) ; G : Grammage (filter mass per area unit) (kg. m⁻²) ; z : filter thickness (m) ; ρ_{fiber} : fiber density (kg. m⁻³)	Model of cylinder fibrous filter placed in a flow field (flow - filter)

Experimental results of gas stream behaviors around a sphere (C N Davies, 1945) or in a tunnel (J. P. Holman & Bhattacharyya, 2011) indicates that the flow could be in laminar ($Re < 2300$), turbulent ($Re > 4000$), or an intermediate between these two regimes ($2300 < Re < 4000$). Transport of particles in a medium is defined by Péclet (Pe) number (Hinds, 1999).

While the diffusion phenomenon dominates for a Pe near 0, advection of particle mass occurs when Pe value extends towards infinity. A particle floating in a flow depends and has more or less influences on the flow. Furthermore, Stokes number (Stk) can track particle pathways in a flow. PMs can follow the air streamlines ($Stk < 1$), or detach from the flow due to gravitational attraction or drag forces ($Stk > 1$), etc. This phenomenon could be quantified more precisely by the Stokes number with Cunningham slip correction factors which takes into account the air drag force on particles (Davies, 1953; Raffel et al., 2017; C. Yang, 2012). The Knudsen (Kn) number determines flow regimes around a fixed body, considering here the filter fiber (Knudsen & Partington, 1934). Streamlines near the fiber are modified from continuum (flow field is forcefully changed by the fiber, $Kn < 1$) to free molecular flow (fiber has no effect on the streamlines, $Kn > 1$), depending on the fiber diameter (Table 1), as illustrated in figure 2C. In place of having a model of the whole filter, a simple 2 dimensions cross section of a long cylinder with diameter corresponding to one single fiber is often used, called Kuwabara model (Ku) (Kuwabara, 1959). This model is largely taken as a basic study case for fiber filter simulation or particle deposition behaviors (Dassios et al., 1995; Kanaoka et al., 2001; K. W. Lee & Liu, 1982; P. Li et al., 2014). Flow and particle interactions with the fiber can also be described by the Ku , which is dependent on the filter solidity α - characterized by fiber structure. Kuwabara (Ku) number is also used for calculating the efficiency of each filtration mechanism, between electrical deposition, diffusion, interception and inertial impaction (Fig. 3A and 3B).

Berry et al. (Berry et al., 2023) summarized the efficiency of each deposition mechanism of PM on a single fiber. Considering perfect spherical particles and cylindrical fiber, the interception parameter R is the ratio of particle diameter to fiber diameter, which has influences on particle-fiber interactions. The general filter efficiency can be expressed as Eq.1 (Davies & Paulus, 1973; Y. Gao et al., 2022; R. Thakur et al., 2013), with Eff_{SF} as the overall efficiency of all PM deposition mechanisms on a single fiber. Where α is the volume fraction of fiber, z is the filter thickness (m), d_f is the fiber diameter (m).

$$Eff_{filter} = 1 - \exp \left[\frac{-4 \cdot Eff_{SF} \cdot \alpha \cdot z}{\pi \cdot d_f \cdot (1 - \alpha)} \right] \quad (Eq. 1)$$

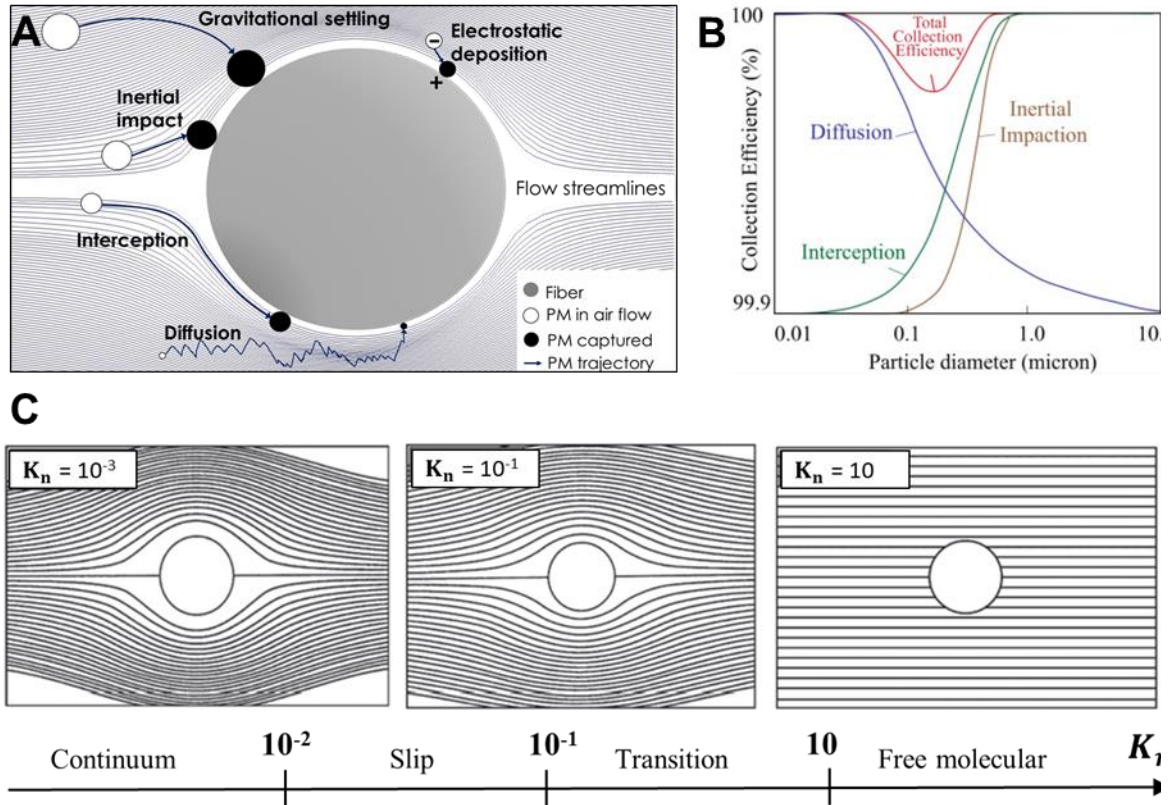


Figure 3 | **A.** Illustration of different filtration mechanisms of a fiber cross section with various particles moving in a flow. Reproduced from the original figures in (Hinds, 1999; C. Yang, 2012). | **B.** Relation of relative trapping efficiency in function of particle diameter (only in HEPA filter) (Zeinali et al., 2022) - Copyright with Elsevier license number 5966400613674 5976551049839. | **C.** Influence of the Knudsen number on the flow (parallel black lines), this number depends itself on the fiber diameter (fiber cross section is represented by a white circle) (P. Li et al., 2014; Maze et al., 2007) – Copyright with Elsevier license number 5966400613674.

Hinds (Hinds, 1999) established an equation that takes account of significant interception enhanced by diffusion, and put aside the others negligible interactions. The equation Eq. 2 defines the total efficiency calculation depending on the five main methods, in order, interception, inertial impaction, diffusion, gravitational settling, electrostatic, diffusion-interception interaction.

$$Eff_{SF} = 1 - (1 - Eff_{inter})(1 - Eff_{imp})(1 - Eff_{diff})(1 - Eff_{settling})(1 - Eff_{elec})(1 - Eff_{di_inter}) \quad (Eq.2)$$

For the sake of clarity, the following equations still consider α as fiber volume fraction, Ku the Kuwabara number, R the interception parameter, Pe and Stk in order for Peclet and Stokes

number. A table of nomenclature terms can be found before the References section of this article. Interception of PM on single fiber happens when particles follow streamlines and come in contact with the fiber (Hinds, 1999; K. W. Lee & Ramamurthi, 1993). The efficiency of this method increases when R value rises (bigger particle or smaller fiber) due to the higher impaction between the particle and the fiber.

$$\text{Eff}_{\text{interception}} = \frac{1 - \alpha}{K_u} \cdot \frac{R^2}{1 + R} \quad (\text{Eq. 3})$$

Diffusion usually occurs when an ultrafine particle (d_p around $1 \mu\text{m}$ or smaller) moves randomly between streamlines. This movement can be referred to Brownian movement when PMs randomly collide with gas molecules or other particles (Berry et al., 2023).

$$\text{Eff}_{\text{diffusion}} = 2,58 \cdot \left(\frac{1 - \alpha}{K_u} \right)^{1/3} \cdot \text{Pe}^{-2/3} \quad (\text{Eq. 4})$$

As particle deposition on fiber by interception and diffusion modes imposes mainly on particles of small size, under $1 \mu\text{m}$ (PM_1), these two mechanisms can have more or less influences on each other. For example, Brown motion represents particle trajectories in diffusion mode, can randomly bring particles to flow near a fiber, where particles follow it and are captured by interception deposition. Hinds (119) and Berry (126) defined this relation in equation Eq. 5.

$$\text{Eff}_{\text{diffusion_interception}} = \frac{1.24 \cdot R^{2/3}}{(K_u \cdot \text{Pe})^{1/2}} \quad (\text{Eq. 5})$$

At the threshold of $\text{Stk} = 1$, particles become too big to follow streamlines due to the gravity attraction. Inertial impaction and gravitational settling begins to be the main mechanisms of PM trapping. For inertial impaction, particles cannot follow the abrupt change of streamlines around fiber. Thus, PMs detach of streamlines, impact and stick on the fiber (Ellenbecker et al., 1980; Hinds, 1999; Stechkina et al., 1969) (with $0 \leq R \leq 0,4$; $0,035 \leq \alpha \leq 0,111$).

$$\text{Eff}_{\text{impaction}} = \frac{\text{Stk}}{2 \cdot (K_u)^2} \cdot [(29,6 - 28 \cdot \alpha^{0,62}) \cdot R^2 - 27,5 \cdot R^{2,8}] \quad (\text{Eq. 6})$$

Gravitational settling efficiency depends on the flow velocity U and deposition velocity. With flow velocity sufficiently low, PM deposit vertically or horizontally on the fiber by

gravitational attraction (R. C. Brown, 1993; Hinds, 1999). The sign of equation Eq. 7 can be subsequently changed, depending on the observation point, flow direction, fiber arrangement, etc. With U as the flow velocity and V_d the particle deposition velocity, both in $\text{m} \cdot \text{s}^{-1}$.

$$\text{Eff}_{\text{gravitational settling}} = \frac{V_d}{U} \cdot (1 + R) \quad (\text{Eq. 7})$$

Electrostatic force is usually ignored in classical filtration theory because this force is negligible on most of the particle sizes, and this force could be too small compared to other mechanisms. However, in recent years, with the development of electrospinning fibers, electret filters, or electrostatic field filters, the performances of such mechanism have been reconsidered. Chen (H. Chen et al., 2018) listed three parameters K which correspond to three electrostatic forces K_{in} , K_{im} , K_c which respectively correspond to three electrostatic induced situations, and Coulomb force efficiency (Table 2). More details about K parameters and electrostatic efficiency could also be consulted at these studies (Y. Gao et al., 2022; C. S. Wang et al., 1980; C.-S. Wang, 2001).

Table 2 | Relation of K parameters with charging situations of particles and fiber

	Particle is uncharged	Particle is charged
Fiber is uncharged	No force	K_{im} – image force
fiber is charged	K_{in} – induced force	K_C – Coulomb force

With each K parameter, an electrostatic efficiency can be listed below (H. Chen et al., 2018; Kanaoka et al., 1987):

$$\text{Eff}_{\text{electro-induced}} = 0.06 \cdot K_{in}^{0.4} \quad (\text{Eq. 8})$$

$$\text{Eff}_{\text{electro-image}} = 1.5 \cdot K_{im}^{0.5} \quad (\text{Eq. 9})$$

$$\text{Eff}_{\text{electro-Coulomb}} = 0.06 \cdot K_{in}^{0.4} + 0.067 \cdot K_C^{0.75} - 0.017 \cdot K_{in}^{0.5} \cdot K_C^{0.5} \quad (\text{Eq. 10})$$

Other filter materials differ from fiber, such as carbon-based (Chitranshi et al., 2022; S. Yang et al., 2017), electrostatic filters (Z. Wu et al., 2024), etc. have the same or similar listed filtration mechanisms. Particles are filtered through pores and filter depth by interception, diffusion, gravitational settling, or be adsorbed on the filter surface by sieving. For electret or

wet electrostatic precipitation, electrostatic is the most used force for a good particle retention or particle coagulation on filter surface after penetrating in the electric field (R. Thakur et al., 2013; P. Wang & Chen, 2021; L. Xiao et al., 2023). With the rapid development in technology, another mechanism can be developed and applied, depending on quantity, size, natural of particles.

II.2. Active filtration systems

Active ventilation is a common method of using outdoor air as a supply for regulating the circulation of air in buildings and reducing PM indoor pollution through physical trapping and/or air circulation regulation. In such case, polluted air is aspired through the filter material by mechanical ventilation (Zhivov et al., 2020). As the air flow can be controlled by a fan or an air extractor, active PM filtration concerns a large range of filters, from gross coal dust to nanoparticle capturing (P. Li et al., 2014). In Table 3A and 3B, Appert-Collin (Appert-Collin & Thomas, 2017) regrouped EN779 norm (EN779, 2012) which was replaced by EN1822 norm (EN1822, 2019), in order to classify filter materials based on their efficiency.

Table 3.A | Classification general ventilation air filters EN779 norm (Appert-Collin, 2017)

Filter group	Filter class	Gravimetric yield A_m (%)	Mean efficiency Eff (%) (for the most penetrating particle size)
Coarse (G)	G1	$50 \leq A_m < 65$	-
	G2	$65 \leq A_m < 80$	-
	G3	$85 \leq A_m < 90$	-
	G4	$90 \leq A_m$	-
Medium (M)	M5	-	$40 \leq \text{Eff} < 60$
	M6	-	$60 \leq \text{Eff} < 80$
Fine (F)	F7	-	$80 \leq \text{Eff} < 90$
	F8	-	$90 \leq \text{Eff} < 95$
	F9	-	$95 \leq \text{Eff}$

Table 3.B | Classification general ventilation air filters EN1822 norm (Appert-Collin, 2017).

Filter group	Filter class	Global efficiency (%)	Local efficiency (%)
		(for the most penetrating particle size)	
EPA (E)	E10	≥ 85	-
	E11	≥ 95	-
	E12	$\geq 99,5$	-
HEPA (H)	H13	$\geq 99,95$	$\geq 99,75$
	H14	$\geq 99,995$	$\geq 99,975$
ULPA (U)	U15	$\geq 99,9995$	$\geq 99,9975$
	U16	$\geq 99,99995$	$\geq 99,99975$
	U17	$\geq 99,999995$	$\geq 99,9999$

Filter quality is an important indicator for evaluating filter performance. General filter quality factor (QF_f) could be estimated by the equation Eq. 11 (C. Y. Chen, 1955). With Δp as filter pressure drop (Pa), C_{IN} and C_{OUT} represents PM concentration at upstream and downstream of filter ($\mu\text{g. m}^{-3}$), respectively.

$$QF_f = \frac{-\ln(C_{IN}/C_{OUT})}{\Delta p} \quad (\text{Eq. 11})$$

This criterion is useful for comparing the different filters because it contains at the same time PM reduction ratio and pressure drop parameters. However, for the same filter, QF_f can change over time, from new filters with high penetration rate and low Δp , to filters at the end of a lifetime, which are often clogged, and thus, display higher Δp . In the last case, filtration could be performed by cake filtration which could still reduce PM concentration, but have high risks of bacteria and mold accumulation in the cake layer, which can then be released into the air (Bourrous et al., 2016). In addition, cake filter necessitates high energy to overcome the pressure drop across the filter device, which is not environmentally compatible, due to its associated high carbon footprint. In order to have a good evaluation on filter quality (P. Li et al., 2014), other parameters should be taken into account as well, such as efficiency of a single fiber then of the whole filter, pressure drop, filter lifetime, PM retention capacity, etc.

The pressure drop is defined by the resistance of the whole filter structure to the airflow. This parameter is indispensable for estimating the lifetime of a filter and for the environmental issue as a high-pressure drop across the filter calls for high energy input to operate the system. As a fiber filter is constituted by many small fibers, the general pressure drop will be the total of drag forces exerted by air on each of the single fibers. Davies (Davies & Paulus, 1973) and Li (P. Li et al., 2014) highlighted the equation Eq. 12 for pressure drop calculation, with void fraction limit $0.006 < \alpha < 0.3$.

$$\frac{\Delta p}{z} = \frac{\eta \cdot U \cdot 64 \cdot \alpha^{1.5} \cdot (1 + 56 \cdot \alpha^3)}{d_f^2} \quad (\text{Eq. 12})$$

With Δp (Pa) the pressure drop of a filter which has a thickness z (m), fiber volume fraction α (-) and diameter d_f (m). The airflow is characterized by velocity U (m. s⁻¹) and dynamic viscosity η (kg. m⁻¹. s⁻¹). In normal conditions (no PM leakage during filtration), pressure drop increases with filtration duration due to the pores plugging as a function of the solid PMs accumulation. At a certain time, particles accumulated forms on the filter surface a layer strengthened by filter structure. This phenomenon is called cake layer or clogging filtration. Depending on fiber and particle size, clogging situations can be defined differently. i.e., HEPA filters (Bourrous et al., 2016; Penicot et al., 1999), clogged by solid particles (Song et al., 2006), clogged by liquid particles (Contal et al., 2004; Frising et al., 2005). The variation of pressure drops and the holding capacity, also lifetime of a filter depends on many parameters, such as PM concentration and nature, flow viscosity and velocity, etc. As the target of active filtration can be various, i.e., outdoor spaces, underground or semi-open parking or train station, household and building ventilation, hospital or chemical hazard, biohazard risks, etc., filter type and material can be selected in order to adapt the user requirements and economical yield. In most cases, filter characteristics like fiber diameter, packing density (fiber volume fraction), filter thickness decide whether or not a filter has a good capacity of PM penetration and retention (Davies, 1974).

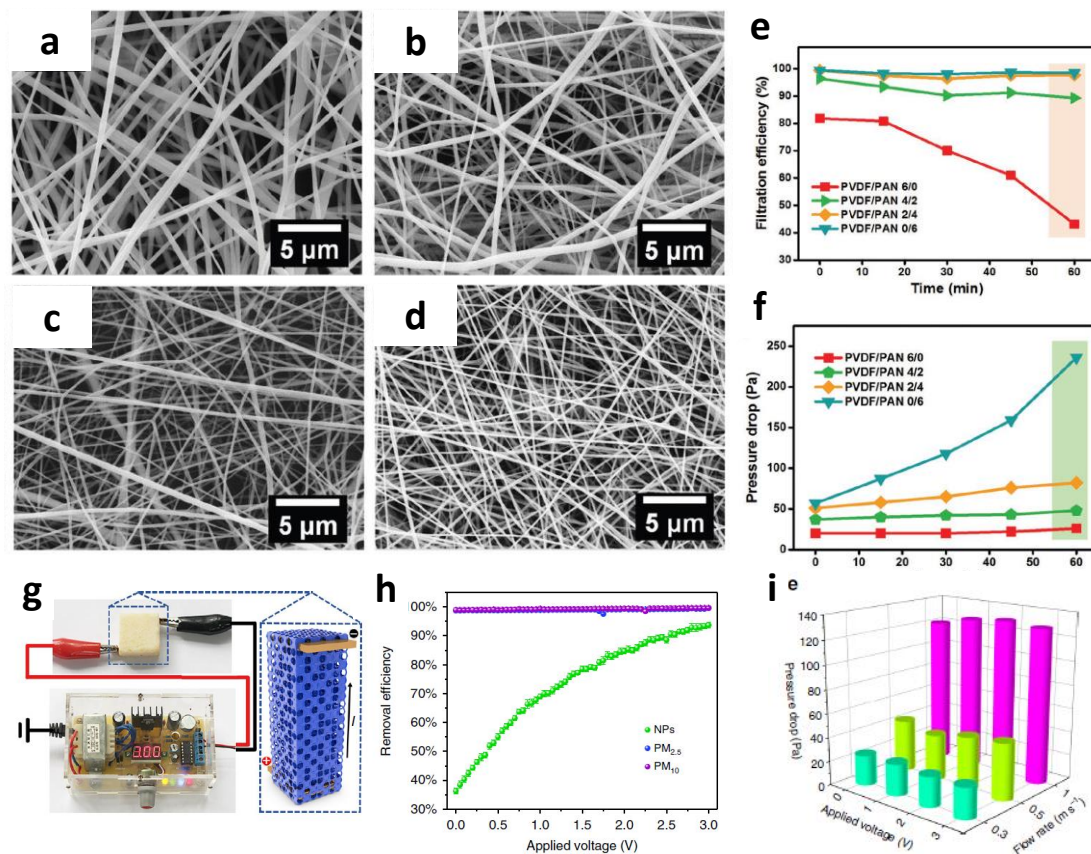
Besides air filters in HVAC systems, active outdoor air filters are installed in urban areas as a temporary remediation for reducing localized PM pollution. Devices of active filter function by air aspiration can provide the reduction of PM and other pollutants in urban area, especially at locations with dense populations and low air refreshment through weather (wind,

rain). Precisely, 17 of Mann+Hummel outdoor air filter cubes can purify $170,000 \text{ m}^3 \cdot \text{h}^{-1}$ air by reducing 10.4 % ($6.3 \mu\text{g} \cdot \text{m}^{-3}$) at 16 m away off the measurement station, of PM_{10} near the federal highway B14 at Stuttgart, Germany (Bächler et al., 2021). Or the giant filter-contained updraft tower in Beijing, China (Cao et al., 2018; D. Tan et al., 2017) was estimated to reduce the local concentration of 6.2 % PM_{10} in average ($6.72 \mu\text{g} \cdot \text{m}^{-3}$ out of over $100 \mu\text{g} \cdot \text{m}^{-3}$ PM_{10} concentration) in 2012. A similar tower was also built in Xian in Shaanxi Province, China (Fig. 1G) (Cao et al., 2018). Since becoming operated in 2017, the city air purifier tower has noticeably reduced harmful $\text{PM}_{2.5}$ particles in the surrounding 2.6 square mile area. It is worthy to note that while not eliminating air pollution, the tower provides cleaner air in its immediate vicinity. The different active air filtration devices have also been developed across China to provide residential fresh air through the abatement of $\text{PM}_{2.5}$ from outdoor, especially during cold weather where PM emitted from residential heating is at its highest level (X. Zhang et al., 2021). In China, which frequently faces outdoor air pollution period, active development of vehicles cabin air filters (VCAFs) is also underway to prevent the passengers from inhaling PM passing from the outdoor environment (Lim et al., 2021; C. Wang et al., 2024). Indeed, passengers in the car not only being exposed to the ambient PMs but also to a local ultrafine particles (UFPs), which were released by the exhaust outlet of the vehicle ahead. Due to the close distance, especially during traffic jams, these UFPs are not dispersing away and remain in the vicinity of the traffic lane inducing a local pollution.

Another most polluted country, i.e., India, has also developed different active air filtration to jugulate the problem of outdoor air pollution by PMs as among the world's 30 cities with the most air pollution, 21 are in India. India has developed Dubbed Verto, a 5.5 meter-tall device to trap nitrogen oxide and fine particles in New Delhi's Sunder Nursery. Such device displays a filtration capacity of 600,000 cubic meters of air a day and can be scaled up to clean large public areas in order to reduce the level of air pollution in the city (Holland, 2023). Zhao et al. (X. Zhao et al., 2017) have recently reported the use of electrospinning composites, i.e., superhydrophilic polyacrylonitrile/silicon dioxide fibers and hydrophobic polyvinylidene fluoride fibers, to efficiently capture $\text{PM}_{2.5}$. the representative SEM micrographs of the PVDF/PAN confirm the random orientation 3D membrane (Fig. 4A-D). The morphology of the as-prepared fibers is significantly influenced by the PVDF/PAN jet ratio during the processing. The introduction of PAN fibers also significantly improves the filtration efficiency compared to PVDF alone, due to the decay of its surface potential consecutive to the presence of humidity in the flow (Fig. 4E). However, the high hydrophilicity of the composite could

induce strong interaction with water molecules presence in the filtration medium, which dispersed onto the hydrophilic surface via capillarity (Gostick et al., 2006; X. Xiao & Qian, 2000)

Recent developments have made use of a combination of ionic liquids (ILs) and polymers to generate new filtration devices for $PM_{2.5}$ and PM_{10} capture. The incorporation of ILs into the polymer induces a significant conductivity enhancement. So the ILP (ionic liquid polymer) composites can generate a high electric field under a low voltage (Teo et al., 2017), which results in the attraction of particulates, i.e., $PM_{2.5}$ and PM_{10} , through electrostatic interactions to influence the motion of particles in a flow stream (L. Zhang, Yuan, et al., 2019, p. 201). Recently, Zhang et al. (G.-H. Zhang et al., 2020) have reported a high performance particulate matter filtration for nanoscale PM_1 removal by a self-powered air filter based on the use of an ionic liquids-polymer (ILP) composite distributed onto a sponge of melamine-formaldehyde (MF) to generate a porous ILP@MF filter. Such porous structure allows the polluted air to flow adequately through the sponge channels, leading to a high trapping removal at apparent low-pressure drop. A schematic representation of the filtration device is depicted in Fig. 4G. The removal efficiency of the different particulates by the filter is illustrated in Fig. 4H as a function of the applied voltage. Fig. 4I displays the relationship between the pressure drop of the filter under various applied voltage (0, 1, 2, and 3 V) and at different air flow rate (0.3, 0.5, and 1.0 $m \cdot s^{-1}$). The average pressure drop of the filter with a 3V voltage is only 26 Pa at a flow rate of 0.3 $m \cdot s^{-1}$, which is far lower than the fine standard of the US Department of Energy (ca. 325 Pa at an air flow rate of 5 $cm \cdot s^{-1}$). The reported results clearly evidence the relentless pace in the development of new active filtration devices for the reduction of the PM pollution problem.



II.3. Passive filtration (tree, passive house, etc.)

Vegetation and passive house aeration are commonly known as passive and eco-friendly solutions to reduce air pollution, including PM concentration (Tang, 2023; P. Thakur, 2019). While trees and green walls capture PM in air by dry deposition on vegetation surface (Ysebaert et al., 2021), passive air regulation is based on aerodynamics of natural convection by heat transfer (Nazaroff & Cass, 1989a).

Beside their undeniable benefits for human health and the environment, many studies discussed the efficiency of PM reduction of trees and vegetation (Budaniya & Rai, 2022; Heshmatol Vaezin et al., 2021; Pettit et al., 2017, 2020; Steinparzer et al., 2023; Terzaghi et al., 2013). Green roofs and facades, tree canopy, herb, etc. have a capacity of PM capturing and retaining in a passive way (Popek et al., 2022). With the variation in leaf traits, climate zones and urban planning, PM removing capacity is, nonetheless, different between species, PM sources, and seasonal period (Petroff & Zhang, 2010). The trapping also depends on the surrounding weather, hot weather with high humidity or tempered weather with low levels of humidity. Indeed, dry deposition mechanisms could be applied for most cases, as illustrated in Fig. 5A. The description of sedimentation, impaction, interception, diffusion and resuspension procedures are very likely the same as for the particle's deposition on a fibrous filter, presented previously in II.1 part of this paper.

In addition to aesthetic decoration, noise and heat reduction, vegetation is used like a barrier in order to prevent exposure to PM pollution exhausted from urban traffic. Many projects of PM monitoring and leaf traits were studied. For example, the green roof in Manchester (Speak et al., 2012) and living wall of Stoke-on-Trent in the UK (Weerakkody et al., 2018); green wall on the street canyon of Modena, Italy (Donateo et al., 2021), cf. see figures Fig. 1E, 1F, 6A, 6B. Tree canopies of windbreak barriers in Zhangbei, China, were analyzed to reduce dust from natural or agricultural airborne deposition (Chang et al., 2019). The most studied tree part for PM trapping is leaves, which is commonly divided by broad or needle-like leaves (conifers). Leaf Area Index (LAI) is the ratio of total leaves surface with their covering ground area (equation Eq. 13). The higher LAI number is, the higher the surface covering and PM contact, and therefore, the higher capture capacity.

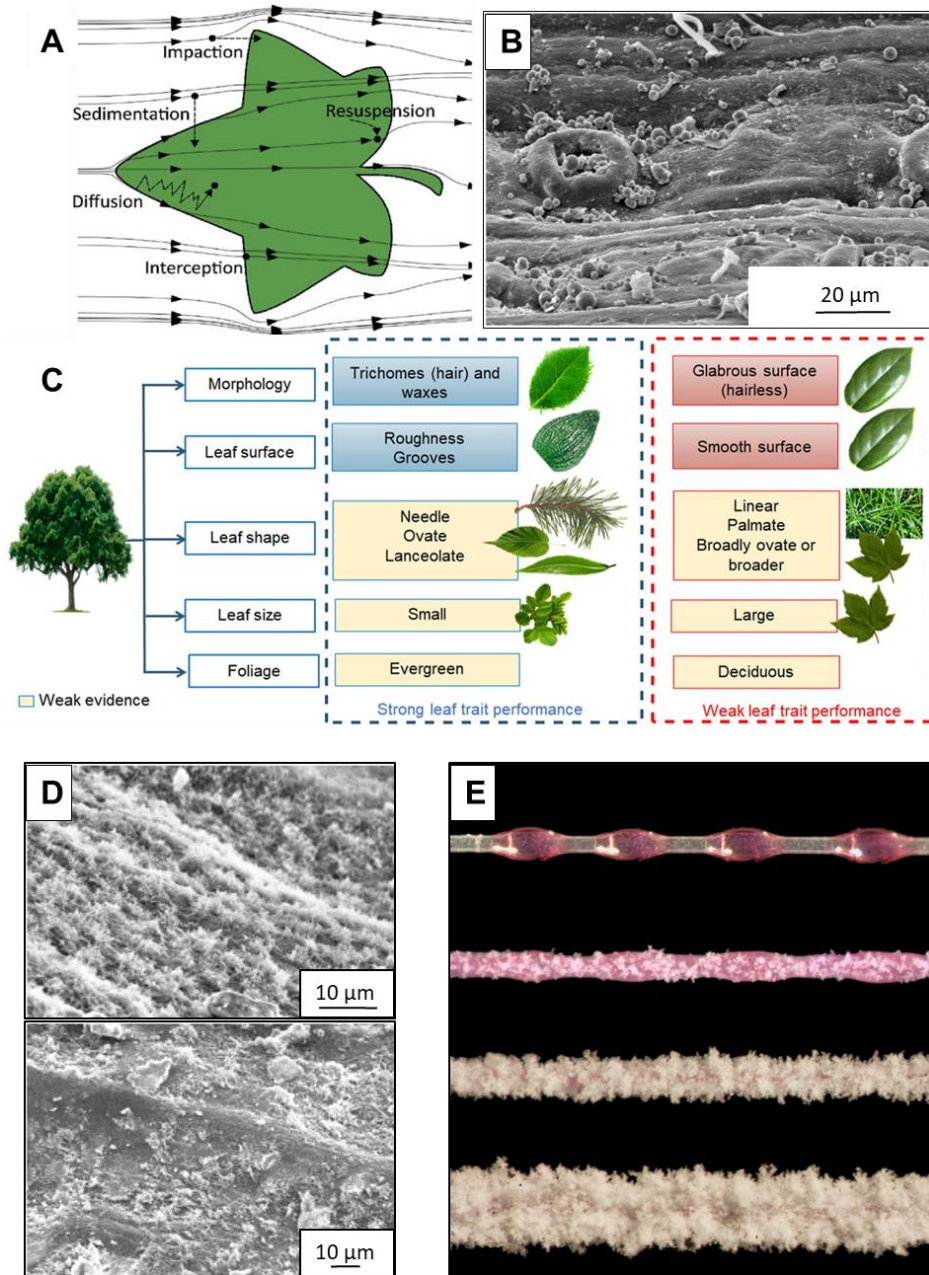


Figure 5 | **A.** Illustration of dry deposition mechanisms of PM on leaf traits (Ysebaert et al., 2021) – Copyright with Elsevier license number 5966420316217. | **B.** Micrograph of *Quercus acutissima* leaf surface after 28 days exposed to $300 \mu\text{g. m}^{-3}$ of fly ash concentration (J. Lee et al., 2024) – Open access copyright. | **C.** Global comparison of leaf traits and tree species in PM trapping performance in urban areas (Corada et al., 2021) – Copyright with Elsevier license number 5966411108614. | **D.** Micrographs of surface of *C. deodara* with wax crystal formed on the leaf surface (above) and PM accumulation after 6 months of exposure at outdoor environment (below). (H. Wang et al., 2013) – Copyright with Springer Nature license number 5977130771256. Wax and ridges on the leaf surface are considered to increase the PM retention quantity | **E.** Extract of different steps of $2.1 \mu\text{m}$ silica mono-spheres PM loading on a $44 \mu\text{m}$ nylon fiber, coated by dyed WD-40 oil (T. K. Müller et al., 2014) – Copyright with Elsevier license number 5966430356227. The oil layer was considered to prevent rebound forces of PM on the fiber.

Quantification of PM flux deposition rate [$\text{Mass} \cdot \text{Length}^{-2} \cdot \text{Time}^{-1}$] is estimated by equation Eq. 14. Models of leaf traits, PM deposition procedure, PM resuspension, water storage, rainfall wash off, etc. are further described in the works of Nowak et al. (D. Nowak et al., 2008; D. J. Nowak et al., 2006, 2013), Yseabert et al. (Ysebaert et al., 2021) and Gaglio et al. (Gaglio et al., 2022). With $\sum \text{Surface}_{\text{leaf}}$ the total of one-sided surface of each leaf count in the study (m^2), $\text{Area}_{\text{covered ground}}$ as the ground area covered by these leaves (m^2), PM_{flux} for the PM flux deposition rate as a function of time ($\text{g} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$), the deposition velocity as V_d , j as the deposition parameter (-), and C as the PM concentration ($\mu\text{g} \cdot \text{m}^{-3}$).

$$\text{LAI} = \frac{\sum \text{Surface}_{\text{leaf}}}{\text{Area}_{\text{covered ground}}} \quad (\text{Eq. 13})$$

$$\text{PM flux (t)} = V_d(t) \cdot j \cdot C \cdot \text{LAI} \quad (\text{Eq. 14})$$

The deposition velocity coefficient j is equal to 3 in cases of needle-like leaves, and < 3 for the most of broad leaves (Gaglio et al., 2022). The tree canopy and other vegetation have various PM reduction potential between species. Needle-like leaves species form increases PM deposition and recapture after rainfall, also prevent them from resuspension (Andrade et al., 2022; L. Chen et al., 2017; Corada et al., 2021; Sgrigna et al., 2020). Some species with substrate layers, rough or hairy surface (Fig. 5C) so-called trichomes, leaf wax, or epicuticular wax have higher efficiency in PM capturing than smooth and linear surface (Leonard et al., 2016; Sæbø et al., 2012). This coating layer could reduce impaction of PM with the filter or leaf surface (Fig. 5D), reducing probability of particle rebound, increasing particle-coating-surface bonds by capillary forces, similar in polymer coating on fiber PM filter experiments (Byun et al., 2020; Davis et al., 2002), cf. see Fig. 5E.

A case study (Oxford Analytica, 2017) of PM reduction in India mentioned the method of using mist diffusion canons for neutralizing the high PM concentration in air (Anti-SMOG gun – cf. Fig. 6C). This method also represents PM reduction by wet deposition. The mist diffusion has double interests: precipitation of PM in suspension, plus scrub off PM on leaf and road surfaces. The wet deposition after these artificial rains can be considered as a temporary solution for reducing the high local PM concentration. Otherwise, this method cannot radically remove PM, because particles can probably re-suspend once dried, or re-join the run-off water to the sewer system and pollute the water cycle, including underground and oceanic water.

PM residues on leaf surfaces could be rinsed by rainfall, which reduces PMs density on the leaf surface but does not remove PM in ecosystems and remains in circulation in other areas as wastewater treatment plant is not able to remove all of these PMs in the entrance stream. Some studies (Kwak et al., 2023; Tang, 2023; L. Zhang, Zhang, et al., 2019) consider that natural cleaning is a way to wash off PM and mark the beginning of a new filtration cycle. Nevertheless, PM once falls off the leaf, could be back on suspension, or rejoin run-off water and make another pollution type such as microplastic or water contamination, as the complete removal is not possible (L. Chen et al., 2017; Kjær et al., 2011; Sénéchal et al., 2015). As many PM sources are from anthropogenic activities, accumulation of PM in rain or run-off water creates a big concern for environment and human health (Boucher & Friot, 2017). Recent publications pointed out that microplastics from tires wear are one of the major sources of anthropogenic pollution by microplastic into the ocean (De Souza Machado et al., 2018; Kooi et al., 2016; Sommer et al., 2018). Indeed, such microplastics are so small with low surface reactivity to be efficiently removed by traditional wastewater treatment plant. It is now recognized that microplastics can enter different living systems and end-up in daily consuming food and beverages as recently demonstrated in some recent reports (De Souza Machado et al., 2018; Neale et al., 2021). The transmission chain is presented in Fig. 6D, showing the integration of microplastic through different intermediates including the food chain. In addition to the microplastics, other inorganic components also contribute to the pollution of the water source: metals and alloys from break wear, and carbon nanoparticles from road abrasion. In their studies (Gaglio et al., 2022; D. J. Nowak et al., 2006), authors simulated and certified the undeniable benefits of vegetation in PM filtration. A zone totally covered by the tree canopy can have 8 % less of PM₁₀ pollution than an exposed one. Thus, vegetation passive filtration cannot provide a radical solution, for a full-scale eradication of PM out of ecosystems. In conclusion, air pollution mitigation by vegetation can be summarized by green walls (Tang, 2023), green roofs (Pons Fiorentin et al., 2024), urban forest (Han et al., 2020), leaf traits and vegetation barriers (Barwise & Kumar, 2020; Corada et al., 2021), cost benefice (Manso et al., 2021; Teotónio et al., 2021). In their studies, Agranovski et al. (Agranovski et al., 2002; Agranovski & Braddock, 1998; Agranovski & Whitcombe, 2001) and others (T. Müller et al., 2014; Raie et al., 2023) described the improvement in PM capturing of fibrous filters after applying as a coating on the fiber surface, which could be related to the similar phenomenon observed on leaf surfaces.



Figure 6 | **A.** Green roof planted on a plant in Michigan, US. Photo credit: Bradley Rowe (Rowe, 2011) – Copyright with Elsevier license number 5966490500078. | **B.** Living wall for traffic-generated PM capturing in Stoke-on-Trent, UK (Weerakkody et al., 2018)– Copyright with Elsevier license number 5966490740990. | **C.** Anti-SMOG gun, a temporary solution in Delhi City, India for reducing air pollution by wet deposition after mist spray on outdoor air. Image source: IndiaToday | **D.** The different processes in the generation of microplastic and its ingestion by different living organisms. Image credit Barbara Aulicino (Mason, 2019).

In a recent study (Trinh et al., 2024), the oils' sticky property keeps oil and PM on the fiber without detaching from the fiber. The main advantage of this oil-coated filter is that it can be operated under passive filtration mode where no external energy is required. The oil-coated structured filter displays a relatively high total PM mass captured with various sizes, especially PM₁ which is the most dangerous for human health (Fig. 7A to 7C). In addition, the spent filters can be regenerated by washing away the oil layer containing PMs and to be re-impregnated with a new oil layer and reused. The possible regeneration of the spent filter represents an advantage by reducing the associated waste and to mitigate the environmental impact. In such study, the spent filter was washed with water containing surfactants to remove the oil layer and the trapped PMs. The wastewater is further processed to remove the PMs before further processing. According to the authors, the PM trapping capacity remains similar between the fresh and regenerated filter (Fig. 7D).

Passive houses are commonly designed for the thermal comfort of inhabitants, or for building structures which are not compatible for the installation of a ventilation system (Z. Jiang et al., 2023; Pabiou et al., 2015). In this practice, indoor air can be exchanged with outdoor air by windows, aeration holes, with or without an air filter in between. The hourly air exchange rate (ACH , in h^{-1}) can be expressed as presented in equation Eq. 15, with Q as the airflow rate ($m^3 \cdot s^{-1}$) and V_{room} for room volume (m^3). A healthy air change rate should be kept at least over 0.35 of outdoor air per indoor air per hour, recommended by the American Society of Heating, Refrigerating and Air Conditioning Engineers - ASHRAE standard 62.1 (ASHRAE, 2022).

$$ACH = \frac{Q \cdot 3600}{V_{room}} \quad (\text{Eq. 15})$$

In modern passive house (without active ventilation systems), air exchange with outdoor environment is performed through the window and passive lift/hole for air shifts, cf. Fig. 7C_{iii}. This design guarantees a minimum air circulation in the room while keeping the windows closed, and without perturbing the thermal isolation of the room (Hoffmann et al., 2021). For favoring air exchange, windows can often be or permanently opened, giving the possibility to apply the passive window paper filters (Yee et al., 2023), cf. Fig. 7E.

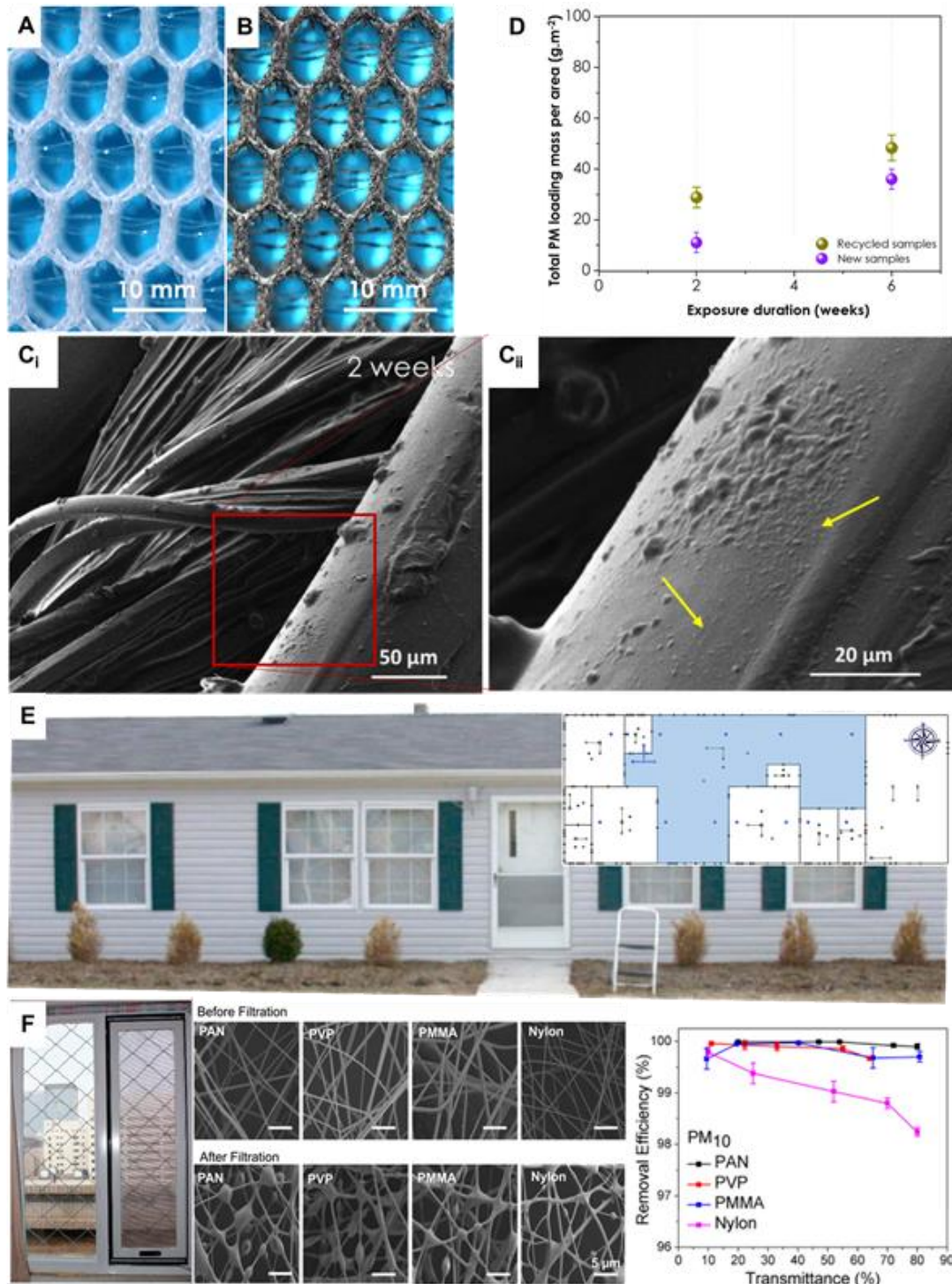


Figure 7 | **A** and **B**. Digital photo of fibrous filter structure coated by a vegetable oil coating layer, before and after being exposed to outdoor air pollution. | **C_i** and **C_{ii}**. Microscopic image of fiber after 2 weeks exposed at a prototype in Strasbourg, France. Image is showing captured PMs of various sizes. | **D**. Comparison of filter performance between new and regenerated samples. Images source: (Trinh et al., 2024) - Copyright with Elsevier license number 5966430045511. | **E**. Hanji paper window as passive filter setup (using MERV8 – filter with a minimum efficiency reporting value of 8). (Yee et al., 2023) – Copyright with Elsevier license number 6017550045399. | **F**. Innovative blow-spinning nanofibers on window screen for passive PM filtration (Khalid et al., 2017) – Open access copyright.

In high-polluted regions (Ji et al., 2023) reviewed various advance materials of air filtration, applicable for both passive and active filtration. Depending on the financial investment that these high potential materials could be developed for larger-scale infrastructure. In the same publication, the authors also highlighted smart, transparent windows (cf. Fig. 7F) that can process PM trapping by using a specific layer of nanofiber that can easily install and remove, without excessively modify the design or interfere the airflow.

Concerning PM regulation of the indoor environment, isolation is the most common method to block PM pollution from outdoor, but cannot prevent PM accumulation from indoor sources (Ścibor et al., 2019). A totally closed window with no leak can block nuisances like PM, insects, heat and traffic noise. Meanwhile, reports (Hoffmann et al., 2021; Lai et al., 2018; Verbruggen et al., 2021) pointed out that even in cold climate, open shortly the window every day can help to improve indoor air quality. In fact, PM concentration and other compounds like CO, CO₂, HAP, etc. can rise drastically in a short period due to human activities like wood heating, cooking, smoking, etc. The air exchange allows the rapid reduction of the PM and VOC in indoor area and thus prevent health problem for the people living in these close areas. In absence of physical perturbations in a sufficiently long period, particles could deposit on the floor due to gravitational settling (Christoforou et al., 1994, 1996b; Nazaroff & Cass, 1989b). The adsorption of PM on a surface is described in the following reports (Nazaroff & Cass, 1989a; C.-J. Tsai et al., 1991; R. Tsai & Lin, 1999). Nevertheless, the adhesion by electrostatic forces or Van-der-Waal interactions are mostly weak connections, and particles could be put on suspension again by any movements of people, objects, airflow, etc. Without a mechanical ventilation system, window regulation is a common use for improving indoor air quality but this method is closely dependent to the outdoor air quality, which is not always, meets the WHO recommendation in some countries. Many research and case studies highlighted cross ventilation (natural convection) which is based on temperature gradient and flow exchange between indoor and outdoor air. i.e., Fig. 8A represents a simple study case of Christoforou et al. (Christoforou et al., 1996a). However, in highly polluted area, especially during the winter, when outdoor air is saturated with PM, the air exchange between outdoor and indoor remains unsafe due to the large concentration of PM from outdoor which will enter the house.

For individual building or passive house design, passive air circulation could be created by the pressure gradient or by heat-transfer law (Kao et al., 2009; P. Thakur, 2019; Zhivov et

al., 2020). Air circulates naturally from higher to lower pressure zones. Meanwhile, cold air with higher density has a tendency of sinking while hot air moves up, called convection or buoyancy effect (Z. Jiang et al., 2023). The following equations represent different approaches of natural air circulation in the study case of Christoforou (Christoforou et al., 1999):

$$\frac{1}{2} \cdot \rho_o \cdot U_2^2 \cdot \text{Coeff}_K + \frac{1}{2} \cdot \rho_a \cdot U_1^2 \cdot \text{Coeff}_K = g \cdot \Delta h \cdot (\rho_a - \rho_o) \quad (\text{Eq. 16})$$

With ρ_o and ρ_a represent the density of outdoor and indoor air ($\text{kg} \cdot \text{m}^{-3}$), respectively; U_1 and U_2 the air velocity ($\text{m} \cdot \text{s}^{-1}$) at the first and second positions illustrated in figure Fig. 8A, respectively; the pressure drop coefficient Coeff_K (-) for flow through an opening is depended on the shape and size of the duct (Legg, 2017). In equilibrium, the total pressure drop of the exchanging flows is proportional to the gravitational acceleration g ($\text{m} \cdot \text{s}^{-2}$), and Δh (m) the differences of height of two flows (entering and exiting air).

For the hypothesis in this 2nd approach, air density is considered the same for both outdoor and indoor air; specific heat of air measured at constant pressure and volume are, in order, c_p ($\text{J} \cdot \text{K}^{-1} \cdot \text{kg}^{-1}$) and c_v ($\text{J} \cdot \text{K}^{-1} \cdot \text{m}^{-3}$); room volume is V_{room} (m^3); Q_t is the total airflow through the structure at time t ($\text{m}^3 \cdot \text{s}^{-1}$); $heat_i$ ($\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$) stands for the heat transfer coefficient for flow over the i^{th} surface S_i (m^2).

$$\rho_a \approx \rho_o \approx \rho \text{ and } \frac{\rho_a - \rho_o}{\rho_o} \neq 0 \text{ and } \frac{\rho_a - \rho_o}{\rho_o} \approx \frac{T_o - T_a}{T_o}$$

$$\rho \cdot c_v \cdot V \cdot \frac{d}{dt}(T_a) = \rho \cdot c_p \cdot Q_t \cdot (T_o - T_a) - \sum_{i=1}^n heat_i \cdot S_i \cdot (T_a - T_w) \quad (\text{Eq. 17})$$

Direction of convection heat transfer between indoor and outdoor air depends on the difference of temperature, which can vary between day and night-time. Furthermore, Zhang et al. (H. Zhang, Yang, et al., 2021; T. Zhang et al., 2018) evaluated the efficiency of PM and other pollutants removing capacity of natural or mechanical ventilation or the combination of 2 methods. Depending on the house direction, PM concentration, weather, etc., the combination of cross and forced ventilation proved to be an effective way to improve indoor air quality.

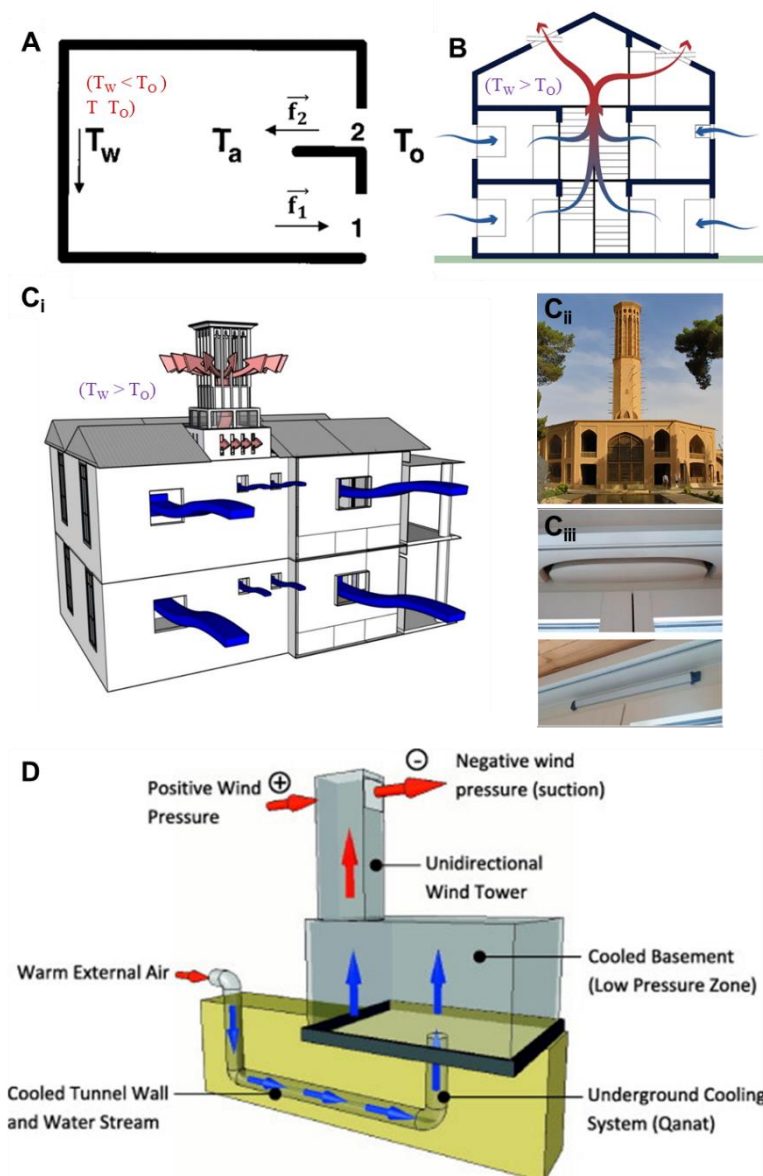


Figure 8 | **A.** Cross section of a simplified room with doors or windows at two elevations ($h_1 < h_2$). T_o is the outdoor air temperature. Room temperature is T_a , and T_w is wall temperature. Black arrows indicate the direction of airflow movement. In this study case, $T_w < T_o$. If not, the air will flow in the opposite direction. U_1 , U_2 are in order flow velocity at position 1 and 2, respectively (Christoforou et al., 1999) - Copyright with Taylor & Francis order number 5971251382258 | **B.** Illustration of passive house aeration. Red arrows indicate hot air while blue arrows represent cool air. Image source: (Didier Jordan, 2023). | **C. i)** Schema redrawn by the authors, based on publication of (Jomehzadeh et al., 2020). Outdoor air is cooler than indoor. **ii)** Iran's windcatcher system Badgir, digital photo credit of Bernard Gagnon. **iii)** Passive window ventilation opening, a small air inlets integrated in the window frame in modern house design, for keeping the standard air exchange rate even when the window is closed (Hoffmann et al., 2021) - Copyright with Elsevier license number 6017711322757. | **D.** This system can also be integrated with Qanat in purpose of cool down the inlet air by underground water canal, the rising hot air is discharged by the badgir column (Hughes et al., 2012) – Copyright with Elsevier license number 5966510293222.

Ancient structures in the hot climate zones around the world can have aeration system which maximizes air exchange and provide fresh air for indoor without the need of any energy source other than natural air flow and the air current created by the difference in pressure between indoor and outdoor environment. As illustrated in Fig. 8A and 8B, thick wall of stones (natural caves or the Egyptian pyramids for example) can block the penetration of heat from outside while continuing to cool down the incoming hot air (Christoforou et al., 1996a). Another good example is the Badgir air exchange column of Iran's architecture (Fig. 8C and 8D). This design can be combined with the underground water system (Qanat) for regularizing the temperature in the building by using 100% of natural air circulation (Jomehzadeh et al., 2020). These ingenious structures still have many values and inspiration to modern building design.

In some circumstances, when mechanical ventilation cannot be installed due to financial or technical issues, passive air filters could be instead installed for reducing PM concentration incoming from the air flow. Hereby study cases represent the installation of a basic air filter on the window and the door for passive PM filtration: transparent nanofibers e-spinning coated by C or Cu as transparent air filter on the window (C. Liu et al., 2015); natural convection passive air filter in Yungang Buddhist cave temples, China (Christoforou et al., 1996a, 1999); paper as PM filters for both indoor and outdoor air on the window (Yee et al., 2023); wool-based indoor filter (McNeil & Zaitseva, 2015). Filtration efficiency in these cases depends on selected materials for filters and also weather conditions such as wind velocity, outdoor pollution concentration, etc. The installation of passive air filters was proven to have the ability to reduce PM concentration in local area. Passive filter cannot compete with active ones for the efficiency in the PMs capture. However, such a low-cost filter could play a complementary role to prevent the outdoor-indoor PM exchange, and especially PM_{2.5} from traffic, which is one of the most contributors to air pollution in cities. While modern buildings prefer to have a complete HVAC system for all the building, the complexity of installation and maintenance for individual house (periodically replacing a spent filter with a new one at every window) remains a big drawback for passive indoor air filtration. The following section will have a closer look at the costs benefits, and also drawbacks of the mentioned air filter systems.

II.4. Energy consumption, costs benefits and regenerability

Modern air filter materials do not incline only to maintain a low-pressure drop while having high filter efficiency. Depending on market demands, many materials with special abilities were studied for air filters application. These studies (H. Liu et al., 2020; Mohammed et al., 2022; J. Xiao et al., 2018) reviewed main filtration methods and materials in the actual market and developing technologies. Some examples of developing advanced materials as alternatives for classic woven filter: electrospinning aluminium nanofiber which gives filter thermal stability and flexibility (Y. Wang et al., 2014), various polymers electrospinning (Robert & Nallathambi, 2020; Russo et al., 2022; Sundarrajan et al., 2014) is also under development as a flexible, multi-usage, polyvalent technique to develop nonwoven air filter membranes. C-based material filters have also been developed: carbon nanotubes (CNTs) on active carbon fiber (S. Yang et al., 2017), graphene coating membranes (Jung et al., 2018; Karanjikar et al., 2022), etc. as high porosity and high electrical conductivity materials for membranes air filters (Fig. 8N and 8O-8T). However, nanocarbons as filters are not unanimously recommended as their degraded small particles could diffuse in air and pose health problems. Other filters use electricity field for triggering electrical coagulation PM filtration (Bai et al., 2018; Y. Gao et al., 2023; Jeong et al., 2017) or UV light integrity in PM filters for antibacterial properties (P. Li et al., 2024), and particular materials with controlled wettability (capacity of holding or releasing PM depending on humidity) (P. Li et al., 2013), or flame retardancy (K. Liu et al., 2018) for specific usages. Filter material costs may vary on a relatively large range based on raw materials, production, logistics, sale and marketing. A careful choice of filter material, which is close to the end-use objective, could valorize the cost-benefit ratio.

Liu and co-workers (C. Liu et al., 2015) have developed a series of electrospun filters for the reduction of indoor PM pollution and also to prevent outdoor pollution from entering the indoor area. The small diameter of the electrospinning polymer fibers and the high entanglement between them provide high filtration efficiency, alongside with good optical transparency, low resistance to airflow and light weight, to the filter as depicted by the results presented in Fig. 9A-9J. In such filtration derive captured particles could move along the polyacrylonitrile (PAN) nanofibers to form aggregate and larger particles leaving behind space for additional capture. The long-term performance of the filter was evaluated under relatively harsh conditions, i.e. $PM_{2.5}$ index > 300 and a mild wind condition (< 1 miles per

hour). The filter still displays a high PM capture efficiency for at least 100 h of operation (Fig. 9K). SEM analysis evidences the formation of aggregates up to 20–50 μm (Fig. 9L and 9M). The aggregates are well attached to the filter as no detachment was observed using clean air to blow through the spent filter. The filter was also used as a scavenger to prevent outdoor pollution during the indoor-outdoor air exchange as it allows the purified air to enter the house while trapping most of the PMs from outdoor air. However, the electrospinning filter is relatively fragile and thus, recycling is not straightforward which renders the device less attractive compared to others recyclable ones.

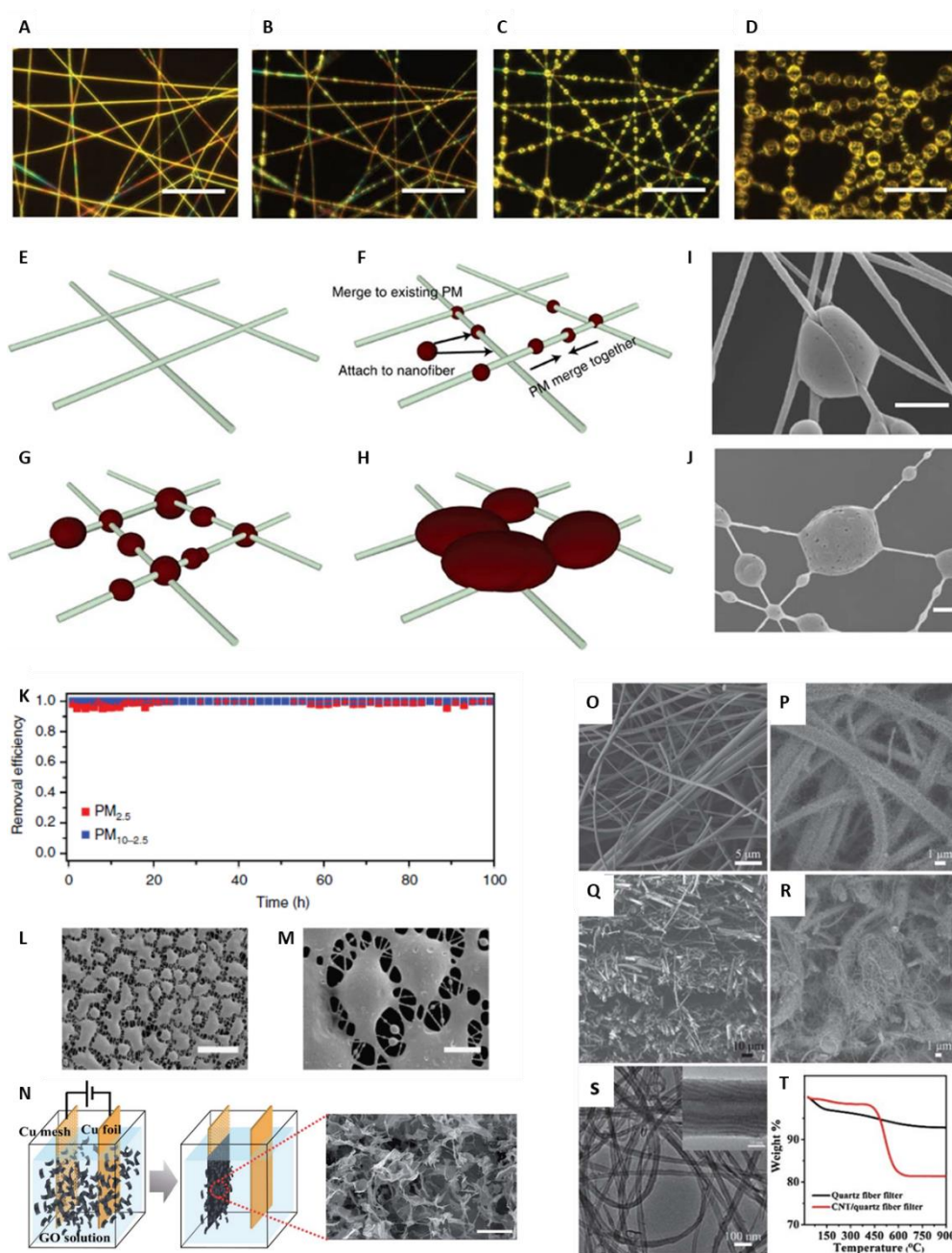


Figure 9 | In situ time evolution study of PM capture by PAN transparent filter. | (A–D) In situ study of PM capture by PAN nanofibre characterized by Optical Microscope showing filter morphologies at different time sequences during a continuous feed. Scale bars, 20 μm . The timescales are in order 0, 5, 120 and 600 s, respectively. | (E–G) Schematics showing the mechanism of PM capture by nanofibrous filters at different time sequences. | (I) SEM image showing the detailed morphologies of attached soft PM that formed a coating layer wrapping around the PAN nanofibre. Scale bar, 1 μm . | (J) SEM image showing that the nanofibre junction has more PM aggregated to form bigger particles. Scale bar, 1 μm . PAN transparent filter long-term performance and field-test (Beijing) performance. | (K) The long-term $\text{PM}_{2.5}$ and $\text{PM}_{10-2.5}$ removal efficiency by PAN transparent filter of 70% transmittance under continuous hazardous level of PM pollution. | (L, M) SEM showing the PAN transparent air filter morphology after 100-h PM capture test. Scale bars, 50 and 10 μm , respectively. Images source A-M: (C. Liu et al., 2015) – Copyright with Elsevier license number 5977130239141 | (N) Fabrication of IMA-GO (ion-mediated assembled graphene oxide) air filter (Jung et al., 2018) – Copyright with Royal Society of Chemistry license ID 1578088-1. The displayed scale bar is 50 μm . | (O–T) Carbon nanotubes (CNT) based coating on Quart fiber (QF) (P. Li et al., 2013) – Copyright with Royal Society of Chemistry license ID 1578095-1. (O, P) in order, SEM images of the QF fiber and the QF coated by CNT respectively. (Q, R) SEM images of the cross-sections of the QF fiber then QF coated by CNT, respectively. (S) TEM images of the CNTs (the scale bar is 100 μm), inset: higher resolution of CNTs (the scale bar is 10 nm). (T) TGA traces of the pristine QF filter and the CNT/QF filter indicate the %weight loss in function of temperature. It proves the endurance of the CNT/QF to high heat.

Installation, maintenance and disposing process costs are dependent on filter quantity, life duration, and wages for hand labors. For individual household air filters and air conditioners, people usually change filters when they are clogged, or when dust accumulates around air vents. Conventional filters are expected to have a wide range of exposition time, from new to clogged filters. The duration depends on various factors, such as PM nature and concentration, airflow rate, filter efficiency (porosity, degree of entanglement) and pressure drop, etc. For example, HEPA filters attain their limit of life cycle when the pressure drop reaches 2 times of the initial value (Xu et al., 2014). The same reasoning is applicable for filters in the HVAC system, which assures air quality for a group of apartments, a house, or the entire building. After a certain exposure duration, pollutants such as dust, fungi, mold, but also bacteria and viruses start to accumulate on the filter which could alter indoor air quality as they can be released back from the filter due to the high-pressure drop (IAQ) (Aquino et al., 2018). HVAC systems filters are recommended to be changed depending on the filter lifetime, from 3 to 9 months of exposure, even not in the clogged state (Morgan et al., 2017; Moyer et al., 2007).

However, air filters should not be changed too often either, for minimizing the costs of materials and hand labor to install new filters and remove the used, which also generates waste if the filter cannot be recycled or reused. In the case of green walls and green facade, the cost is mainly for tree plantation and plant cares for long-term benefits (Manso et al., 2021). These costs vary in function of the filter or vegetation selected, HVAC type, and the local wage norms for laborers. Nevertheless, a customized estimation and trial should be realized before each air filter installation in order to have maximum economic benefits while keeping good Air Change per Hour rate (ACH - see part II.3 - section passive house filtration).

For every active air filter, including the individual house air purifier device and HVAC system, energy consumption is one of the major costs. As the air exchange needs to be kept permanently in function, energy consumption is closely related to air flow and pressure drop. The faster clogged the filter is, the lesser fan driven efficiency n (%), leading to more energy lost (G. Liu et al., 2017; Matela, 2006). Energy consumption in Wh can be estimated by equation Eq. 18. With Q , Δp , and t , respectively the inlet flow rate ($\text{m}^3 \cdot \text{s}^{-1}$), pressure drop (Pa), and filtration duration t (s).

$$\text{Energy}_{\text{consumption}} = \frac{Q \cdot \Delta p \cdot t}{n \cdot 1000} \quad (\text{Eq. 18})$$

On average, 20% of the total electricity used in buildings (which represents 10% of overall electricity consumed by human society) worldwide is attributed to air conditioners and electric fans for cooling purposes (IEA, 2018). In the same investigation, electricity systems in many countries are put in strained situations, caused by rising demands of electricity for household cooling appliances. For example, in some emerging and developing countries, power supply for some facilities and residences could be scheduled to be cut off in order to avoid shortening of energy in hot periods (Sasges & Ziegler, 2024). With the evolution of climate change and extreme weather, energy consumption for air conditioners and HVAC is skyrocketing. Predicting models estimated 6200 TWh of electricity for indoor cooling in 2050, three times higher than the consumption in the studied period (IEA, 2018). The choice of material or device of long life cycle before clogging, with the less energy consumption possible, should be carefully considered. According to such energy consumption, one can clearly state that reducing outdoor air pollution goes alongside with the reduction of energy consumption which could be both benefit for human health. Indeed, the reduction of outdoor

air pollution allows increasing the natural remediation of indoor pollution through natural air exchange, which could contribute to the reduction of associated energy consumption.

In order to limit environmental impacts by waste generation, the possibility of recycling the materials used as a filter is an important criterion for any sustainable structure. On one hand, passive filter methods such as passive house air regulation or vegetation facade rely on natural remediation of wind to renew air circulation, or rainfall to clean leaf surface before another filtration cycle. Even though the PM is removed from the house or leaf surface, these mechanisms are just transporting the PM from one location to another. On the other hand, new materials of active filtration technologies tend to be able to renew filter structure usage by removing pollutants after exposure time. Henning (Henning et al., 2021) highlighted two methods to regenerate air filters. Polymer based membrane and fiber can be regenerated up to 270 cycles of filtration-wash-dry (Kaang et al., 2020). The used filters are treated by a liquid of mixture from water, detergent (diluted acid or solvent), agitated by sonication for ensuring PM-solvent interaction. In such case, the trapped PM can be disposed and destructed instead of being transported from one area to another and finally, end-up in the sewer before releasing in ocean. Bacteria, virus, or other contaminants can be removed by dry heating treatment (>250 °C), even calcination (>500 °C). This method is applicable up to 50 times to thermal stability materials, like Ag/SiO₂-TiO₂ (B. Wang et al., 2019), or Pt/Al₂O₃ (Y. Wang et al., 2018). Biosource degradable materials also have great potential because of their eco-friendly aspect (Rana et al., 2023). However, the costs of production and maintenance still is the biggest drawback of these materials (Table 4).

Table 4 | Synthesis of cost benefits and drawbacks of some sustainable materials air filters systems using passive, active and hybrid methods. ND: No Data. MPPS: Most Penetrating Particular Size. Because each type of material/filtration method has various aspects and production procedures, **only one** example from a scientific article will be cited for each sustainable filtration material type.

Active: A Passive: P Both: AP Outdoor: O Indoor: I	Air filter material	Reference	Eff. MPPS removal (%)	Energy consumption (kWh.m ⁻²)	Pressure drop clean filter (Pa)	Costs	Status	Possibility of reuse/ recycle
P-I	Cross ventilation by passive house design	Air exchange indoor-outdoor (Z. Jiang et al., 2023)	ND	0	ND	House design	Market commercialized	Air is renewed by windows opening
AP-I	Energy management system active - passive ventilation	Passive house design + HVAC (Sorgato et al., 2016)	ND	35–344 kWh per month, depend on thermal comfort and air exchange rate	ND	Synergy of two methods	Study case	ND
P-O	Evergreen vegetation system	Green facades (wall, roof), living walls (Manso et al., 2021)	ND	0	ND	107 USD.m ⁻² green facades; 270 USD.m ⁻² living wall	Market commercialized	PM washed by rainfall or resuspended by wind
AP-O	Green wall + ventilation system	CityTree (CT) outdoor air filtration system (Donateo et al., 2021)	Up to 38% (active mode) thermal 4° cooling capacity	0.35 kWh per day, filter capacity 1250 m ³ .h ⁻¹ air each m ²	5–14 Pa at 0.1 m.s ⁻¹	CT installation and care	Market commercialized	Moss regeneration

A-O	Glass fiber Mann+Hummel	Glass fiber outdoor filter cube (Bächler et al., 2021)	10.4%	14.7 kW for 4 Mm ³ air per day	120 Pa at 2 m.s ⁻¹	ND	Market commercialized	ND
A-I	Metal E- spinning	Aluminium E-spinning fiber (Y. Wang et al., 2014)	> 99.8%	ND	239 Pa at 5.3 cm.s ⁻¹ (membrane calcined 700 °C)	ND	Laboratory test	Calcination (up to 900°C)
A-I	Polymer E- spinning	Poly- acrylonitrile/ SiO ₂ fiber (X. Zhao et al., 2017)	99.99%	ND	86 Pa at 5.3 cm.s ⁻¹	ND	Laboratory test	Washable by 1- methoxy-2- propanol
A-I	Carbone nano tube (CNT)	Composite CNT carbone active (Chitranshi et al., 2022)	> 90%	ND	High pressure drop, 290 Pa at 10 cm.s ⁻¹	ND	Market commercialized	Reusable (7 cycles tested)
A-I	Reduced graphene oxide (rGO)	rGO solution on Cu foil (Jung et al., 2018)	> 95%	ND	5 Pa at 1.1 cm.s ⁻¹	ND	Laboratory test	Washable by deionized water
A-I	Electrical Ag fiber	Ag nanowire percolation network on nylon mesh (Jeong et al., 2017)	> 99.99%	ND	10 Pa at 11 cm.s ⁻¹	ND	Laboratory test	Washable by deionized water + ethylene glycol + ethanol

However, for a long-term PMs reduction, reduction or PM trapping at the source should be prioritized. For example, Pui et al. (Pui et al., 2014) reviewed many studies of methods and industries filters for reducing PM emissions, mostly from coal-fired power plants in China. Wet- or electro-scrubber, electro precipitator (ESP), electro cyclone, wet flue gas desulfurization (WFGD), bag house filters, and combination of different methods were evaluated regarding their capacity in energy performance and collection efficiency as a function of their sizes. In general, the hybrid complex of ESP-baghouse filters has the most advantages in PM control from the source. SMOG towers are active outdoor filters, functioned by HEPA filtration and dry electrostatic precipitators, which are deployed in testing for air pollution reduction in China, India, Poland, etc. Unfortunately, the effectiveness of these SMOG free towers did not meet the expectation to discard PM pollution in these cities (Arun et al., 2022; D. Tan et al., 2017). Therefore, these towers will be considered just as a device for an active outdoor filter and do not be considered as sustainable a solution for PM reduction in outdoor air. Such device could be used as an alternative to the reduction of PM for a given area where high peak of PM pollution could occur periodically.

III. Numerical modeling

III.1. Application of computational fluid dynamics in structured air filter modeling

Numerical modeling is an excellent support for developing and testing air pollution mitigation solutions. Before installation of a project, it helps planners to estimate environmental, eco-sociological impacts for simulated scenarios while evaluating its functionality and cost benefits. Simulation process could be done at large-scale to define the geometry of the future construction site with respect to the local natural factors, i.e., wind direction, humidity, density of traffic, etc. These factors will be of great help to reduce as much as possible the exposure of the residents to the outdoor air pollution and for the future implementation of efficient filtration systems, which will contribute to the reduction of outdoor PM concentration. With these preliminary assessments, unnecessary costs and wasted time could be avoided and the most suitable solutions can be kept. In fact, air filtration is a complex procedure of multiphase interactions between particle-particle, particle-flow, flow-

filter and particle-filter. As particles usually have a large quantity, and the filtration process takes a long lap of time (filter life cycle $\gg$ time required to capture one particle), models are made for understanding filtration mechanisms, particle deposition, and other specific solutions to solve equations or hypothesis (B. Li et al., 2024; X. Zhang & Liu, 2022). Simulation process also allows defining the filter parameters, i.e., quantity, orientation, arrangement with respect to the specific area and the nature and concentration of the emitted PMs. Simulation could help to modify the circulation conditions or to implement limitation speed to reduce the PM emission. In order to reduce simulation time and focus on the filtration process, simplifications are usually applied for numerical models. Multiphase filtration models could be influenced by many factors (flow velocity and viscosity, particle diameter and density, filter porosity and fiber diameter, etc.) but also environmental conditions, especially for outdoor filtration, such as weather variations (altitude, temperature, humidity, wind direction and velocity, pollution concentration, ...). A wise choice of which parameters to keep and others to simplify or neglect is very important for reducing the amount of work to perform, while keeping as much information and parameters as possible (Toparlar et al., 2017). In the last decades, many empirical and numerical models were developed in order to assess pollution behaviors in urban environments, highlighted in the works of Blocken et al. (Blocken, 2014, 2015). PM from different sources can have distinct properties and, thus, influence differently air quality and human health (Hien et al., 2022; W. Li et al., 2023; Plasencia Sánchez et al., 2023; R. Zhang et al., 2015). Concisely of the complex mechanisms of PM dispersion, further from the original source, PMs are more diluted and/or mixed with another source. Airflow from natural wind or movements of physical objects (advection) is the main PM transportation mode (Csizmazia & Nagyné Polyák, 2001; H. Zhang, Yang, et al., 2021). Generally, the flow is considered as a continuum, incompressible fluid. Such ideal fluids do not exist but are generally assumed because of its simplicity to be simulated in numerical models, compared to multiphase and compressible flow (Chandra et al., 2024), while still leading to satisfactory results (Martín et al., 2024). Furthermore, almost every scenario related to aerodynamics can be simulated by Computational Fluid Dynamics (CFD) (Reiminger et al., 2025; Tominaga & Stathopoulos, 2013). A well-simulated model can contribute to pollution mitigating sustainable solutions in infrastructure constructions (Reiminger et al., 2023), installation of air filters (Trinh et al., 2024) or vegetation in public spaces (Vos et al., 2013).

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many factors (flow velocity and viscosity, particle diameter and density, filter porosity and fiber diameter, etc.) but also environmental conditions, especially for outdoor filtration, such as weather variations (altitude, temperature, humidity, wind direction and velocity, pollution concentration, etc.). A wise choice of which parameters to keep and others to simplify or neglect is very important for reducing the amount of work to perform, while keeping as much information and parameters as possible (Toparlar et al., 2017). Furthermore, air pollution is usually a complicated mixture of gas, solid, liquid, vapor (Kamiński et al., 2022). In order to successfully simulate the dynamic of such complexion, simplifications and idealization conditions should be chosen (e.g., reduction of phases, gas fluid becomes incompressible, homogeny, and in some case, permanently steadily or turbulent).

III.2. Simulation of fiber filter, vegetation and passive house methods

In CFD models, fiber filters are usually modeled as single fibers particles trapping, for the sake of simplicity. With efficiency equations discussed in II.1., 2D or 3D models of single fiber simulations have been based on the Kuwabara model (Kanaoka et al., 2001; Kuwabara, 1959) of PM deposition and dendritic formation. Flow field, fiber diameter and other parameters calculation could be described according to the models developed by Chandra et al., (Chandra et al., 2024) and by Zhang and Liu (X. Zhang & Liu, 2022). The boundary conditions of models are defined as rectangular or square conduct, which contains a cylinder inside, while cylinder diameter is inferior to conduct diameter (Fig. 10A). The process of PM deposition and accumulation on the cylinder are simulated by the studies of Cai and Zhang (Cai & Zhang, 2016), Dong et al. (Dong et al., 2019), and Hosseini (Hosseini & Vahedi Tafreshi, 2012). These models predict the influences of time or flow velocity variation, particle size on pressure drop evolution and dendritic formation (Fig. 10B), etc. Because particles can be detached from fiber after a certain time of exposure to the flow, the PM quantity on the fiber filter can steadily stabilize when PM deposited is equal to PM detached in the same time interval, i.e., equilibrium state. PM detachment phenomenon is described in the work of Li et al. (B. Li et al., 2024). Active filtration using electric potential of filter material was described in part II of this review. CFD simulation of filter performance and the interests of choosing a high conductivity material are mentioned by Hou and Tafreshi (Hou et al., 2019). Last but not least, passive methods require outdoor natural wind prediction in which CFD models can be used in scenario analysis, for both stable and unstable weather conditions (Reiminger et al., 2023).

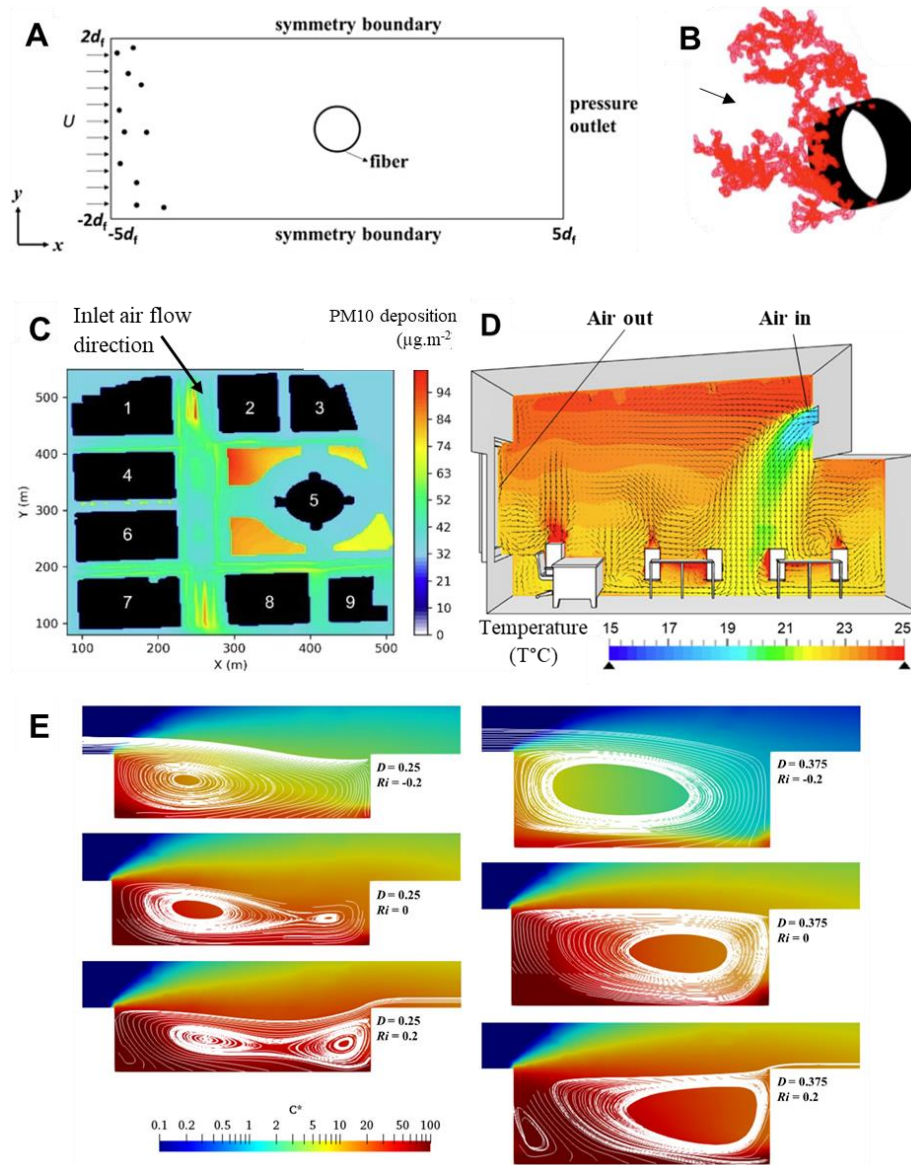


Figure 10 | **A.** Domain of a single fiber PM filtration in a gas flow field ($0.26 \text{ m} \cdot \text{s}^{-1}$), fiber diameter (d_f) and particle diameter (d_p) are fixed at $1 \mu\text{m}$ and $0.25 \mu\text{m}$, respectively (Cai & Zhang, 2016) – Copyright with Elsevier license number 5966560265837. | **B.** 3D illustration of dendritic formation on fiber cylinder surface in an interception-dominant stream. Flow direction is indicated by a black arrow, d_f and d_p are $4 \mu\text{m}$ and 250 nm , respectively. Image redraw from the work of (Hosseini & Vahedi Tafreshi, 2012) – Copyright with Elsevier license number 5966561380952. | **C.** CFD simulation of particle deposition on the ground level ($z = 0\text{--}2 \text{ m}$) or on vegetation surface (trees surrounding 5th building, green walls and roofs, as well as green corridor). Airflow comes from NW at $2 \text{ m} \cdot \text{s}^{-1}$ and PM_{10} background concentration were set to $20 \mu\text{g} \cdot \text{m}^{-3}$ (Rodrigues et al., 2024). | **D.** CFD model of natural ventilation a passive house designed classroom without mechanism ventilation. Outdoor air is cooler than indoor air (Khan, 2023) - Open access copyright. | **E.** Evolution of wind speed and streamline in a depressed road under unstable atmospheric stability showing recirculation patterns (Reiminger et al., 2023) – Copyright with Elsevier license number 5966570905031. With D as road depth, and the Richardson number (Ri) which indicates the thermal (also atmosphere) stability.

Applications of numerical modeling of outdoor air pollution are multiples, from tracking PMs and pollutant sources to assessing their environmental impacts. Apart from minor scales of single fiber, CFD simulations can also occur in up-scaling models of urban management solutions, including green wall and green roof plantation, and passive house design. Forests, trees, shrubs, etc. are selected as barriers for reducing PM and other forms of air pollution (see part II.3). The benefits of green walls, green roof, trees and other vegetation on urban climate are reviewed by Barwise and Kumar (Barwise & Kumar, 2020). Apart from a single fiber simulation, models of PM filtration through vegetation generally take into account a community of trees or vegetation infrastructure, instead of a single leaf or tree alone. CFD is also used in plant characterization for understanding different mechanisms such as transpiration (Plas & De Paepe, 2021) or PM removing (D. J. Nowak et al., 2013), etc. As mentioned in II.3, leaf-trait and tree species can differ from one to another in PM trapping (Gaglio et al., 2022). In order to compare their efficiency in air filtration, models need to include structures of scale-up deployment (Fig. 10C), even forest and ecosystem in urban environments (Corada et al., 2021; D. Nowak et al., 2008). Otherwise, in closed spaces such as indoor air quality assessment, aerodynamic models help to improve thermal comfort and air flow rate regulation in HVAC systems or passive house design (Ryhl-Svensden & Clausen, 2009; Saran et al., 2020; Smedemark et al., 2020; Zhivov et al., 2020). Based on buoyancy effect (see part II.3), many models studied different aspects of the passive house concept (Fig. 10D), as a solution for saving energy while assuring indoor-outdoor air exchange (Z. Jiang et al., 2023; Pabiou et al., 2015; J. Wang et al., 2017). CFD models are also practical in estimating energy performance and PM transportation (Kao et al., 2009; T. Zhang et al., 2018). Models based on experimental studies of combining active and passive ventilation (Z. Jiang et al., 2023; P. Thakur, 2019; H. Zhang, Yang, et al., 2021) reviewed the benefits of smart synergy. A significant case study of PM removal in a semi-enclosed environment was presented by Blocken (Blocken et al., 2016). Thermal comfort, PM reduction and energy saving are the advantages of dynamic switching between two modes compared to single one. Indeed, active air filtration during highly degraded air quality conditions, and natural ventilation by opening the window soon in the morning or before rush hours are, for now, the best options suggested by models. Lastly, emerging artificial intelligence (AI) models trained with CFD results have shown impressive performance in urban air quality modeling (Martín et al., 2024). These models integrate AI's predictive capabilities to accurately forecast pollutant dispersion (Fig. 10E) and atmospheric concentrations in complex urban

environments (Jurado et al., 2023). However, they currently do not account for vegetation, which can play a critical role in enhancing air quality by acting as natural filters, modifying airflow patterns, i.e., winter or summer period, and regulating urban microclimates. Incorporating vegetation and other active and passive filtration effects into CFD-driven AI models would enhance prediction accuracy and enable their application in the context of particulate matter (PM) filtration. Nonetheless, this integration has yet to be fully achieved. At some points, AI model based on results issues from CFD results could yield credible predictions which could be very useful for urban planning and management. However, details such as vegetation, building dimensions, weather variations, etc. are needed for improving the accuracy of CFD simulation and the AI prediction models.

IV. Conclusion and perspectives

In summary, multiple choices of methods exist for developing efficient and sustainable outdoor air filtration. Whether for promoting healthy building ventilation or enhancing outdoor air quality, traditional woven and nonwoven filters as well as emerging materials are continuously evolving to meet diverse requirements. Advanced filtration materials demonstrate promising capabilities in PM capture, energy efficiency, and recyclability while significantly reduce the associated energy input for operating the system. However, comprehensive scale-up and field-testing are imperative to thoroughly assess the benefits and limitations of these filters. Maintenance and survey procedures are crucial for ensuring optimal air quality and functionality of filtration systems. In the case of air filtration in an HVAC system, a timely replacement of filters is essential to prevent clogging. Factors such as filter lifespan, installation, and maintenance costs vary depending on filtration needs and market provisions.

Active filters have been developed in a large number of cities around the world to reduce the problem linked with outdoor particulate pollution, which represents one of the main source of indirect diseases, especially for countries with high population density living next to large chemical industrial parks. However, it worthy to note that active filters offer superior filtration efficiency but often come with higher costs and lower energy efficiency, contributing to a larger carbon footprint. Active filter also displays some drawbacks regarding its deployment: (i) such system needs to dispose a source of energy nearby, which is not always compatible with the existing installation, and (ii) such system also generate noise which could pose some

problem for the neighboring. At the present state-of-the-art development, the model of active filtration tower as that developed in China urban area, represents the most advanced system for large area outdoor depollution. Optimization process by introducing renewable energy source, i.e. solar or small wind turbine, to power the system could be regarded as an interesting alternative for the deployment of these filter devices. Such system could also be activated when particulate pollution significantly exceeds the tolerated thresholds in order to locally and punctually reduce the impact of this pollution on the local population, and more specifically the elderly and young children.

Conversely, passive filtration operates using natural airflow mechanisms, requiring no energy input, yet may require enhancement for more optimal performance. Such passive filter could be implemented in different areas, which is not the case for active ones as discussed above, and could represent a smart and ecological solution for the reduction of outdoor air pollution in outdoor or in semi-closed area. Currently, in order to reduce outdoor air pollution and as a consequence, to consecutively improve indoor air quality, a hybrid approach, of combining passive and active filtration systems, appears to offer the most promising solution for sustainable air filtration in urban environments. As each situation of outdoor air filtration needs (public space, traffic, industry, HVAC) have different circumstances and requirements, air filters selection can be based on predictable criteria (air quality norms, financial means, etc.).

In most cases, CFD modeling is the best option for understanding filter mechanisms and filter testing before real deployment. With the development of CFD technology and artificial intelligence, filtration methods can be simultaneously simulated and preselected in order to save time and resources. With the applications of these models and AI supports for data treatment, manual or automatic decisions can be made for optimizing the processes (window opening control in a smart house system in the interest of energy saving in temperature and air quality control for example). Thus, simulation models provide simplified perspectives and conceptual plans, no matter for filter technology research, or urban management. On the track of seeking a circular economy model (K. Wang et al., 2022), regeneration should be considered as an important criterion in air filter selection. This concept will contribute to reducing material consumption in filter production, as well as waste products after filtration cycle. However, PM collected from recycling procedures is still an important problem as it can generate secondary pollution by resuspension or rejoin the run-off water cycle. Appropriate solutions for PM management of after-recycle filter need to be developed for

optimizing recycling effectiveness, i.e., wastewater treatment following by safety disposal. Besides filter efficiency, lifespan, installation and maintenance costs, sustainable criteria such as energy consumption and regenerability should be important criteria for air filter selection in the future PM filter generations.

Taken into account the relentless pace in the industrial development of some countries and the great access of the associated population to transport, especially individual passenger cars, the pollution by PMs, i.e., PM_{2.5}, will probably continue to increase in the coming years, despite the significant replacement of combustion engines by electrical ones. Such health issue should be treated in a serious and cooperative way between national and regional administration, as it will represent a most significant threat for the health sector and to the economical one. It is expected that new combined solutions should be developed to jugulate the problem of air pollution by PM in the coming years. It should be noted that reducing air pollution by particles also involves reducing emission sources, where particle concentrations are high and therefore their capture is more effective in reducing overall air pollution problems. The best option should be the combination of PM reduction at the source and advanced filtration devices to concomitantly reducing the problem of air pollution by PMs. In the following section, some developments are presented and discussed.

The reduction of PMs at their emission sources is expected to be the most efficient solution to the atmospheric depollution. Here, we will report on the different existing and upcoming solutions to address such problem. Technology revolution brings creative solutions for PM reduction, not only by developing filtration equipment, but also the observation and monitoring which can greatly help the urban management control the situation and have the suitable strategies. In their studies (Ayodele et al., 2023) used multi-temporal / spectral imagery of Landsat satellites to analyze PM pollution of Lagos City at different periods. Such observations system can help to point out the hotspot of PM pollution (ring roads, city center, industrial, construction, etc.). Based on the environmental policy of the country/region, many solutions can be considered (e.g., reduction of speed limits, development of public transport, installation of vegetation infrastructure, etc.). Doğan and Tuğba (Doğan Güzel & Alp, 2024) proved that PM monitoring sensors systems can also demonstrate the profit of in air quality improvement of Istanbul City (Turkey) as a result of renovation in automobile fleet. Beside these modern solutions, the green spaces in cities are also very important in the plan of pollution mitigation, as the example of Sao Paulo city (Brazil), where urban parks played a critical role in PM reduction (Connerton et al., 2025). Other benefits of green spaces like anti-

urban heat, noise reduction, biodiversity valorization are reported in (Shushunova et al., 2023). Thus, air pollution mitigation needs long-term strategies with the synchronization between technology modernization and urban management, and the close collaboration of government policy and individual household solutions.

Progress has also been made by tire manufacturers to reduce the microplastic resulting from tires abrasion (Neupert et al., 2024), and on the other side, constructor companies also significant improve the mechanical resistance of the road (Fransesqui et al., 2022). The PMs released from braking, especially for heavy trucks and underground transport, has also received great improvement in order to meet the future Euro 7 norm, which mandated a release of 7 mg. km⁻¹ for combustion engines and 3 mg. km⁻¹ for electrical vehicles. In order to meet such requirement a new vacuum cleaner system, TAMIC® for “Technologies d’Aspiration des MICro-particules de freins”, has been developed by Tallano Com. to prevent the emission of brake PMs for underground trains and heavy-duty vehicles (Fig. 11A), and a similar system has been developed by Mann+Hummel system (Fig. 11B). These systems of PM trapping is estimated to be able to capture up to 80 % of PM emission of break wear which contains mainly harmful metal particles. Such in-situ PM captors are very promising for larger-scale deployment in automobile industry, especially for the incoming burst of electrical vehicles which do not have any exhaust emission but more of non-exhaust PM emission due to their weight.

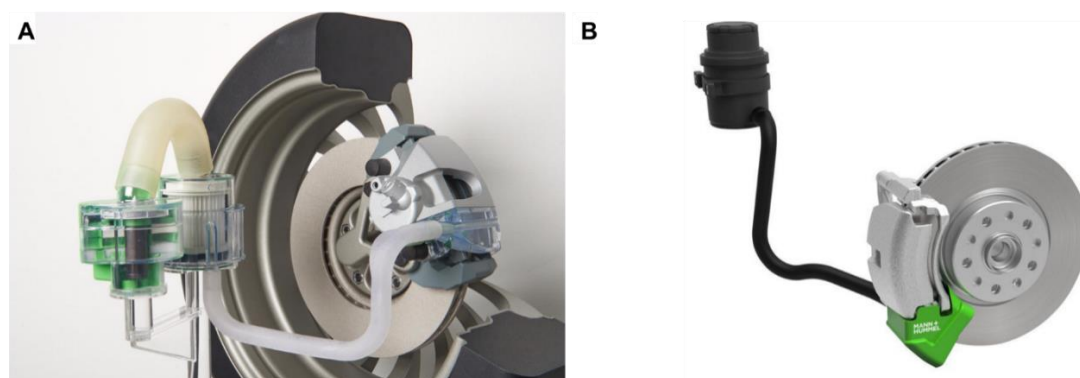


Figure 11 | **A.** Brake wear aspiration system of TAMIC. Image source: (Tallano, 2025). | **B.** Mann+Hummel system for auto capturing particles from brake disk. Image source: (MANN+HUMMEL, 2025)

New legislation has been issued by policymakers to enhance the electrification of different sectors, and especially the chemical sector, by the deployment of renewable electricity to provide heat for operating industrial chemical processes instead of using

conventional gas burners (Truong-Phuoc et al., 2025). Such electrification process will significantly reduce the emission of PMs from the chemical sector where large plants are concentrated, which represents one of the largest scale emission sources for CO₂ and PMs, alongside with the steel and construction sectors. The replacement of electricity-driven process could significantly reduce the emission of VOCs components, which contribute in an important way to the production of SOA (secondary organic aerosol), identified to be one of the most harmful components in air pollution. Polycyclic aromatic hydrocarbons (PAHs) can be generated from incomplete combustion of various fuels and represent important components of industrial emissions (Kong et al., 2013; Xing et al., 2020). The secondary PM aerosol can also contain metal compounds through reaction with intermediate metal-containing species, i.e., arsenic (As), antimony (Sb), and lead (Pb), which could be originated from coal-fired power plants (Hsu et al., 2021). Thus, urban planners should prioritize low-energy passive filters near residential zones, supported by CFD-aided placement optimization and lifecycle-based material selection.

V. Scope and outline of the thesis

Air pollution is the main cause of 6.7 million premature deaths worldwide every year. In the same report, WHO confirmed the alarming situation of air pollution around the world, with a great contribution of particulate matter (PM) pollution. As one of main anthropogenic emission sources, PM from traffic has become a big nuisance for citizen health quality, especially in large and mega cities. Thanks to regulations and continuing technology advancement, exhaust emissions from combustion engines have been reduced step-by-step. However, non-exhaust emissions of fine particles from brake wear, tires and road surfaces abrasion remain, even for electricity vehicles. Due to the above-mentioned problems, transport continues to represent as a significant source of fine particles pollution, especially in cities with dense traffic and high population density. In addition, secondary reactions between the emitted fine particles and other volatile organic/inorganic compounds, i.e. nitrate and sulphur derivatives, also constitute a source of threat to the population, especially during cold periods when pollution dispersion is ineffective.

In order to find an alternative solution for the management of urban air pollution, this thesis develops and then exploits prototypes of passive traps (operating without energy input) to reduce fine particles near major urban traffic routes before their dispersion by natural

factors. The project objectives concern the evaluation of the prototypes' performance in an outdoor environment, either in city centers, where heavy traffic leads to a high concentration of PM_{2.5}, or along suburban expressways, under real operating conditions (wind variability, humidity, temperature, etc.). The experiments, lasting several months, make it possible to evaluate the filter's effectiveness for long-term operation in the event of commercial deployment. The results obtained will make it possible to determine the effectiveness of these passive traps in reducing fine particle pollution, as well as the possibility of reducing very small particles, PM₁, which represent a significant source of danger for people due to their small diameter. This project is carried out within a collaboration between academic and industrial partners: ICPEES, SICAT-Saint-Gobain, AIR&D, TrapAparT, and with a financial support of ADEME and Eurometropole of Strasbourg.

Chapter 1 presents the fundamental concepts of the different filtration methods for the removal of fine particles from outdoor air. Active and passive filtration methods are presented and discussed, in order to understand their advantages and disadvantages in trapping particles as well as the associated cost for the maintenance and disposal. Innovative materials and technologies are also reviewed, and the advantages and disadvantages of each technique are discussed. The chapter also includes the future development of trapping systems that are being implemented in various sectors, especially in closed underground environments, i.e., subways or parking lots, where fine particle pollution is extremely high and poses serious problems for the health of passengers.

In Chapter 2, a passive trapping system based on alveolar fibrous structures covered with a thin layer of oil is used for the capture of fine particles along a densely populated and heavily trafficked road, Avenue du Rhin in Strasbourg. The characteristics of the filter material and the passive filtration concept used for the passive trapping of fine particles, as well as the washing mode to recover adsorbed particles and the regeneration of the filters, are described. The advantage of such a system lies in the low pressure drop across the filter and a large geometric surface allowing a better circulation of air laden with fine particles through the trap structure. The results obtained showed that the filtration system remains effective, under real operational conditions, during an exposure period of several weeks before reaching saturation. A capture efficiency of around $50 \pm 8 \text{ g. m}^{-2}$ of PM is obtained after 14 weeks of exposure of the Avenue du Rhin (ADR) prototype. On average, 40% to 50% of the captured particle volume is PM₁₀ and below, according to the results of the particle size analysis. Elemental analysis indicates that besides C and O, metallic particles are relatively abundant, which could

be issued from the degradation of brake pads during braking at traffic lights and of the clutch when restarting. In addition, the system can effectively capture PM₁ particles, the most harmful given their small size. The system can be regenerated by a washing step before a new oil infiltration. The regenerated filter displays the same efficiency as the original, thus considerably reducing the environmental impact of such a system. Indeed, current passive filters, generated by electrospinning, are not reusable and generate secondary pollution problems as well as high operating costs. The results obtained are also modeled to determine the optimal operating conditions and also to calculate the location and number of filters needed to sustainably reduce particle pollution in the experimental area.

In Chapter 3, the results of the ADR prototype will be compared with data collected on another similar prototype, but located along the RM35 ring road (RM35) which is a fast lane with a larger number of cars localized at the exit of the city. In addition, the fast lane is not surrounded by buildings, which can act as a windshield and slow down the dispersion of particles by natural factors. In total, $84 \pm 6 \text{ g. m}^{-2}$ of PM were captured after 14 weeks of exposure on the RM35 prototype. The results are also confirmed by repeated tests during the experimental period, which lasted for several months. The higher amount of PM captured next to the RM35 can be directly related to the larger number of cars and also to the absence of vegetation around the trap, which could partly trap the particulates, as in the case of the ADR prototype. The results obtained indicate that the amount of PM captured and its nature are directly related to the location of the trap in relation to the emission sources and to the meteorological variations from one place to another. The particles collected on the RM35 are mainly carbon by-products related from tire and road wear, with traces of metal particles related to high-speed braking. However, the RM35 metal particles are bigger than those from the prototype located at the ADR where braking is frequent and lower speed. The results also showed that throughout the year, weather and seasonal variations have an impact on the amount of PM captured. As divergence parameters, a high wind speed accompanied by rain could reduce the concentration of PM in the air, and consequently, the amount of PM passing through the filter. Conversely, a stable temperature (above 20°C) without precipitation could allow the system to capture particles more efficiently and extend its operation before saturation. This capture system could be integrated into the noise reduction panels that are already installed along the road, thus partially reducing particle pollution for roadside homes.

In Chapter 4, mobile trapping, a derivative passive trapping method, was tested in two locations in the city of Strasbourg: the first test area is located in the city center and next to

the relatively dense traffic lanes, while the second area is located on the outskirts of the city characterized by low traffic and high dispersion rate. In this study, the filters are mounted on bicycles that circulate during the same period in both areas. The trapped PM is analyzed in the same way as that used for the ADR and RM35 tests described in the previous chapters. Field tests demonstrated that the passive filter system remains effective in motion, successfully capturing airborne particles without imposing significant mechanical constraints. Its lightweight construction facilitates its integration into bicycles. We found that the lateral position (on the bicycle frame) captures better than the frontal position (perpendicular to the traffic) due to aerodynamic phenomenon. Both tests reveal that the nature of the PMs captured is similar between the two areas, in the absence of particulate pollution generated by domestic heating and others. The quantity of PMs captured during the tests in urban areas, near traffic routes, is greater than that in peri-urban areas and confirms that the trapping mechanism remains similar for passive filters and is directly proportional to the PM concentration. However, it was noted that for the tests in urban areas the quantity of PM_{2.5} is higher, around three times, compared to that captured in peri-urban areas. These results could be explained by the fact that the dispersion of PM by wind is more effective for very small particles and less for particles of slightly larger size. In addition, city center is surrounded by buildings which could hamper the dispersion of the emitted PMs. This study allows one to build a detailed and precise mapping of particulate pollution by sector of the city, and the results thus obtained could be used for the installation of particle capture systems adapted to the sectors in order to reduce the impact of this problem on the population.

The final section presents the conclusions drawn from all the results obtained within the framework of the thesis as well as the future prospects for the development of this type of filtration, which combines efficiency, recyclability and energy efficiency.

Nomenclature

Term	Description	Unity
C_c	Cunningham correction factor	-
$Coeff_K$	Pressure drop coefficient for conduct shape	-
c_p	Specific heat of air measured at constant pressure	$J. K^{-1}. kg^{-1}$
c_v	Specific heat of air measured at constant volume	$J. K^{-1}. m^{-3}$
Eff_{di_inter}	Single fiber diffusion enhanced interception efficiency	%
Eff_{diff}	Single fiber filtration diffusion efficiency	%
Eff_{elec}	Single fiber filtration electrostatic efficiency	%
Eff_{filter}	Overall filter efficiency	%
Eff_{imp}	Single fiber filtration impaction efficiency	%
Eff_{inter}	Single fiber filtration interception efficiency	%
$Eff_{settling}$	Single fiber filtration settling efficiency	%
Eff_{SF}	Single fiber filtration combined efficiency	%
$Energy_{consumption}$	Energy consumed by filtration system	Wh
$heat_i$	Heat transfer coefficient for flow over the i^{th} surface	$W. m^{-2}. K^{-1}$
K_C	Electrostatic parameter corresponds to Coulomb force	-
K_{im}	Electrostatic parameter corresponds to image force	-
K_{in}	Electrostatic parameter corresponds to induced force	-
QF_f	Filter quality	Pa^{-1}
Q_t	Total airflow through the structure at time t	$m^3. s^{-1}$
Δh	Elevation difference between inlet and outlet of air	m
Δp	Pressure drop	Pa
A	Area of a surface (i.e. wall, floor, ceiling)	m^2
ACH	Air change per hour	h^{-1}
A_m	Gravimetric yield	%
$Area_{cov. ground}$	Area of the ground covered by leaf	m^2
C	Particles (PM) concentration	$\mu g. m^{-3}$
CFD	Computational Fluid Dynamic	-
$C_{IN} ; C_{OUT}$	PM concentration at upstream and downstream of filter	$\mu g. m^{-3}$
d	Diameter	m
D	Self-diffusion coefficient of material	$m^2. s^{-1}$
d_f	Fiber diameter	m
d_p	Particle diameter	m
E	PM emission rate	$\mu g. s$
EPA	Efficiency Particulate Air	-
g	Gravitational acceleration	$m. s^{-2}$
G	Grammage (filter mass per area unit)	$kg. m^{-2}$
GDP	Gross domestic product	-
HEPA	High Efficiency Particulate Air	-
HVAC	Heating, Ventilation, Air Conditioning	-

IAQ	Indoor Air Quality	-
j	Deposition velocity parameter	-
Kn	Knudsen number	-
Ku	Kuwabara factor	-
L	Characteristic length	m
LAI	Leaf Area Index	-
n	fan drive efficiency	%
Pe	Péclet number	-
PM flux	PM flux deposition rate	$\text{g. m}^{-2} \cdot \text{s}^{-1}$
PM ₁	Particulate matters of diameter inferior to 1 μm	-
PM ₁₀	Particulate matters of diameter inferior to 10 μm	-
PM _{2.5}	Particulate matters of diameter inferior to 2.5 μm	-
Q	Air flow rate	$\text{m}^3 \cdot \text{s}^{-1}$
R	Interception parameter	-
r	Average of distance travelled	m
Re	Reynolds number	-
SOA	Secondary Organic Aerosol	-
Stk	Stockes number	-
Surf. _{leaf}	Leaf one sided surface	m^2
T	Fluid absolute temperature	K
t	Time	s
U	Flow velocity	$\text{m} \cdot \text{s}^{-1}$
ULPA	Ultra Low Particulate Air	-
V	Room volume	m^3
V _d	PM deposition velocity	$\text{m} \cdot \text{s}^{-1}$
WHO	World Health Organization	-
z	Filter thickness	m
α	Volume fraction of fiber (solidity)	-
γ	Kinematic viscosity	$\text{m}^2 \cdot \text{s}^{-1}$
η	Dynamic viscosity	$\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$
λ	Mean free path	m
ρ_f	Fiber density	$\text{kg} \cdot \text{m}^{-3}$
ρ_p	Particle density	$\text{kg} \cdot \text{m}^{-3}$

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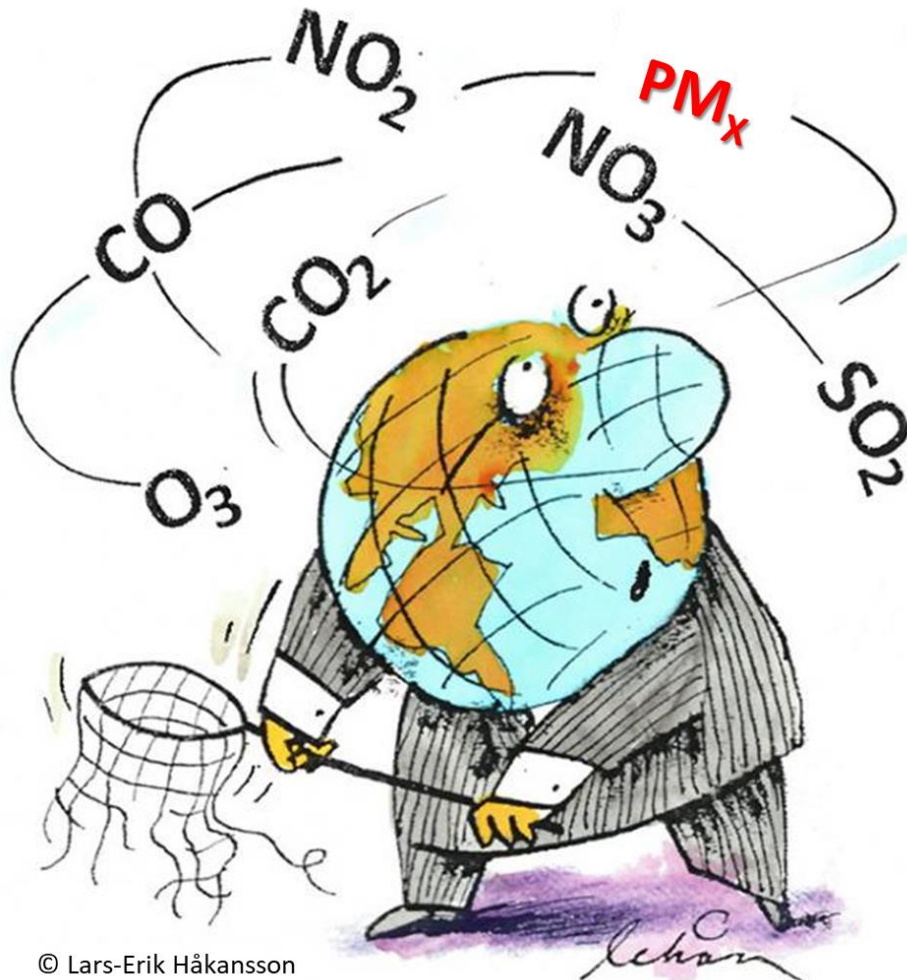
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CHAPTER 2

PASSIVE PM TRAPPING DEVICES : CITY AREA



Washable Oil-Coated Structured Support For Passive Outdoor Particulate Matters Trapping

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Abstract

Direct outdoor air depollution represents an interesting path for preventing indirect disease. In the present work, a simple and efficient PMs trapping media based on the use of an oil-coated structured polymer media was developed for passive trapping of various PMs, ranging from coarse (PM_{10}), to fine ($PM_{2.5}$) and ultra-fine (PM_1) dimension in outdoor environment. The device can be easily regenerated by a simple washing with a mixture of water and detergent followed by a new oil coating cycle. The total PM loading mass of the passive trap and the recovered PMs are analyzed through different techniques and confirm the great efficiency of such filter to trap various PMs when exposed to a high traffic road. The spent filter can be regenerated through a simple washing step and can be repeatedly re-used with similar PM loading mass. The high and long-lasting total PM loading mass were also supported by numerical simulations based on computational fluid dynamics, also used to propose an optimization implementation of such system for future deployment at scale.

I. Introduction

Particulate matter (PM) pollution, which is originated from concentrations of solids, liquids-solids or gas-solids/liquids emitted in the air by natural diasters or by anthropogenic activities, represent a major concern for human health (R. Chen et al., 2016; W. Chen et al., 2020; Deary & Griffiths, 2021; Kumar et al., 2014; L.-Z. Lin et al., 2022; Posner & Pandis, 2015; Schraufnagel et al., 2019; H. Wang et al., 2022). PM is categorized by three main categories based on the diameter of particles, i.e., PM₁ (ultrafine), PM_{2.5} (fine) and PM₁₀ (coarse), which refer to particle sizes below 1, 2.5 and 10 µm, respectively. PM₁ and PM_{2.5} pollution is particularly harmful since it can penetrate human bronchi and lungs owing to the small particle size (Gualtieri et al., 2010; Pope, 2007). Nowadays, the number of premature deaths attributed directly or indirectly to air pollution each year is around 8 million for both outdoor and indoor air pollution according to the World Health Organization (WHO) (WHO, 2021). In addition, the risks over human health are increased for people living in the vicinity of high-traffic roads where small and ultrafine particles, i.e. PM_{2.5} and PM₁, are frequently observed and which can be carried by wind or turbulence from the vehicles far from the emission area (H. Chen et al., 2017, p. 201; Finkelstein et al., 2004; Peters et al., 2004). Due to their harmful effects, PMs reduction in cities has received a high public interest in order to reduce as much as possible disease for the citizen (Künzli et al., 2000; H. Zhang et al., 2021). Furthermore, reports also pointed out that about 30 % of the pollution by microplastic particles in rivers, lakes and oceans is originated from tire wear debris and will significantly increase in a proportional way to the number of Light Duty Vehicle (LDV) (De Souza Machado et al., 2018; Kooi et al., 2016; Sommer et al., 2018).

During the last decades, a large number of reports dealing with the PMs removal from outdoor air have been published (Jung et al., 2018; C. Liu et al., 2015; Schwotzer et al., 2022; Z. Wang et al., 2015; Xiao et al., 2018; R. Zhang et al., 2016; X. Zhang et al., 2018). However, most of them were based on the use of active filters which operated with an external energy input (H. Liu et al., 2020). Active filtration is carried out using a fan or air extractor to force the airflow through the filter where the PM are trapped when it comes into contact with the filter device. In addition to such mechanical capture some proactive capture processes are also developed to improve the trapping efficiency by charging the PM with an ioniser or by using advanced filtration materials with high dipole moment to improve the capture through chemical forces. Such filtration mode is frequently used for indoor as well as for outdoor depollution (Bai et al., 2018; Bourrous et al., 2016; Gao et al., 2023; Tan et al., 2017; Thakur

et al., 2013; Yang, 2012). However, active filters present several drawbacks: (i) the system must be connected to an external energy source to powering the air flow through the filter, or, to induce charging of either the PM or the filter; The primary issue is that in certain specific locations, such as open urban areas or underground train stations where electrical connections are tightly regulated, it is not always possible to access an external energy source to power the system, (ii) the air extractor generates a relatively high noise which could pose problem for the neighbouring, especially at night, and (iii) active filtration devices usually uses small aperture filters which can be rapidly plugged with low amount of PMs trapped inducing large pressure drop across the filter and necessitate short-term replacement. It is anticipated that replacing active filtration devices with passive ones for PM reduction will be of great interest, as they are less energy-intensive and more environmentally friendly. On the other hand, passive filter are relatively inexpensive, require no electricity to operate, and can be deployed at numerous locations easily and cost-effectively. The possibility of regenerating the spent filter and reuse also represent interesting environmental and economic alternatives with respect to active filtration devices. Some passive filters have been developed based on the use of weblike electrospinning structure which displays a high total PM loading mass (Lu et al., 2021; Xu et al., 2016; Y. Zhang et al., 2016). The main drawbacks of the electrospinning filters are the relatively high-pressure drop and that they cannot be effectively regenerated, thus hindering their industrial development for large-scale deployment. On the pathway for understanding and finding solutions for PM mitigation in urban environments, experimental and computational studies are needed. The danger of PMs and associated methods for PMs characterization in urban environments were highlighted (Amato et al., 2010; J. Gomes et al., 2013; J. F. Gomes et al., 2012; Han et al., 2020). Solutions of outdoor PM filtration were tested such as active PM tower filtration (Tan et al., 2017; H. Zhang et al., 2021), vegetation PM filtration (Han et al., 2020), etc. Computational fluid dynamics (CFD) models are becoming a useful method to simulate air pollution. Reiminger and Jurado et al. (Jurado et al., 2022, 2023b, 2023a) computed models of air pollution, while using deep learning methods to compute spatial data, a promising pathway in air pollution study.

In the present work, a PMs trapping media has been put under experiments for passive trapping of PMs in the outdoor environment, which can be reused after a washing step to remove the trapped PMs (Masquida et al., 2018; Pham et al., 2021). The system is simple for operating and consists of a structured polymer media coated with vegetable oil which traps the PM when it encounters the surface. The trapping experiments were carried out directly in

an open space located next to a high traffic road crossing the city of Strasbourg, France, with high frequency of stop-and-go significantly consuming brakes and tires. The device can be regenerated by a simple washing with a mixture of water and detergent followed by a new coating cycle. The total PM loading mass of the passive trap as a function of exposure duration, and the recovered PMs are analysed through different techniques as well as numerical simulations regarding the future deployment of such systems at a bigger scale. The main purpose of this paper is double: verifying the oil coating concept of air filtration, and testing the passive PM capture on the near-source outdoor environment. As described in (Agranovski, 2010; Müller et al., 2014), the oil coating layer is used for enhancing PM capture and retention on a low pressure drop filter structure. This work aim is not to develop a brand new air filter, but to demonstrate the real potential of this concept in PM capturing in various complicated environments like outdoor. Different from indoor air filtration, outdoor or semi-closed spaces like parkings are frequently subject to many weather parameters and PM variations, adding to limits of material choices and energy source installation. Based on weather conditions and nature of PM emissions, materials of filter structure and oil coating can be carefully selected in order to have the maximum performance without conflicting with the safety norms of the location. The materials and labour costs can vary depending on country and market situation, but the choice of a regenerable material may reduce environmental impacts while keeping its effectiveness.

II. Materials and methods

II.1. Materials

The passive PM trapping process was carried out using an open box which can host twenty filters and different sensors to monitor the different parameters implemented next to an urban area with high PM pollution (Fig. 1A and B). The schematic representation of the whole filtration device is displayed in Fig. 1C for the sake of clarity. The media is consisted with commercial polyester (hereafter noted “Aerosleep”) structured host matrices with large exposure surface area to offer a maximum surface contact between the polluted air and the trapping media (Fig. 1D) alongside with an extremely low-pressure drop. The PM total loading mass was significantly improved by depositing a thin layer of vegetable oil, on the topmost surface of the host substrate (Fig. 1E & 1F). The oil layer with sticky properties

allows one to harvest any PMs which come in contact with the media regardless their size and shape as well as nature, i.e., organic, inorganic or even living matter such as pollen or insect with size ranged from tenths few nanometers to several hundred micrometers or even millimeters. The PMs trapping was realized through contact between the PM airborne and the filter surface and it is mostly depending on the outdoor air flow rate passing through the filter media.

II.2. Characterization Techniques

The samples, fresh and spent, were characterized by different techniques to investigate the characteristics of the media and the quantity, nature and size distribution of the trapped PMs.

II.2.1. Scanning electron microscopy (SEM)

Analyses were carried out on a ZEISS 2600F microscope with a resolution of 5 nm. A sample with the following dimension was analyzed: width, 10 mm, length, 10 mm, thickness, 6 mm. Before analysis, the sample was oven dried at 60 °C for overnight in order to reduce the oil layer thickness which could hinder the detail analysis of the trapped PMs. The sample was deposited onto a double face graphite tape to avoid charging effect during the analysis. For each sample, statistical analysis with different magnifications were carried out on at least four zones in order to provide a global distribution of the trapped PMs. The statistical SEM results were also used for the measurement of the PM size distribution and compared with that determined by DLS technique.

II.2.2. Pressure drop measurements

Experimental pressure drops (ΔP) across each sample was measured using a home-made apparatus consisting with a tubular reactor with the following dimension: 80 cm high, 4 cm internal diameter. The sample is located at the middle of the set-up and hold by a ring seal on both sides to maintain it steady during the different measurements. Gas velocity is measured with anemometer Testo 435-1 equipped with hot wire probe (0–20 m.s⁻¹). Hot wire probe, due to its small diameter, was chosen to limit the gas flow perturbation. Pressure drop was measured with differential pressure sensors (Digital Manometer Ehdis CR410). Pressure drop was measured on 6 mm long foam varying the gas velocity in the 0–10 m.s⁻¹ range.

II.2.3. Viscosity characterisation protocol

The oil viscosity was measured with a TA Instrument DHR3 rheometer containing a Pelletier disc. For each sample, 0.6 ml of liquid was taken to perform two tests: viscosity as a function of temperature and as a function of shear rate. In the first test, the viscosities of the oils were measured at a fixed frequency (10 rpm for 20 minutes), with the temperature ranging from -15°C to 80°C. On the other hand, the temperature in the second test was fixed at 40°C with the shear rate gradually increasing (frequency ranging from 3 to 50 rpm for 5 minutes). Before each test, the sample was conditioned for 2 minutes to ensure good homogeneity in temperature and density (absence of air bubbles that could influence the measurement). Between two consecutive analyses, the Pelletier disc was cleaned with ethanol and acetone.

II.2.4. Transmission electron microscopy (TEM)

Analysis were carried out on a JEOL ARM-200F working at 200 kV accelerated voltage, equipped with a probe corrector for spherical aberrations, and a point-to-point resolution of 0.2 nm. The sample was dispersed by ultrasounds in an ethanol solution for 5 minutes and a drop of the solution was deposited on a copper covered with a holey carbon membrane for observation.

II.2.5. Granulometric analysis

5 mL of the suspension is sampled from the homogenised mixture of washing solution for DLS analysis. Analyses were carried out on a granulometer MALVERN Mastersizer 3000 with water as solvent without any additives. The suspension was ultrasonicated for 2 min before analysis. The analysis was realized with a stirring and pumping speed of 50 % and the particles in the size ranged from 0.01 to 2,000 μm were analyzed.

II.2.6. Filter washing

Spent filter was treated with solution of 5-10% detergent (Alcohol C9-C11 ethoxylated, KOH) mixing with distilled water at 80°C, followed by 15 min ultrasonication. The washing cycle can be repeated until no particle remain visible on the filter. After the washing step, filter can be dried in the oven at 60°C overnight before re-use, preceded by a new oil layer coating step.

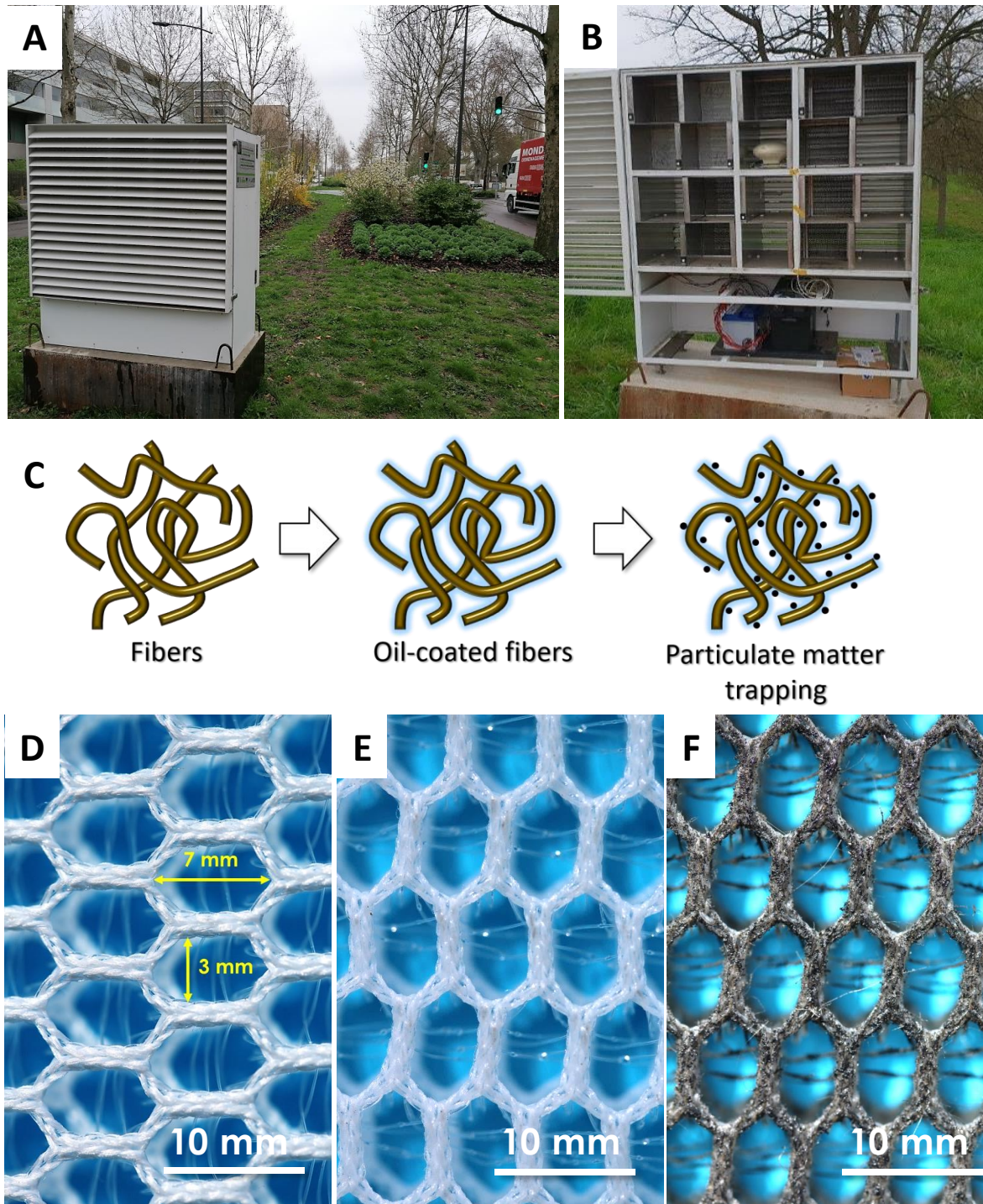


Fig. 1 | (A, B) Digital photos of the trapping device located in an urban area and the trapping media. (C) Schematic representation of the hosting device and the detailed structure of the passive filter. (D) Digital photo of the structured filter as received, (E) after coated with a thin and homogeneous layer of vegetable oil; some small oil beads can be observed on the intermediate plastic fibers within the large hexagonal aperture, and (F) after passive filtration for 4 weeks where the filter color has drastically changed from white to dark gray due to the presence of large number of PMs trapped on its surface.

II.2.7. Numerical simulations

Numerical simulations were carried out through Computational Fluid Dynamics (CFD) modeling using the Unsteady Reynolds-Averaged Navier-Stokes (URANS) methodology. The simulations were performed on OpenFOAM 9.0 with an unsteady solver validated for outdoor air quality assessment purposes in urban areas. This solver solves the continuity (E.1) and the momentum (E.2) equations from the Navier-Stokes' system as well as the advection-diffusion equation (E.3). These equations are given hereafter:

$$\nabla \cdot u = 0 \quad (1)$$

$$\frac{\partial u}{\partial t} + u \cdot \nabla u = -\frac{1}{\rho} \nabla p + \nu \Delta u \quad (2)$$

where u is the velocity [m.s^{-1}], p is the pressure [$\text{kg.m}^{-1}.\text{s}^{-2}$] and ν is the kinematic viscosity [$\text{m}^2.\text{s}^{-1}$] and t the time [s].

$$\frac{\partial C}{\partial t} + \nabla \cdot (Cu) - \nabla \cdot \left[\left(D_m + \frac{\nu_t}{Sc_t} \right) \nabla C \right] = E \quad (3)$$

where C is the pollutant concentration [g.m^{-3}], u is the velocity [m.s^{-1}], D_m is the molecular diffusion coefficient [$\text{m}^2.\text{s}^{-1}$], ν_t is the turbulent viscosity [$\text{m}^2.\text{s}^{-1}$], Sc_t is the turbulent Schmidt number taken as 0.7, t is the time [s] and E is the emission of pollutants [g.s^{-1}]. To solve the Navier-Stokes equations using URANS methodology, the RNG k- ϵ turbulence closure scheme (Yakhot et al., 1992) has been used. The simulations were performed using second-order schemes, and the results were extracted after that the convergence was reached. All simulation results were obtained with residuals lower than 10^{-5} .

Finally, all the recommendations given by Franke et al. (Franke & Baklanov, 2007) for the simulation of flows in urban environments were followed, including:

- Lateral and vertical extension of the computational domain: the top of the computational domain is located at a minimum distance of $5 \times H$ from the highest building and the lateral, inlet and outlet boundaries at a minimum distance of $5 \times H$ from the closest building (with H the height of the highest building in the domain).
- Mesh independence: mesh of 0.5 m near the buildings and the ground were used as they ensure sufficient mesh-size independence for urban environment modeling (Reiminger, Jurado, Vazquez, Wemmert, Blond, Dufresne, et al., 2020).
- Boundary conditions: inlet velocity (E.4) and turbulence (E.5, E.6) profiles following Richard and Norris recommendations (Richards & Norris, 2011), symmetry conditions for the top and lateral boundaries and a free stream condition for the outlet.

$$U(z) = \frac{u_*}{\kappa_{k-\varepsilon}} \ln\left(\frac{z + z_0}{z_0}\right) \quad (4)$$

$$k(z) = \frac{u_*^2}{\sqrt{C_\mu}} \quad (5)$$

$$\varepsilon(z) = \frac{u_*^3}{\kappa_{k-\varepsilon} \cdot z} \quad (6)$$

where U is the velocity [m.s^{-1}], k is the turbulent kinetic energy (TKE) [$\text{kg.m}^{-1}.\text{s}^{-3}$], ε is the turbulent dissipation rate [$\text{kg.m}^{-1}.\text{s}^{-4}$], u_* is the friction velocity [m.s^{-1}], z is the altitude [m], z_0 is the roughness length [m] taken to 0.5 m, C_μ is a CFD constant [-] taken to 0.09 and $\kappa_{k-\varepsilon}$ is the Von Kármán constant [-] taken to 0.41.

The approach and model described previously have been found to be able to reach errors which are less than 10% compared to experimental data as show in (Reiminger, Vazquez, et al., 2020) were more details about the model validation can be found, and a similar approach has been proven to lead to an overall error of around 30% compared to a real situation in an urban area (Rivas et al., 2019).

All the solid obstacles such as buildings present in the computational domain limits were 3D modeled. Two building layouts were considered, the first one without any trap (comparison case) and the second with a line of 50 traps (70 m long) placed between the modeled emission source (road lines) and an elementary school. Traffic emissions set up in the model were calculated using COPERT (Ekström et al., 2004), a calculation method from the European Environment Agency (EEA) considering the French vehicle fleet, the traffic data available on the considered road (38.160 vehicles.day⁻¹ including 8.5 % of heavy-duty trucks, and an averaged traveling speed of ca. 30 km.h⁻¹), and the road length in the model (290 m), which led to PM₁₀ emission of around 23.22 g.h⁻¹ under these assumptions. PM₁₀ trapping was simulated as a mass sink term considering a total PM₁₀ reduction rate of 1.06 g.h⁻¹ (experimental value) with a pressure loss inside the trap numerically modeled by the means of the Forchheimer law using $F = 4.02 \text{ m}^{-1}$ (experimental value).

Lastly, nine simulations were performed considering wind speed of 1.5 m.s^{-1} at 10 m high and coming from nine directions (from 20°N to 340°N with a 40° step), and the results were aggregated considering the continuous methodology described in (Jurado et al., 2021; Reiminger, Jurado, Vazquez, Wemmert, Blond, Wertel, et al., 2020) and the PM₁₀ background

concentration of Strasbourg ($17 \mu\text{g.m}^{-3}$) to obtain annual concentrations, allowing comparison with annual EU and WHO standards.

III. Results And Discussion

III.1. Structured filter support and oil characteristics

The pressure drop measured on the Aerosleep structure under different air flow rate is benchmarked with those obtained on another filter for comparison (Fig. 2A). According to the results, the Aerosleep filter displays the lowest pressure drop even at relatively high linear velocity, i.e., 8 m.s^{-1} , among the evaluated materials such as random particles bed and open-cell foam (Lacroix et al., 2007). For comparison, aluminum entangled filter was also evaluated, and the results are presented in the same figure. According to the results, the high-entangled aluminum structure displays a much higher pressure drop for a given linear space velocity (Fig. 2A). Such results reinforce the choice of Aerosleep as passive filters for the process as for such filter the total PM loading mass is directly dependent to the airflow passing through the filter and high-pressure drop would reduce the airflow leading to a low total PM loading mass. The oil-coated filter displays a very similar pressure drop behavior as a function of space velocity which indicates that pressure drop due to drag forces on the oiled surface is negligible (Fig. 2A). However, for passive trapping mode, the maximum airspeed remains relatively low, within the range of 2 to 4 m.s^{-1} , and thus, leads to a small pressure drop across the filter. It has been reported by Zhang et al. (X. Zhang et al., 2018) that the total PM loading mass increases on a fibrous membrane with high entangled structure but with a detrimental increase of the pressure drop across the set-up.

The evaporation rate and the intrinsic viscosity are important parameters while investigating a liquid behavior deposited on a solid substrate. As evaporation is an endothermic process and based on kinetic energy of individual particle (Royer et al., 2024), weak connection molecules such as water or gasoline with short hydrocarbon chains can evaporate over time depending to the external parameters such as temperature, pressure and relative humidity, even when the external medium not reaching the boiling point (Okamoto et al., 2009). Moreover, mineral or vegetable oil have higher boiling point and evaporate slower than water and gasoline in the same conditions (So Khuong et al., 2024). Olive oil contains mostly long chains of fatty acids such as triglycerides, which require high energy to break-down the chain (Boskou, 2006; Ramírez-Tortosa et al., 2006). Olive oil can even be used for

evaporation-retardant of the tear film lipid layer (Rantamäki et al., 2012). When the ambient temperature is far lower than the boiling point (180°C), evaporation of industrial stabilized olive oil used in this study, i.e. 35 mg. day^{-1} at 60°C is considered insignificant in comparison to the gravitational dripping which is linked with the viscosity of the oil (Fig. 2B). The quantity of adsorbed oil on the trap sharply decreases within the first 2 days, due to the gravitational oil dripping, and remains almost unchanged after 10 days as shown in Fig. 2C which thus confirms that evaporation is not the main cause for the limited adsorption of PM after a prolonged exposure on-site (see results presented later on).

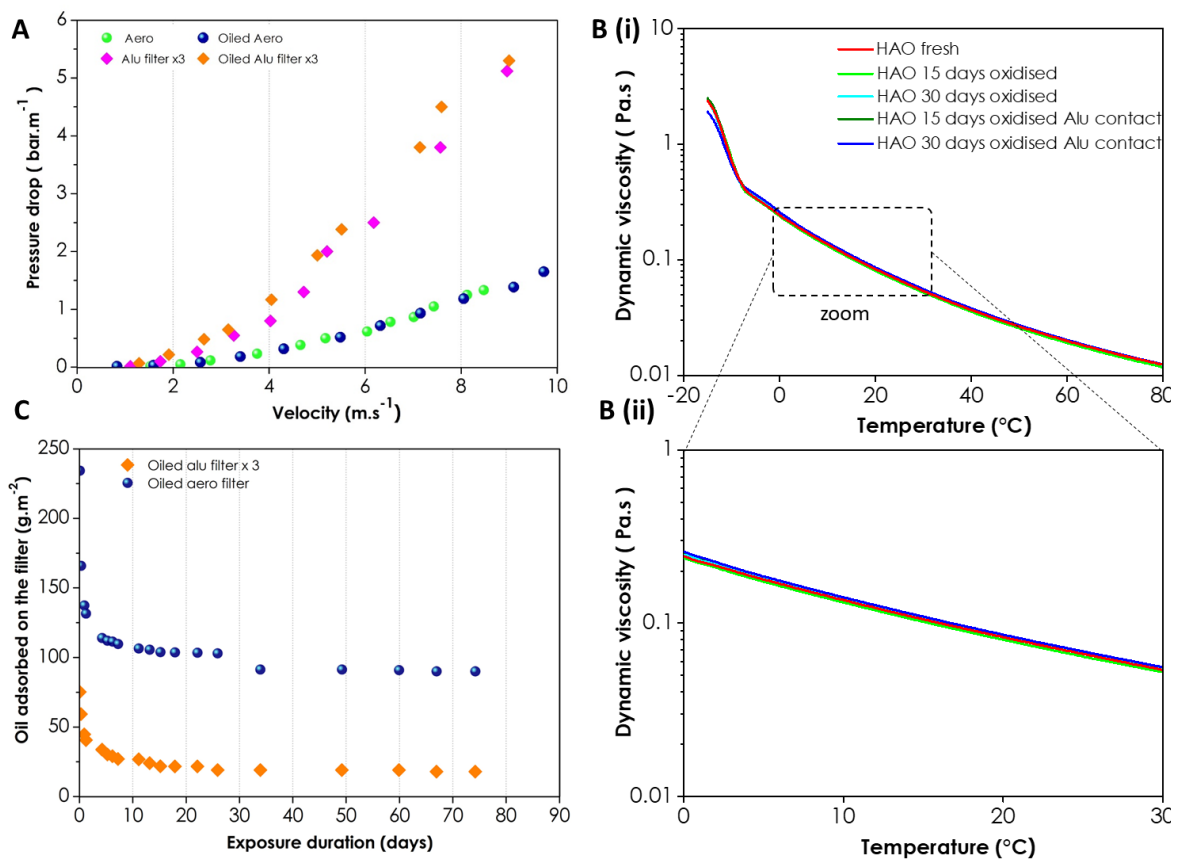


Fig. 2 | (A) Pressure drop measurements on the Aerosleep and an alternative aluminum structure, before and after the oil coating. The aluminum structure was used for highlighting the low-pressure drop across the Aerosleep filter which is the key factor for an efficient harvesting of the PM through such open filter. (B) i) Dynamic viscosity of the olive oil coated on Aerosleep filter vs. Aluminum filter as a function of the temperature. ii) Enlargement of the temperature region of exposure. (C) Oil adsorption capacity measured on the Aerosleep filter vs. an aluminum filter (g. m^{-2}) as a function of time.

The adsorption capacity, expressed in terms of oil weight per surface area of the Aerosleep and the aluminum filter (for comparison) with smaller apertures, was also evaluated and the results are presented in Fig. 2C. The results clearly show higher oil retention in the Aerosleep structure, which could be attributed to some physical retention between the entangled polymer filaments, compared to that obtained on the aluminum structure where lower interaction is expected. Such results confirm the advantage of using a large pore Aerosleep filter for passive outdoor trapping.

III.2. Total PMs loading mass on passive filter

The PM specific total PM loading mass expressed per trapping surface ($\text{g}_{\text{PM}}.\text{m}^{-2}$) of the media filter measured as a function of time of exposure is presented in Fig. 3A. The PM trapped steadily increases with time of exposure and reaches ca. $55\text{-}60 \text{ g}.\text{m}^{-2}$ after about 16 weeks. It is worthy to note that some slight variation can be observed between the different traps which could be due to some inhomogeneity in the air passed through the filter located at different positions. The average PMs loading on the passive traps was calculated from the results obtained on several traps in order to assess the accuracy of the results. It is worthy to note that the error bars become wider with the trapping duration according to the results presented in Fig. 3A. Such results could be attributed to the change of the surface properties of the oil coated film as a function of the exposure duration due to the slowly dries-off of the oil surface. Indeed, at short-term adsorption the oil coated surface remains much sticky which displays higher and reproducible adsorption capacity for PMs, while at long-term adsorption the oil surface could be dried-off and thus, displays lower adsorption efficiency leading to a larger discrepancy between the different measures. However, the adsorption efficiency remains in good agreement with the time of exposure, at least up to 10 weeks, which confirms the advantage of the passive trapping device for outdoor PMs harvesting. The PMs loading attained about 60 g of $\text{PM}.\text{m}^{-2}$ which representing a relatively high loading value for passive adsorption. In addition, the large open structure associates with extremely low pressure drop of our filter also contribute to the avoidance of rapid filter plugging and cake filtration as usually encountered with traditional active filtration devices where low PMs loading could induce high pressure drop across the filter and necessitate higher pumping rate to compensate such phenomenon. Traditional HVAC electret media and nanofiber layer (Tang et al., 2018) or membrane filter (Iritani et al., 2018) displayed rapid increase of pressure drop after a few

gram of PMs loaded, which can lead to cake filtration or PM resuspension, or even the short-term replacement of the filter. The amount of PM slightly decreases afterward for the next consecutive test at 18 weeks. Such results could be explained by the fact that after 14 weeks, the oil layer becomes dry which cannot provide any anchorage surface for trapping PM in the outdoor atmosphere while continuous exposing of the filter results in some PM loss due to the physical detachment of these later from the filter. It is worthy to note that such trapping tests were carried out for a relatively long duration (i.e., several weeks), which confirm the usability of such passive filter for real application. A digital photo of the Aerosleep filter after 18 weeks exposure is presented in Fig. 3B to highlight the dense deposit of PM and aggregates on its surface.

Oil selection procedures were based on laboratory tests on different criteria of diverse vegetable and mineral oils. The preselection is inclined more toward vegetable oil for the reason of their origin, which is not harmful to human health through inhalation, in case of dispersion in air. Deodourized, stabilised industrial olive oil was taken as reference oil because of its weak odour, and stable viscosity after ageing while exposed to temperature and metal contact. The oil amount per filter surface experiment results is shown in Fig. 2C. Oil quantity decreases drastically after infiltration on filters due to gravity and slows down and forms a thin layer on filter structure, reaching approximately $150 \pm 30 \text{ g.m}^{-2}$ on average. After 30 days of exposure, oil can slowly continue dripping, until reaches the stable oil level of 90 g.m^{-2} . Other tested alternatives of olive oil such as sunflower oil (also deodorised and stable in viscosity but higher costs than olive oil) or aqua-soluble mineral oil (easier for washing and regenerable but stronger in odour and higher costs than olive oil) that can be taken into consideration for other outdoor or semi-closed spaces experiments. In Fig. 3H, during the same exposure duration, the coated filter yields much higher than the raw material as a filter support without the oil layer.

Granulometric analysis of the suspension recovered after water washing of a filter exposed for 8 weeks indicates that while fine and ultrafine particles represent a small proportion in the PM distribution by particles volume (Fig. 3C) they are accounting for a much higher proportion when expressed in distribution by numbers of particles (Fig. 3D). These fine and ultrafine particles are the most toxic ones as they easily enter in the alveoli in which clearance is much slower (Peters et al., 1997). A similar trend is also observed for the samples with different exposure duration where fine and ultrafine PMs are clearly visible. The presence of fine and ultrafine PM could be attributed to the traffic conditions of the city road (i.e., stop-

and-go conditions). In such traffic conditions, braking maneuvers are frequent and thus, contribute to the generation of high number of brake-wear particles (Grigoratos & Martini, 2015). The low-speed limit, i.e., 50 km.h^{-1} , also leads to a slow stress for the brake and as a consequence, generates brake particles with smaller diameter compared to those issued from braking at high speed. The influence of the weather on the total PM loading mass is presented in Fig. 3F for different duration and as a function of the time period between March to July 2022. According to the results, the replacement of the filter every two weeks (light blue dot) leads to a slightly higher cumulative total PM loading mass compared to the single filter left for the same cumulative period (i.e., six- and eight weeks vs. two weeks). It is worthy to note that a discrepancy in terms of PM trapping was observed for the period from 25 May to 8 June (indicated with arrow) which could be attributed to the fact that heavy rains occurred during this period which could significantly reduce the PM concentration in outdoor air. Such results could be attributed to the surface properties of the coated oil which could undergo slowly dried off, leading to a lower total PM loading mass, compared to the fresh oil coated for the sample evaluated every two weeks.

Granulometric analysis on various filter samples and different exposure periods show a deficit of PM under $0.3 \mu\text{m}$ of diameter. Furthermore, PM under $0.1 \mu\text{m}$ is nearly missing in both particle number and volume reports. As ultrafine particles typically originate from incomplete combustion of biomass such as wood heating and traffic emissions, the existence of PM_{10} is confirmed, especially in near-source environments such as residence areas or dense traffic roads (C.-C. Lin et al., 2005; Zhu et al., 2002, p. 201). By the reason of the limit of detection, PM concentration data includes undersize PMs in PM_{10} . A few PM under $0.3 \mu\text{m}$ can be detected with SEM images (Fig. 7G and 7H), but their number and volume did not match the bigger range of the granulometric DLS test. Combining with the low-pressure drop of the filter structure, ultrafine particles $\text{PM}_{0.3}$ are likely to follow the airflow and are less captured by the filter than by upper sizes. These results showed real potential of PM trapping from 1 to $10 \mu\text{m}$. Particles and aerosols bigger than $10 \mu\text{m}$ like vegetable debris, dust, insects, etc. can also be trapped by clogging, and removed during the washing step. In order to assess the DLS results obtained on the passive trap we have also compared these results with those obtained in another PM monitoring site (Danube station) of the ATMO Grand Est service, equipped with a TEOM (tapered element oscillating microbalances) system, localized at few meters above the ground in the court of the front building (Solange Fernex elementary school) at a distance of ca. 30 m from our passive trapping device. The data at the same period of

measurement as our passive traps were collected from the on-line website of the ATMO Grand Est (<https://www.atmo-grandest.eu/>). The data from the Danube station are summarized in Fig. 3E and compared with those obtained on our passive traps (Fig. 3D) for the same period of exposure. According to the results the PM distribution as a function of the ultrafine PM particle size ($<1 \mu\text{m}$) remains very close between the two samples. The main discrepancy comes from the large PM particle size ($2.5\text{-}10 \mu\text{m}$) where a higher PM percentage was observed by the TEOM analyzer compared to the passive trapping value. Such difference could be explained by the fact that our passive trapping device is located on the ground between two traffic routes while the TEOM is located few meters above the ground. On the ground level, the passive trapping device is surrounded by vegetation which could adsorb PM_{10} with high inertial energy from the road side through inertial impaction and thus, artificially decreases its concentration while on the other side of the building, part of the PM_{10} can be lifted off by wind and being detected by the TEOM analyzer. Indeed, for small particulates, in the range of $0.05\text{-}0.5 \mu\text{m}$, which are much small to have enough momentum for inertial impaction and thus, their capture becomes most challenging compared to large ones (C.-S. Wang, 2001). All in all, such comparative data confirms in part the relatively high effectiveness of the passive oil-coated traps to adsorb PMs in outdoor air.

Trapping process in outdoor environment could be significantly influenced by the PMs concentration which was directly influenced by the outdoor weather and period of time. For such assessment, two series of trap were evaluated at two different periods of the year, i.e., March and July, where the weather and the traffic induced a significant change of the PMs concentration in the outdoor air. According to the results obtained, the total PM loading mass was almost two times higher, i.e., 30 g.m^{-2} (samples analyzed between June 22nd to July 20th) vs. 17 g.m^{-2} (samples analyzed between March 2nd and March 30th), for the filter exposed during July (Fig. 3F). It is expected that, during July, the decrease in wind speed and the higher traffic of heavy-duty trucks could contribute to the higher PM concentration in the atmosphere which could contribute to a higher total PM loading mass (Le et al., 2020). The increase of the RH could also directly impact the aerodynamic size of the PMs due to secondary reactions with water droplets containing dissolved salt such as ammonium. These results indicate that such passive trapping system can offer a viable alternative for the reduction of outdoor PMs air pollution, and especially during the period of pollution peaking due to an increase of traffic.

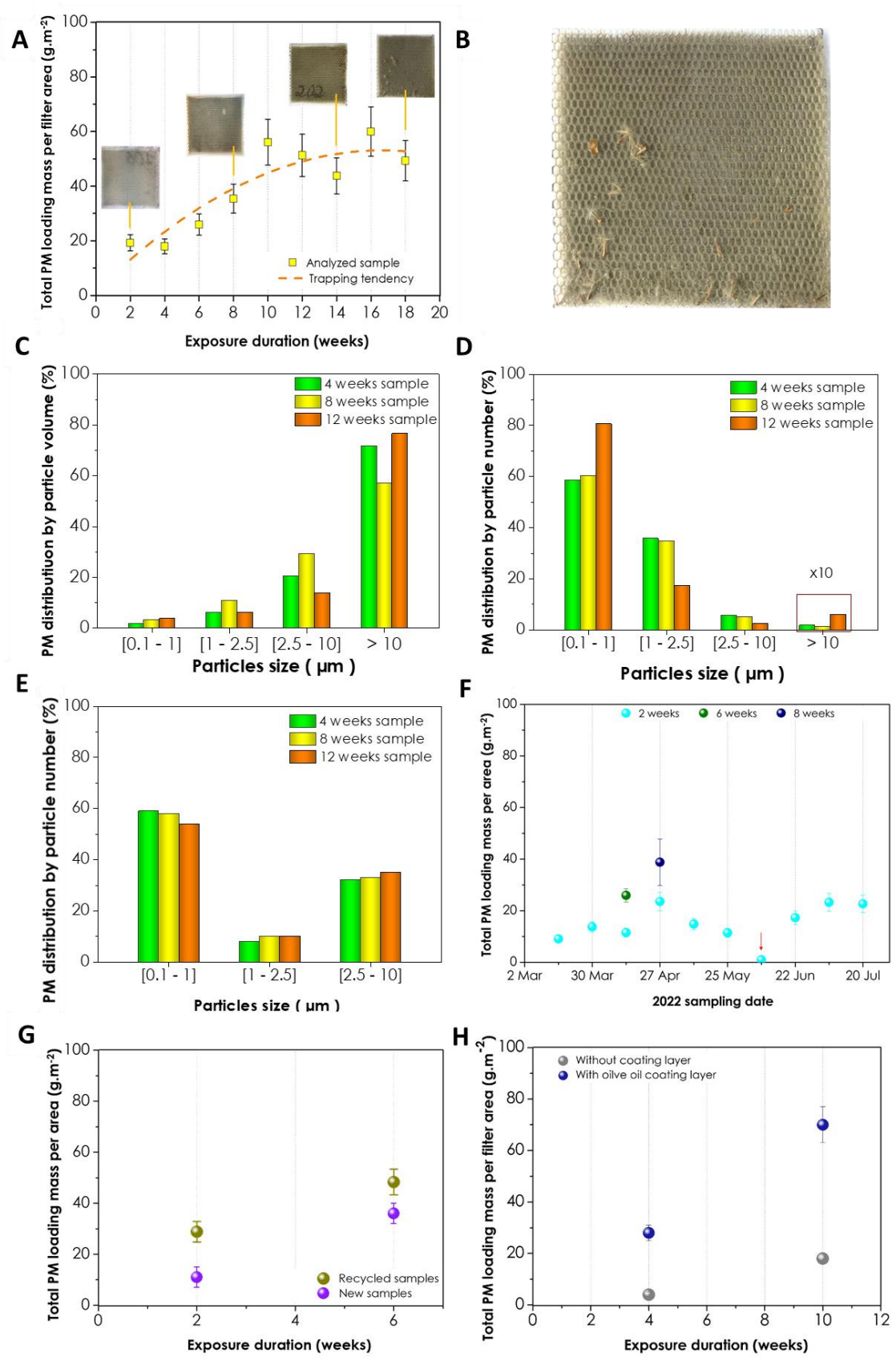


Fig. 3 | PM total PM loading mass per area as a function of time of exposure. **(A)** The average PM in weight trapped per surface unity of the filter as a function of time of exposure next to an urban area. Inset **(B)**: Digital photos of the filter color as a function of time of exposure (2,8, 12 and 18 weeks). **(C, D)** Average distribution of the trapped PM, expressed in terms of particle size distribution in volume and in number, measured by DLS technique in the suspension after a washing step in soap-water solution at 80 °C of the spent filter after 8 weeks of time of exposure. **(E)** PM distribution by particle number, based on PM concentration data collected from ATMO Grand Est. **(F)** Weather impact monitoring using fresh samples at fixed position on the prototype **(G)** PM total loading mass per area between the fresh and regenerated filter showing the complete retention capacity of the total PM loading mass during the same period which confirms the possible re-use of the filter for several trapping processes. **(H)** PM total loading mass per area between samples with and without the oil coating layer, exposed to the same weather condition and equivalent exposure durations.

III.3. Computational simulation

Simulations were firstly carried out to assess the aerodynamics of the trap without any other obstacle and considering a perpendicular incident wind speed of $1.5 \text{ m} \cdot \text{s}^{-1}$ at 10 m high. According to the simulation results illustrated in Fig. 4, the airflow decreases in front of the filtration device due to the formation of vertical and horizontal vortices at the basis of the device (concrete base), but, thanks to the large porosity of the filter media, the flow increases again through the filtration device. Such numerical results confirm the relatively high flow rate passing through the filter to ensure the high PMs trapping, as the loading mass depends on the number of PMs coming in contact with the filter surface. Figure 4 presents the numerical results on airflow, specifically wind velocities and directions, obtained through computational fluid dynamics (CFD) simulations. These simulations were conducted in the absence of any obstacles and assumed a perpendicular wind direction. The primary objective was to understand how wind flows through the filter and to identify any preferential areas of flow using this filter configuration. Reproducing these conditions in a laboratory setting posed significant challenges, primarily due to the size of the device, which would have required a very large wind tunnel as those used in the aeronautic industry. Consequently, numerical modeling was employed as a viable alternative to experimentally investigate the airflow dynamics.

By using the pressure drop data from the experiments, the simulations aimed to provide a realistic representation of the airflow through the filters, ensuring the results were

comparable to experimental conditions even though direct experimental replication was not feasible.

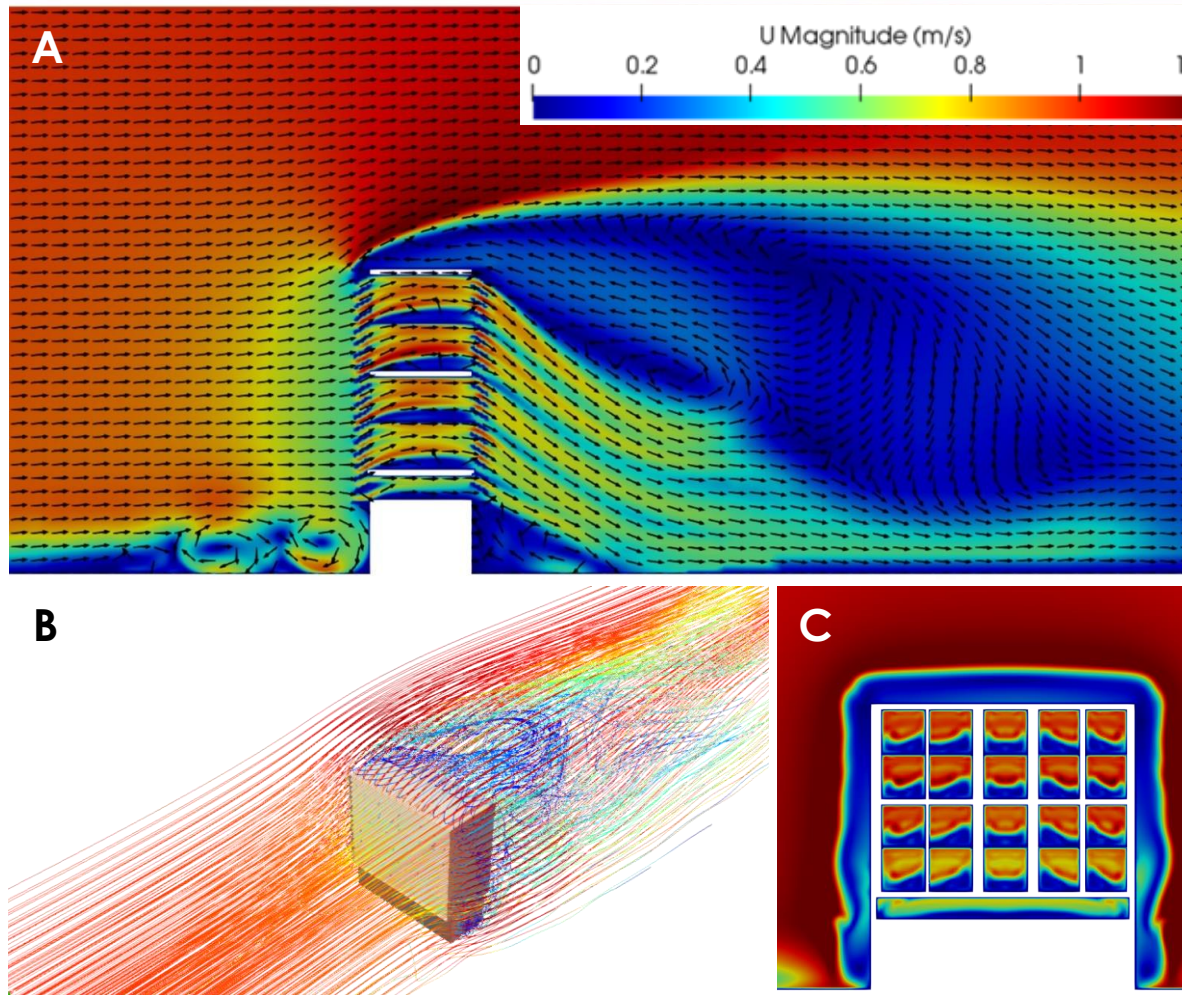


Fig. 4 | Computational fluid dynamics simulation results confirm the relatively high airflow passing per unit of time through the filter to ensure the high PMs trapping. The simulation results were based on the data, airflow and direction, furnished by the meteorology center for the area of implementation. | (A) Lateral view, airflow directions are illustrated by black arrows. | (B) Top view, turbulence is created on the downstream of the prototype. | (C) Wind gradient shows the wind velocity distribution between cases.

The morphology of the PMs trapped on the filter as a function of time of exposure was also analyzed by SEM and the results are presented in Fig. 5. At short exposure time (2 weeks) the surface of the spent filter remains relatively well preserved due to the low density of the trapped PMs (Fig. 5A and B) despite a relatively large number of small PMs, i.e., PM₁₀ and PM_{2.5}, can be clearly observed (Fig. 5C and D). One can also observe the presence of ultrafine

PM₁ in some area of the trap (Fig. 5C). Increasing the time of exposure from 2 to 8 weeks leads to a rapid coverage of the filter surface by a large number of PM with small size as evidenced in Fig. 5E and F. Some aggregates with bigger size can also be observed on the sample after long-term exposure. Such aggregates could be generated through merging of small PM as a function of trapping time into secondary particles with bigger size (Fig. 5E), while small PMs are still being observed on the different parts of the sample (Fig. 5F). Another fact that needs to be taken into account about the size of the trapped particles is the motion and contact of the primary particle with other materials during the lap of time between their emission and their trapping. Indeed, once emitted and deposited on the road surface, tire abrasion particles could attract dust or other elements due to their intrinsic properties, i.e., flexibility and good surface adhesion, and also to their roughness. The aggregates formed thus contain not only the original primary particle but also secondary elements which are present on the shell of the particle.

Continuous exposure time up to 12 weeks leads to a high coverage of the filter surface by PMs as evidenced in Fig. 5G and H. The large aggregates become more present on the filter surface with time of exposure and are in good agreement with the hypothesis advanced above about the merging of small PM with time. However, according to the results presented in Fig. 3A the filter displays total PM loading mass up to 14 weeks despite that the slope of the curve is flattened between the twelve and fourteenth weeks.

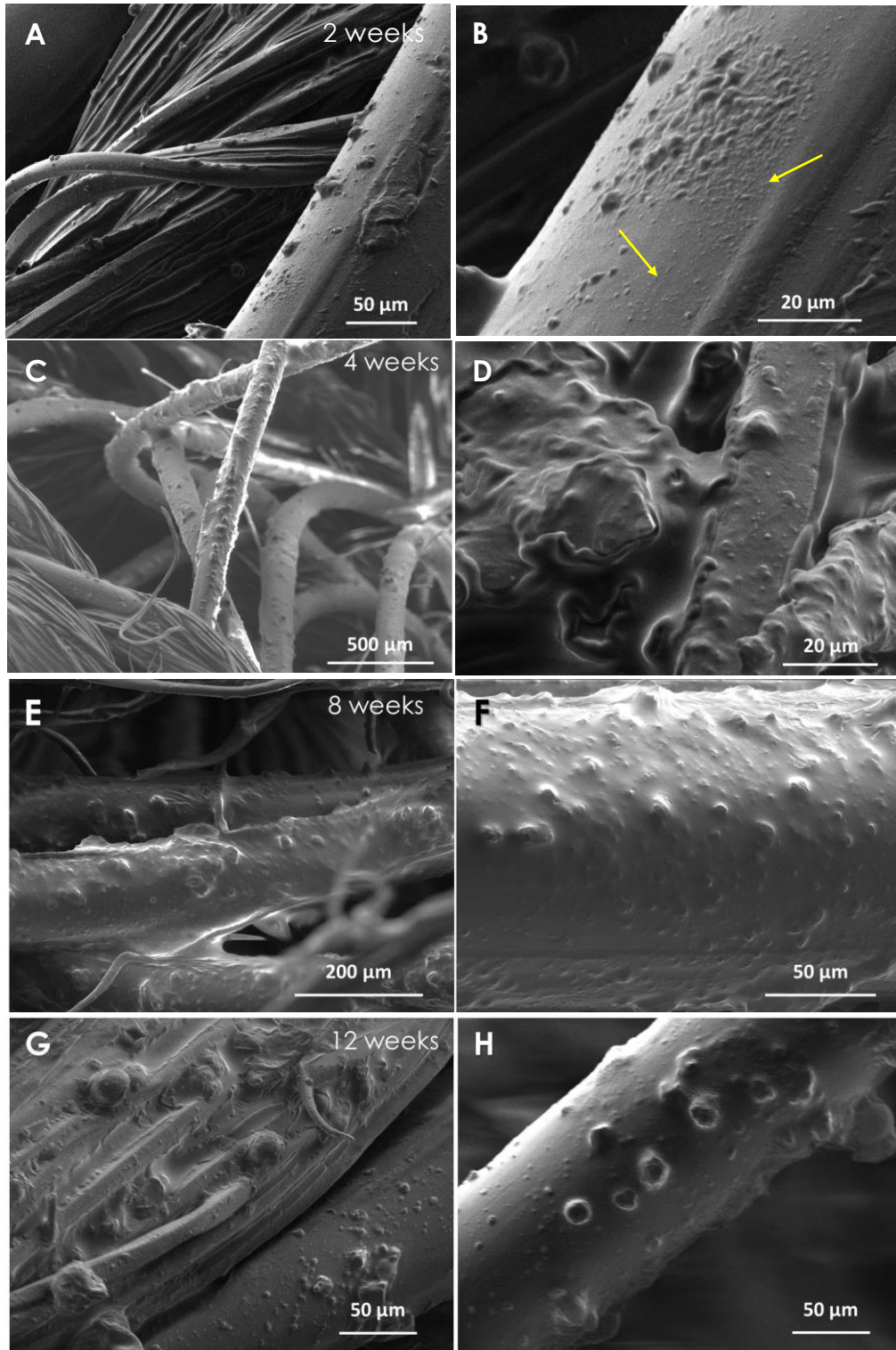


Fig. 5 | Representative SEM micrographs of the trapped PM on the structured filter as a function of time of exposure. (A-B) 2 weeks, (C to D) 4 weeks, (E to F) 8 weeks, and (G to H) 12 weeks. The as-received filters were dried at 60 °C in an oven for overnight in order to reduce the oil thickness on the top surface of the samples before the SEM analysis. The trapped PM started to aggregate from each other as a function of time of exposure leading to the formation of medium to large patches on the surface of the filter.

The representative SEM micrographs of the Aerosleep filter coated with a thin layer of olive oil are presented in Fig. 6 for comparison. On the freshly oil-coated filter, the surface is extremely smooth, and no trace of any solid particles is observed except some very tiny dots which could be due to the air exposure of the sample during the transport to the SEM apparatus.

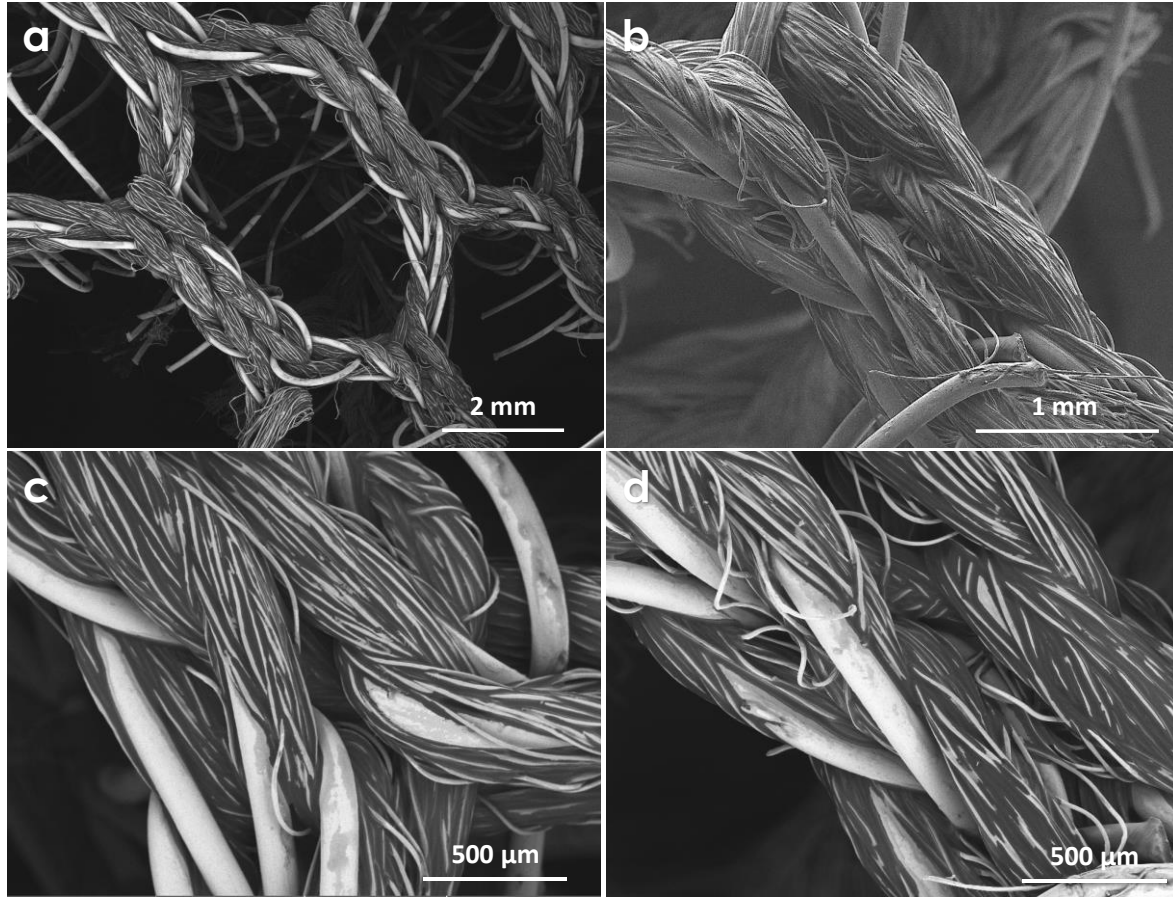


Fig. 6 | Representative SEM micrographs of the Aerosleep filter coated with a thin layer of olive oil before exposure to outdoor air displaying a clean surface.

The EDS analysis of the PM recovered on the filter after 4 weeks of exposure confirm the presence of carbon as the main constituent with some traces of metal (oxides) (Fig. 7A to F). It is expected that carbon-based material is originated from abrasion of the tires in contact with the road. Such carbon element is expected to be constituted by the tire treads which are constituted by styrene butadiene rubber which is mixed with natural rubber and additives (Sundt P., Syversen F., Skogesal O., Schulze P. E, 2015). The metal (oxide) particles, especially Ni and Al, could be issued from the car braking which release hot metal nanoparticles which are further oxidized in air. Silicon (probably in the form of silica or silicate) has also been detected in a non-negligible amount on the filter and could be attributed

to be issued from the abrasion of tires during the contact with the road. However, such element cannot be exclusively ascribed to the tire wear as it is common in other road construction materials, i.e., road wear, concrete and soil. The distribution of the PMs size mapped by SEM was also evaluated and the results are presented in Fig. 7G and H and confirms the performance of the filter for trapping small particles in outdoor air. The results confirm the presence of several main elements (carbon, oxides) in the airborne PM. However, some very small particles, i.e., secondary deposition through contact with the primary particles as discussed above, could represent higher toxicity and cannot be accurately detected by the SEM technique (Malachova et al., 2016; Wik & Dave, 2006). In addition, it is worthy to note that these abraded particles, regardless primary or secondary ones, can be re-suspended by either wind or turbulence create by the passing traffic, especially $PM_{2.5}$ and PM_1 with low sedimentation velocity which can remain for long duration in the atmosphere.

The size distribution of the PM trapped on the filter, according to the SEM analysis is presented in Fig. 7G and H, as a function of time of exposure, i.e., 4, 8 and 12 weeks. The results display lower fraction of fine and ultrafine PM particles compared to that observed by DLS analysis (analyzed with the same filter). Such difference could be simply explained by the fact that for SEM analysis only the visible PM on the surface can be accounted while thus located within the oil matrix are not accessible while for the DLS, all the trapped PM is accounted in the analysis. The SEM analysis also relies on the measurement of the visible PM and thus, some agglomerates of small individual PM could be accounted for one with larger size which could explain the discrepancy between the DLS and SEM methods on the particle size distribution.

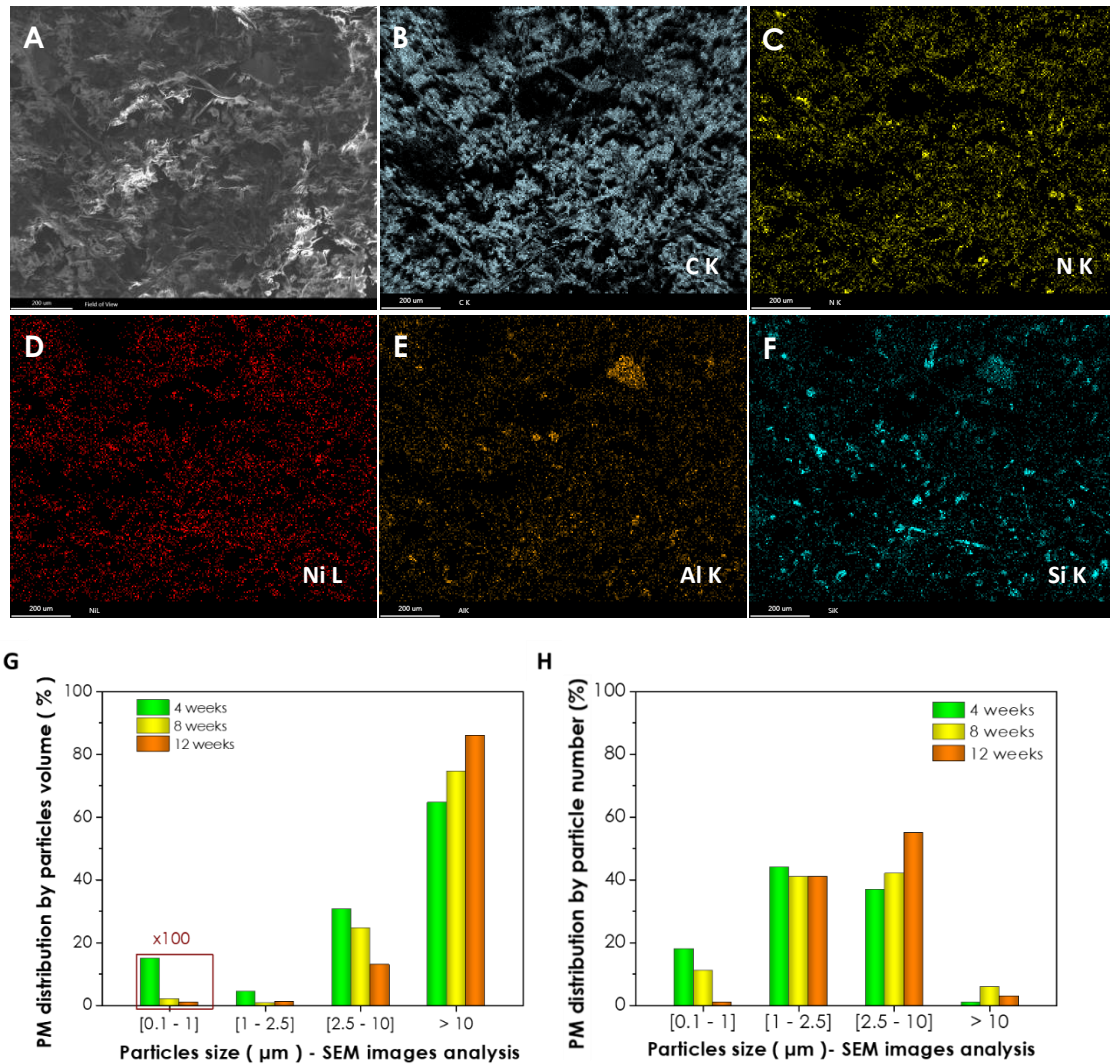


Fig. 7 | (A) Low magnification SEM micrograph of the trapped aggregates recovered on the filter after washing of the filter upon exposure on the test site for 4 weeks. | (B-F) Elemental mapping of the main constituting elements in the aggregates: C, N, Ni, Al and Si. | (G, H) Average particle volume and number as a function of size distribution of the recovered PM trapped determined from statistical SEM analysis. The values were determined from a counting of more than 300 particles.

TEM analysis was carried out on the suspension recovered after a water washing step of spent filters. TEM micrographs clearly evidence the presence of small particles with size ranged between 50 to 200 nm embedded in an agglomerate composite (Fig. 8A, C and E). EDS analysis indicates that these particles are mostly constituted by carbon (tire wear debris as discussed above) and oxygen but different elements such as Si (mostly as silica or silicate), Al, Fe (belonging to tires and brakes degradation) are also detected. Sulfur element was also detected in the sample and could be originated from the tires degradation, but it can also come

from the asphalt as well where it could contribute to 2 to 6 wt.% depending on the origin of the bitumen (Finkelstein et al., 2004). Sulfur could also provide from sulfide species which are part of the lubricants. Such microscopic solid could remain long enough as airborne matter and can enter alveoli during respiration causing health problems such as cardiopulmonary disease and tracheal cancer (Harrison & Yin, 2000; Jeong et al., 2017).

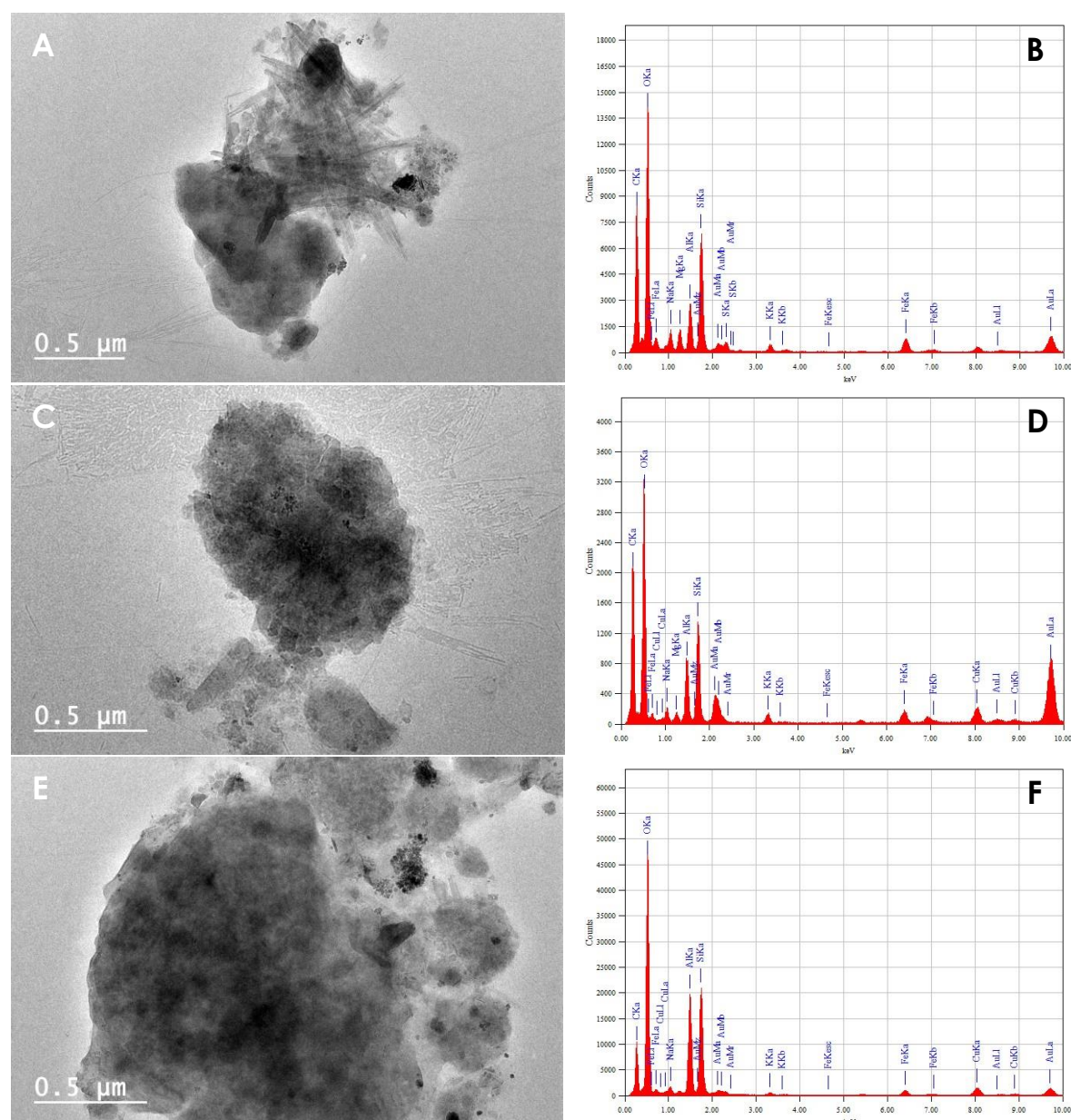


Fig. 8 | Representative TEM micrographs of the trapped PM₁ on the structured filter as a function of time of exposure. (A-B) 2 weeks, (C to D) 4 weeks, and (E to F) 8 weeks. The as-received filters were dried at 60 °C in an oven for overnight in order to reduce the oil thickness on the top surface of the samples before the SEM analysis. The trapped PM started to aggregate from each other as a function of time of exposure leading to the formation of medium to large patches on the surface of the filter.

III.4. Regeneration and re-use

Another parameter which could have a significant impact on the development of such a passive filter is its re-use in order to reduce its environmental impact. Indeed, the new environmental policy significantly pushes ahead the reduction of single-use devices and promotes circularity. For such evaluation the regenerated filter was coated again with an oil layer according to the recipe described in the Materials and Method section and retested for passive trapping during the same period, i.e., mid-June to mid-August with similar weather conditions and similar traffic density. The results clearly confirm the complete maintain of the total PM loading mass of the recycled filter (Fig. 3G). Such possible re-use highlights the advantage of the Aerosleep structure compared to those based on the other filters with single-use which is neither environmentally nor economically affordable despite their high filtration performance (C. Liu et al., 2015; R. Zhang et al., 2016). Representative SEM micrographs of a regenerated filter after exposure to outdoor air are presented in Fig. 9 and confirm the similar total PM loading mass as observed with a brand new filter. Such results clearly confirm the complete regeneration and re-use of the Aerosleep filter in the present work which contribute to the reduction of the cost effectiveness of the process and its environmental impact. The possibility of re-use is also reported by Jung et al. (Jung et al., 2018) on the reduced graphene-oxide foam using model smoke at lab scale.

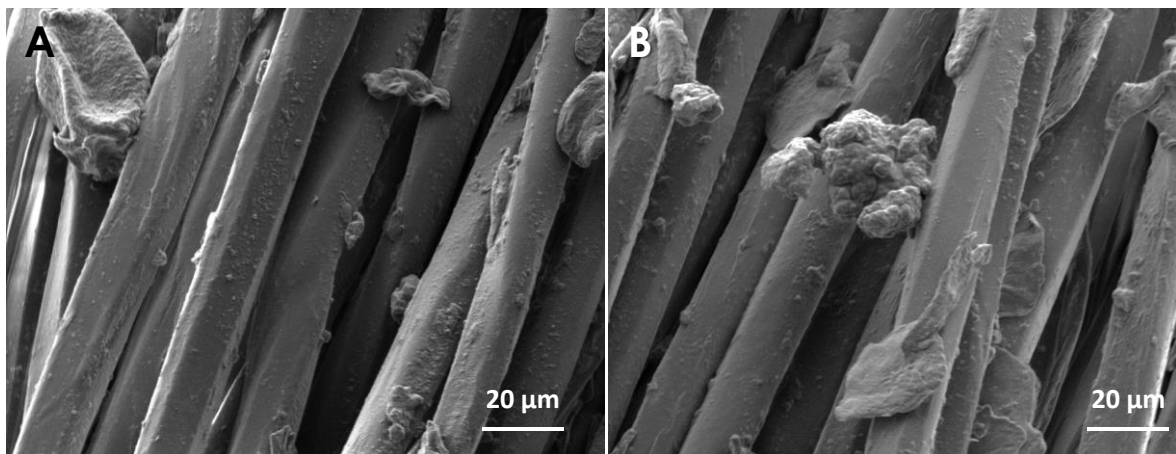


Fig. 9 | Representative SEM micrographs of the trapped PM on the re-use structured filter support, exposed 6 weeks at Rhine Avenue prototype, preceded by washing step and re-infiltration a new coating layer .

The fiber structure, capable of aerosol filtration and reusability (Howarth & Anand, 2016), is made from a washable woven fabric of Polyethersulfone (PES) material, high liquid absorption, resistant to heat and chemical contact (McKeen, 2006). In function of charged PM composition and quantity, as well as the exposure duration, a filter structure can be washed and reused many times without losing its capacity of adsorption oil and PM, as long as the fibers are not damaged and lose their physical and/or chemical properties (degradation of fiber). Fig. 6A to 6D showed the effect of oil infiltration which forms a thin layer of oil on the surfaces of the fibers, and between the fibers themselves. According to researchers (Agranovski, 2010; Müller et al., 2014), this layer can play as the adsorption and retention layer of PM on the support. After the washing step, PM and most of this coating layer are removed from the fibers (Annexe 1). This oil layer can be re-established by renewing the oil infiltration protocol with a new or regenerated support. Last but not least, this concept of regenerable air filtration support, coated by vegetable oil for outdoor passive PM trapping is promising for other materials and oil application. Regeneration would be applicable for non-damaged filter structure, as long as the structure is made from low pressure drop, washable materials, and good for oil adsorption without clogging, coupling with stable viscosity, non-toxic oil.

III.5. Simulation for upscale deployment

In this last section, a global impact on the reduction of PM_{10} for the surrounding area of the trap is investigated based on the numerical model set up with the field results obtained in previous sections. Such simulation is based on the data recovered from different organisms and will concern averaged traffic, wind direction and speed with respect to the road, and the number of filtration devices which could be safely implemented along the road for significant reduction of the emitted PMs.

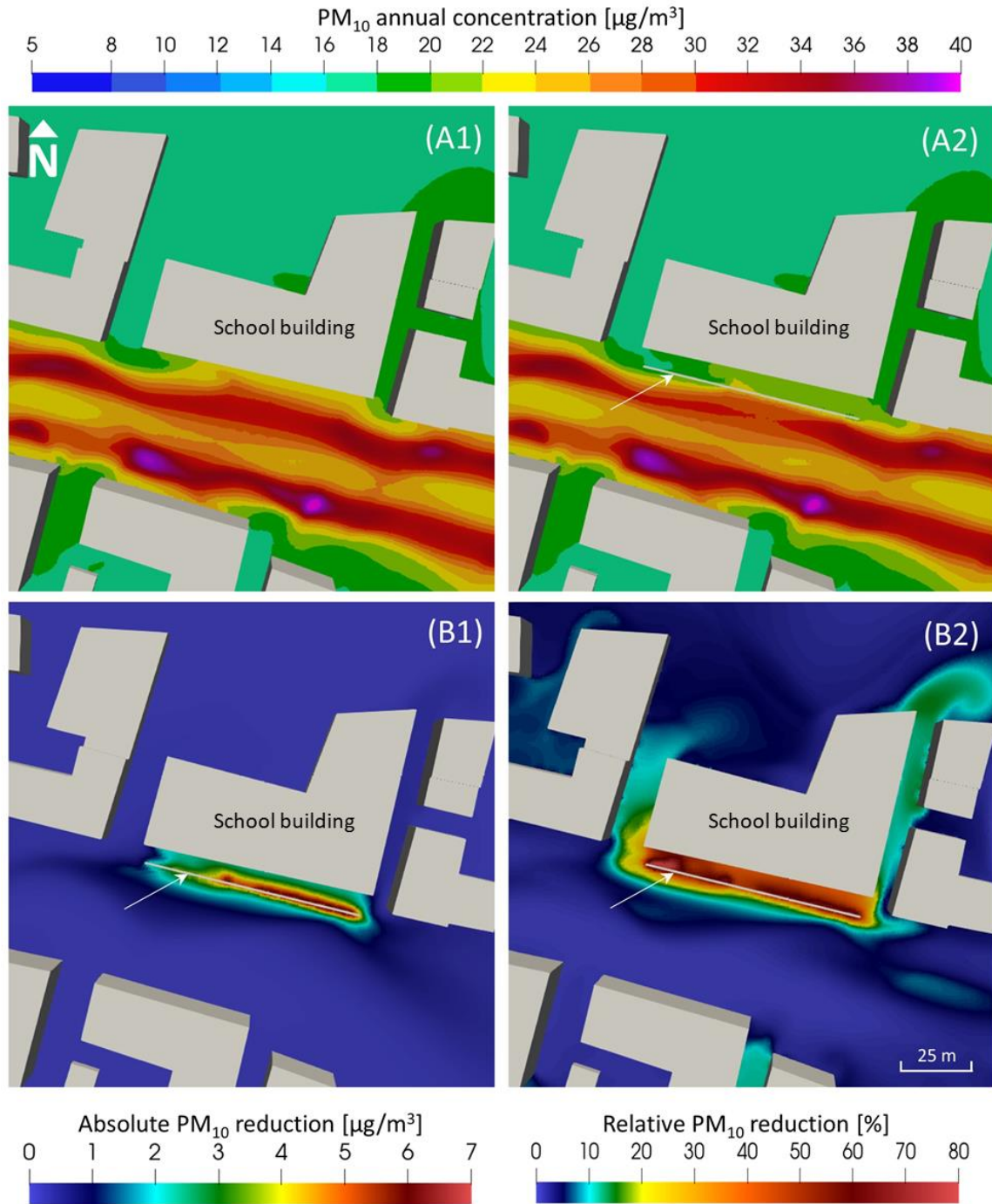


Fig. 10 | Simulation for the reduction of PM₁₀ emitted from the traffic using passive trapping media in (A1) the actual situation without trap and (A2) an up-scaling deployment of the trap between the roadway and an elementary school. | (B1, B2) Modeling results showing the absolute and relative total PM loading mass of the PM₁₀ emitted from the traffic, respectively.

As shown in Fig. 10 (A1), the study area in his actual state has high PM₁₀ concentrations exceeding the annual standard value set by the EU ($40 \mu\text{g}.\text{m}^{-3}$) near the southern road lane, and, more generally in the area, exceeding WHO guidelines ($15 \mu\text{g}.\text{m}^{-3}$). Concentrations can

reach $24 \mu\text{g.m}^{-3}$ on the south side of the school building, and up to $30 \mu\text{g.m}^{-3}$ on the sidewalk. The upscale deployment of traps can reduce these concentrations up to $\mu\text{g.m}^{-3}$ on the south side of the building school and $22 \mu\text{g.m}^{-3}$ on the sidewalk, as depicted in Fig. 10 (A2), corresponding to an absolute PM_{10} reduction of around $3 \mu\text{g.m}^{-3}$ and $7 \mu\text{g.m}^{-3}$ at these locations respectively. Relatively, and without consideration of the local background concentration of $17 \mu\text{g.m}^{-3}$, the use of the present trap induces a reduction of the PM_{10} emitted from vehicles up to 60 % next to the trap, 40 % between the trap and the school, and 10 to 15 % in the alleys adjacent to the school. Finally, as shown in Figures 10 (B1) and (B2), it should be noted that the impact of the trap on reducing ambient PM_{10} concentration is high and significant, but strongly dependent on the trap location, since its beneficial impact on the other side of the road is minimal or non-existent. Its positioning must therefore be strategic and in line with the area to be protected, while CFD modeling can help guide these choices by assessing their impact prior to trap installation.

IV. Conclusion

In conclusion, a new concept of passive coated filter for outdoor PMs trapping has been developed based on the use of a thin film of olive oil coated on a structured polyester host matrix as trapping means. The passive operating mode allows the implementation of such filter device in most of the areas where pollution needs to be reduced, such as stationary or mobile devices, without any need for connecting of the system with an external energy supply source along with a considerable reduction of the carbon footprint as usually encountered with active filtration devices. The low evaporation rate and the sticky surface of the oil film provide highly PM loading surface for airborne particulate matter as well as for long-term operation before the regeneration process, i.e. > 14 weeks. The filter developed can be operated under high natural air flux with very low-pressure drop which allows one to trap a high amount of PMs in the outdoor environment. The spent filter can be easily regenerated and reused without losing PM loading mass capacity. The loading mass remains unchanged which confirms the high stability of the system for repeated uses. The results show that PM trapped along high traffic city roads is mostly consisted with small particles which can be attributed to the low velocity of the cars and frequent stop-and-go conditions. Such passive and highly loading mass potential filter could represent an alternative for the reduction of small airborne PMs, also including $\text{PM}_{2.5}$ and more dangerously PM_1 , which can seriously affect the living environments in terms of air quality and are expected to be at the origin of the reduction of

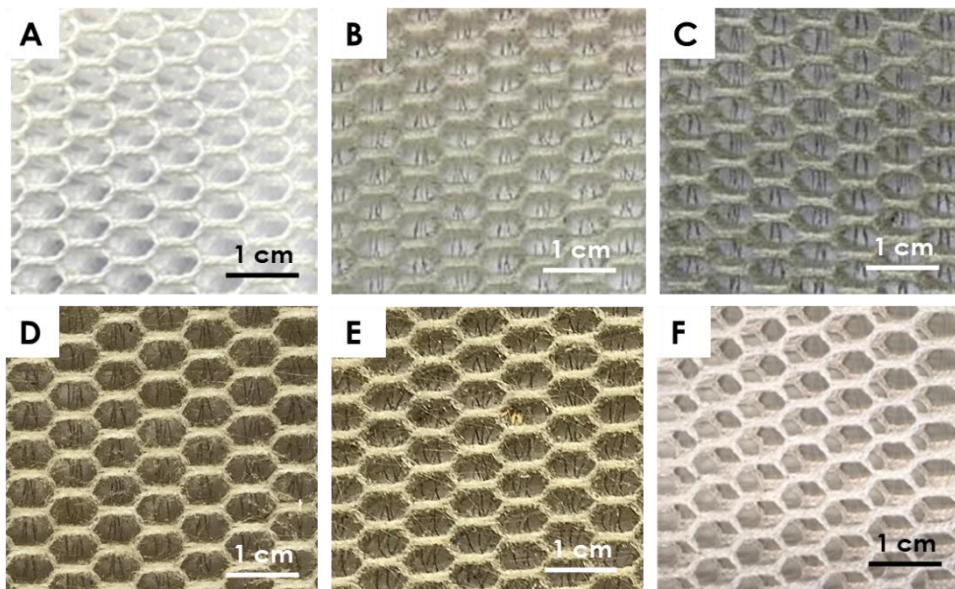
life expectancy. The loading mass of the filters in the outdoor environment being, nonetheless, strongly dependent on their location, upstream studies must be conducted before placing them in order to select their best location with, for example, the help of numerical modeling such as computational fluid dynamics (CFD).

Work is ongoing to evaluate such passive traps in a semi-hermetical environment such as underground train station where large PM concentration, issued from the train braking, especially PM₁ which are unregulated nowadays, is presented which poses serious health problems for the passengers and workers.

Acknowledgements

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Annexe



Annexe 1. Digital photos of the filter structure after exposed at outdoor Rhine Avenue prototype. **A.** 0 week; **B.** 4 weeks; **C.** 8 weeks; **D.** 12 weeks; **E.** 16 weeks; **F.** Washed and dried filter structure.

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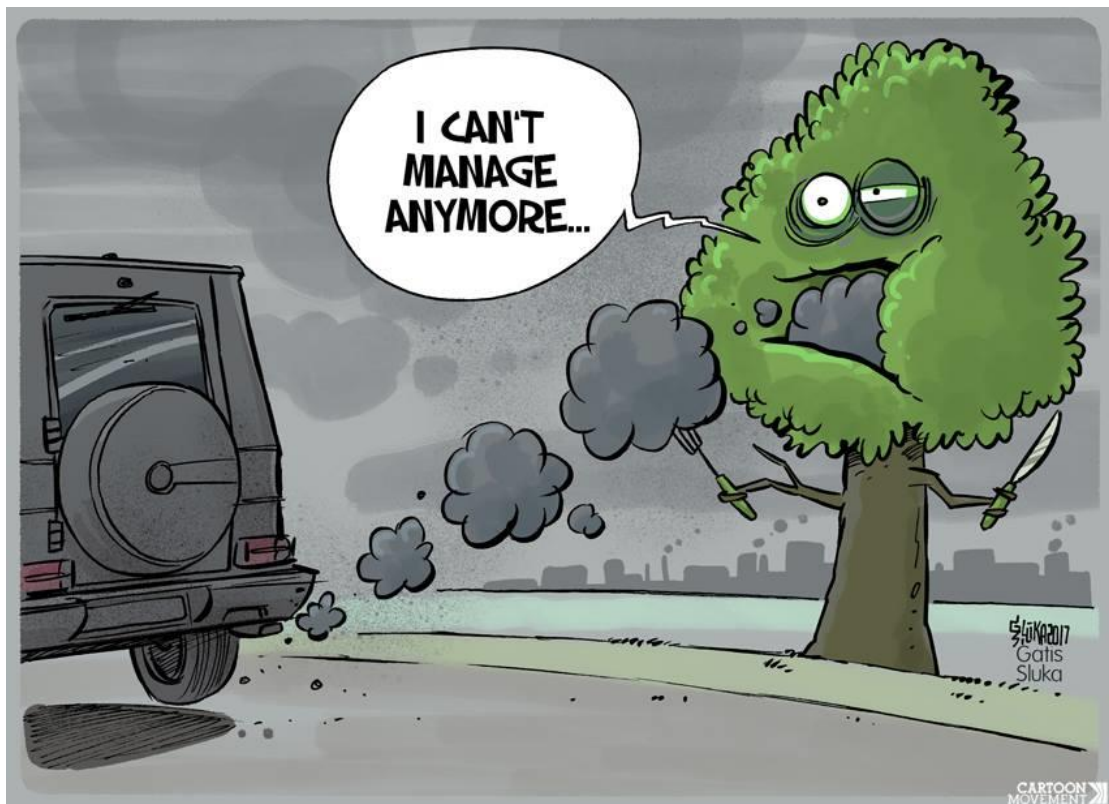
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CHAPTER 3

PASSIVE PM TRAPPING DEVICES : RING ROAD



Passive PM Capture by Reusable Oil-Coated Structure and weather impacts on PM trapping process

(Case study on a busy ring road in Strasbourg City, France)

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Abstract

Particulate matter (PM) from traffic emissions is a major public health issue in urban environments. This study evaluates a novel passive air filtration prototype that was strategically installed along a high-traffic ring road in Strasbourg, France. The filter, composed of a porous polyester fiber matrix coated with a thin layer of vegetable oil, operates without the need for any external energy input. Over a 14-week period, the filter achieved a total PM capture rate of up to $84 \pm 6 \text{ g. m}^{-2}$. Chemical characterization indicated that the majority of trapped particles originated from tire and pavement abrasion, with minor contributions from metallic particles likely related to high speed braking activities. PM capture efficiency varies with meteorological conditions, highlighting the influence of environmental factors on system performance. Regression models demonstrated the impact of oil viscosity on the quantity of PM captured during the experimental period. These findings support the potential of passive, low-maintenance filtration systems as a scalable strategy for reducing PM exposure near roadways, especially in sensitive or semi-enclosed urban settings.

I. Introduction

Particulate matter (PM) refers to solid or liquid particles suspended in the air, typically classified by their aerodynamic diameters as PM₁₀, PM_{2.5}, and PM₁ (particles smaller than 10 µm, 2.5 µm, and 1 µm, respectively). These particles originate from a wide range of natural and anthropogenic sources (Karagulian et al., 2015; McDuffie et al., 2021), with their composition and concentration strongly influenced by emission sources and meteorological conditions. In urban environments, PM has emerged as a major public health concern, alongside other airborne pollutants (Fuller et al., 2022; Pope, 2007; Schwartz et al., 2021; WHO, 2021). Recent research has improved our understanding of PM transport, emphasizing particle tracking (W. Li et al., 2023; Reiminger, Jurado, Vazquez, Wemmert, Blond, Wertel, et al., 2020; R. Zhang et al., 2015) and the role of weather in PM formation, dispersion, and deposition processes (Ehrnsperger & Klemm, 2022; Vallero, 2014).

Among urban sources, traffic-related emissions are a major contributor to ambient PM (Grigoratos & Martini, 2015; London & Romieu, 2000; Pant & Harrison, 2013). These emissions include both exhaust particles, primarily soot from combustion, and non-exhaust particles such as metal debris and wear particles generated from brakes, clutches, tires, and road surfaces (Beji et al., 2021; McDuffie et al., 2021). Many of these particles carry adsorbed toxic or carcinogenic compounds (Lewtas, 2007), significantly contributing to respiratory and cardiovascular diseases. In France alone, PM exposure is estimated to be responsible for up to 48,000 premature deaths annually from both indoor and outdoor sources combined (Pascal et al., 2016). Consequently, reducing PM levels is a critical target for sustainable urban development and public health improvement.

Traffic emissions are broadly categorized into exhaust and non-exhaust sources. While exhaust emissions originate from the engine combustion process and vary based on factors such as fuel type, engine characteristics, and vehicle age (Ropkins et al., 2009), non-exhaust emissions arise from mechanical abrasion processes such as braking, tire wear, and road surface degradation (Piscitello et al., 2021). Despite the increasing attention on exhaust emission control technologies, non-exhaust sources remain largely unregulated and are often underestimated. Moreover, electric vehicles, though free of exhaust emissions, may emit even greater quantities of non-exhaust PM due to their higher weight. These non-exhaust emissions now account for up to 90% of PM₁₀ and 85% of PM_{2.5} in traffic-related air pollution (Timmers & Achten, 2016).

Once airborne, PM can remain suspended in the atmosphere, be dispersed by wind, or be removed by wet deposition. Rainfall plays a key role in PM removal, not only by scavenging airborne particles but also by washing deposited PM from surfaces such as vegetation (Banks et al., 2022a; L. Chen et al., 2017; Kwak et al., 2023; Poeschl, 2006; Tang, 2023). After deposition, PM accumulates on impervious surfaces, where it can be transported by stormwater runoff into drainage systems and eventually reach aquatic environments. Given the limitations of current wastewater and stormwater treatment infrastructure, a significant fraction of road-related PM, especially from tire wear, is likely to enter natural water bodies, contributing to microplastic and chemical pollution in both freshwater and marine ecosystems (Boucher & Friot, 2017; Kole et al., 2017). These observations underscore the need for upstream PM mitigation strategies.

In current air pollution mitigation strategies, outdoor PM filtration can be categorized into active and passive filtrations methods. Active filtration exploits an energy source to power an active ventilation to create airflow through a medium (P. Li et al., 2014; Zhivov et al., 2020). This method allows for controlled air movement via fans or air extractors, enabling the capture of a wide range of PM, from gross coal dust to nanoparticles. Innovative materials such as electrospun fibrous materials (Lu et al., 2021), carbon-based nanotubes (Chitranshi et al., 2022), and electrets for electrostatic precipitators (R. Thakur et al., 2013), have proved high PM removal rates, but also have many concerns regarding material and maintenance costs, energy consumption, and the requirement of an external energy source (Trinh et al., 2025). These drawbacks can affect the cost-benefit ratio of installing these filters, especially in locations with limited access to electricity sources like outdoor environments. In contrast, passive filtration focuses on the use of natural air currents, and the application of thermodynamic laws in the design of house or air filtration systems for profiting the natural airflow and regulating indoor air quality. For example, the Badgir system in Iran plays a crucial role in indoor air regulation, using buoyancy effect and natural airflow (Jomehzadeh et al., 2020; P. Thakur, 2019). In modern house designs, recent studies (De Castro et al., 2020; T. Zhang et al., 2018) suggest the hybrid systems, which alternate between active and passive ventilation modes, and also the possibility to install passive filters on windows for preventing PM (Khalid et al., 2017; Yee et al., 2023). Furthermore, trees and vegetation such as green walls and green roofs at some points can reduce PM pollution (Kwak et al., 2023), but their limit is the destination of PM, once removed off the leaves by rainfall, can pollute the water cycle by rejoining the runoff and sewer system (Sommer et al., 2018). Our recent study

highlighted a prototype of passive air filtration designed for outdoor urban environment, using regenerable, low-pressure drop material, coated by a layer of vegetable oil for enhancing the trapping performance (Trinh et al., 2024). In this investigation, we present experimental results from a passive air filtration prototype deployed along the RM35 ring road in Strasbourg, France. The objectives of this study are twofold: (i) to evaluate the filtration system in a peri-urban location, with dense traffic frequency and higher speed limits compared to the city center avenue studied in our previous publication, and (ii) to investigate the influence of meteorological variables on the variations of PM collected during 10 months of the experiment.

II. Materials and methods

II.1. Prototype of passive PM captation

In this work, we developed a passive, washable and reusable filter designed to capture PM in outdoor environments (Masquida et al., 2018; C. Pham et al., 2021). An experimental prototype was installed from March 2022 to December 2023, positioned 5 meters from the emergency lane of the RM35 ring road of Strasbourg City (48°35'15.7"N 7°43'43.6"E), as illustrated in Figures 1A to 1E. An ATMO Grand Est air pollution monitoring station, which measures NO_x, O₃ and PM concentrations, is located 100 meters from our prototype, at the same altitude and on the same side of the highway. This strategic placement allows for a comprehensive assessment of the filter's effectiveness in real conditions, while also enabling comparisons with established air quality data from the monitoring station.

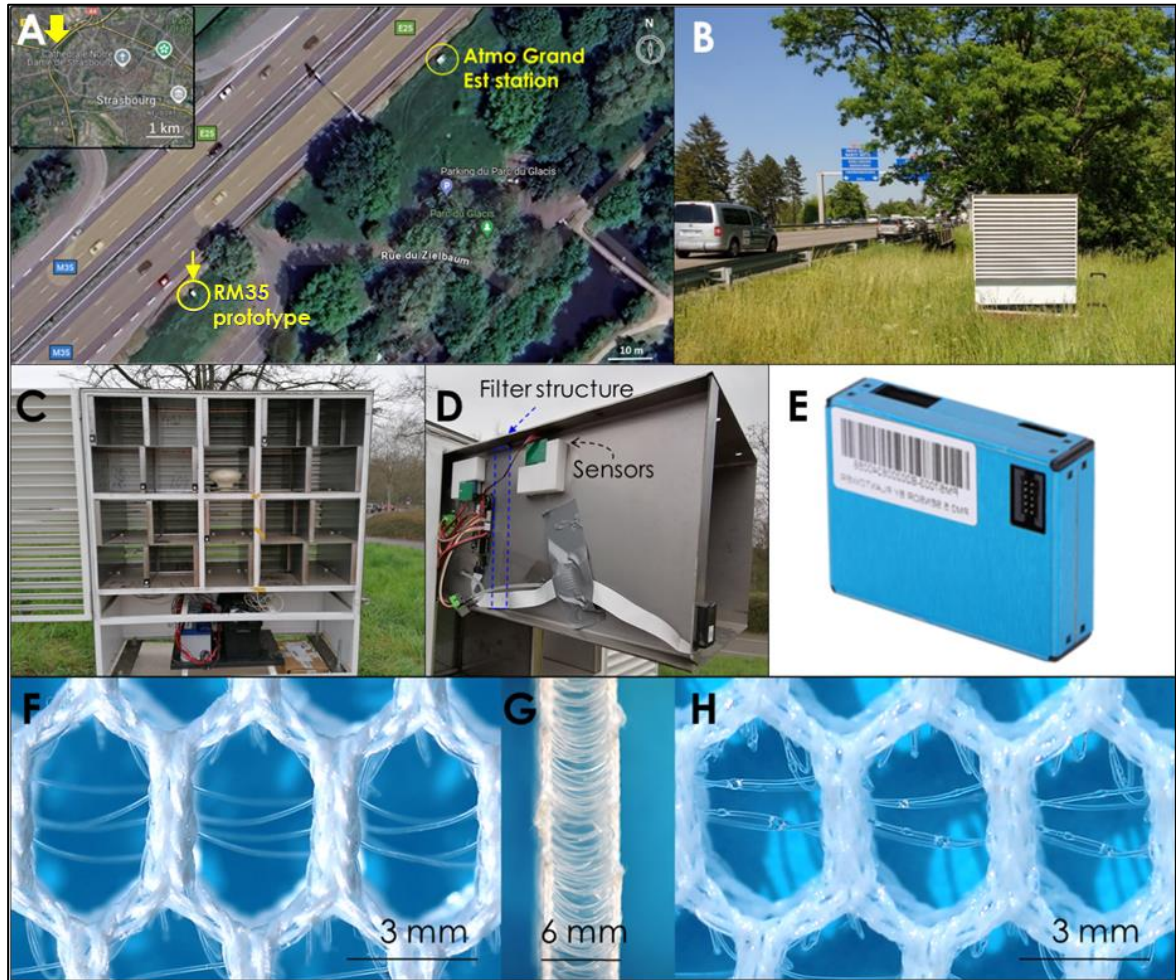


Figure 1 | (A). Position of the prototype few meters from the emergency lane of the RM35 ring road of Strasbourg City, France. | (B & C). Digital photos of the prototype are placed on a concrete socle to ensure stability. The inclined grid prevents rainfall and animal penetration while keeping airflow circulation. | (D & E). Digital photos of Plantower PMS7003 sensor and their installation in the prototype. Two sensors are set on two sides of the filter. | (F, G and H). Digital photos of the filter structure support, before and after coating with a vegetable oil layer. A few oil beads can be clearly spotted on the small fibers

The 24h average concentration of PM₁₀ during this period, estimated using data from ATMO Grand Est, is 25 $\mu\text{g} \cdot \text{m}^{-3}$. Under normal conditions, traffic circulation is limited to 70 km. h⁻¹, with an estimated annual daily average of 164,000 vehicles contributing to PM emissions (EMS, 2024). The prevailing natural wind direction in this area follows a NE-SW axis, which closely aligns with the direction of the traffic route. The prototype box was implanted on a concrete base, with a ventilation grid to prevent precipitation and animal intrusion. This box can contain twenty samples of filters measuring 22 x 22 cm, and it is equipped with different sensors to monitor in-situ weather conditions. Three-dimensional (3D) warp-knitted spacers of Polyethersulfone fabric was used as filter structure for outdoor

PM passive filtration (so-called Aero). This fabric, composed of two layers connected by spacer yarns (Fig. 1F to 1H), offers several advantages, such as a lower pressure drop compared to active filters (Bourrous et al., 2016; Callé et al., 2002), a great resistance to tensile strength and chemical degradation allowing the possibility for washing and reuse (Howarth & Anand, 2016; McKeen, 2006). These last criteria are very important for reducing waste and favoring material reusability and sustainable development.

II.2. Samples preparation and laboratory analysis

Fresh coated filter structures have been prepared and installed in different positions on the prototype. The exposure duration depends on the series of tests conducted, i.e., PM quantity variation with weather monitoring every 2 and 4 weeks; PM quantity evolution over periods of 2, 4, 6, 8, 10, 12, 14, 16, and 18 weeks; PM quantity comparison between different filter structures and coating liquids. In the framework of this part, we will focused exclusively on data related to the 3D warp-knitted spacer structure and coating liquid as a reference (Aero coated by deodorized olive oil), in order to keep the coherence and comparability across different time periods. Scanning electron microscopy (Tescan Vega 3) was used for taking images of the material, filter surfaces, PM, at different scales. Chemical element mapping analyses were performed using a Zeiss Gemini SEM 500 scanning tunneling electron microscope, which is coupled with an energy-dispersive X-ray spectroscopy EDAX SDD system. Particle composition analysis was also conducted using a JEOL ARM 200F transmission electron microscope. The granulometry of particles harvested in the washing solution is classified using a Malvern Mastersizer 3000 granulometer, which analyze particles ranging from 0.01 to 2000 μm . A Testo 435-1 anemometer and a Ehdis CR410 digital Manometer were used in order to measure flow velocity and pressure drop, respectively. The viscosity of the oil was characterized using a TA Instrument DHR3 rheometer, which is equipped with a Pelletier disc. More details about protocols of material selection, preparation and characterization techniques are described in Trinh et al. (Trinh et al., 2024).

II.3. Data collection

As part of our project, low-cost in situ laser sensors, Plantower PMS7003, were used to measure atmospheric parameters, including atmospheric pressure (P), temperature (T°), PM concentration ([PM]), air flow velocity and direction, and relative humidity (%RH) (technical

specifications available in Plantower, 2024). Data was recorded with an interval of 5 minutes and stored in microSD cards, which were collected every 2 weeks during the campaign. To ensure data integrity and coherency, we develop a Python program that calculates the arithmetic average of the recorded data over specified interval. For clarity, we selected a one-day calendar period from 00:00 to 23:59. The daily in situ data was then compared with measurements from the Strasbourg Entzheim meteorological station (48.55°N, 7.63°E) to assess weather variations. PM concentration were measured at ATMO Grand Est stations using TEOM 1405F equipments (tapered element oscillating microbalances), while daily traffic enumeration was conducted by SIRAC of Eurometropole de Strasbourg using electromagnetic sensors implanted in the road and infrared cameras. On behalf of the 24-hour interval average, data analysis will focus more on daily evolution, as well as on different periods of the campaign, which cover from March to July and from September to December 2022. This comprehensive approach will allow us to better understand the variations in atmospheric conditions and their potential impacts over time.

II.4. Interpolation model of the influence of outdoor temperature on oil viscosity

Linear regression models can be used to predict and interpret the influences of various weather parameters on the evolution of pollution (Dominici, 2002; Dr. Rais Abdul Hamid Khan & Mr. Kshirsagar Sopan Babu, 2024; Pearce et al., 2011). In the beginning of our project, in addition to the simulation works (Trinh et al., 2024), the in situ collected data were attempted to construct regression models to analyze the evolution of trapped PM mass and PM₁₀ concentration during the experimental period. The primary objective is to solve the equation E₁ using the solution provided in equation E₂:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_p X_p \quad (E_1)$$

$$\min_{\beta} \sum_{i=1}^n (y_i - \hat{y}_i)^2 + \alpha \sum_{j=1}^p \beta_j^2 \quad (E_2)$$

With Y the predicted value (PM trapped mass, PM₁₀ concentration for example),

X_i the i^{th} weather parameter,

β_i the attributed weight for each parameter,

y_i the actual target value,

$\hat{y}_i$ the predicted value, i ,

α the tuning parameter, regulating the importance of fitting vs shrinkage,
 p number of parameters,
 and n the number of total training samples.

In case of insufficient data, a correlation matrix can be established to define the correlation between various parameters, and point out one or more significant parameters that can impact the quantity of trapped PM.

Moreover, oil viscosity is closely dependent on temperature evolution. Sanchez-Rubio et al. (Sánchez-Rubio et al., 2006) discussed about the variation of viscosity as a function of temperature (Equation E₃). The kinematic viscosity of a liquid (ν) in cSt, can be calculated using the Walther equation below, where T is the ambient temperature in °K, and A, B and C are constants. C is usually attributed a value of 0.7 for all types of lubricants and oils (Deters & Bartel, 2021), while A and B are experimental values that are usually determined by known viscosity at 40°C and 100°C.

$$\text{Walther equation: } \log_{10}(\log_{10}(\nu + C)) = A + B \cdot \log_{10}(T) \quad (E_3)$$

In recent years, the outdoor temperatures in Strasbourg (KASTENDEUCH, 2022) and the temperature during experiments (from March to December 2022) fell within the temperature range of the viscosity analysis, specifically from -15°C to 80°C. The A and B values were calculated using the measured dynamic viscosity of biological, deodorized olive oil at 40°C and 80°C. The dynamic viscosity (η) in cP or Pa.s, can be converted to kinematic viscosity, as mentioned above, using the formula $\nu = \eta / \rho$, where ρ is the oil density, taken as 900 kg. m⁻³ for the chosen reference oil in our experiment.

A statistical isotonic regression model, previously described in many research studies (X. Jiang et al., 2011), was used for interpolating the coating oil viscosity as a function of average daily temperature (Equation E₃). Suppose we have n experimental points $(x_1, y_1), \dots, (x_n, y_n)$ and a partial order ($\preceq$). In the usual one-dimensional case (Luss & Rosset, 2014), $x_i \preceq x_j$ when $x_i \leq x_j$. The model collects all ordered pairs of data that must respect the isotonic constraint in the index set : $I = \{(i, j) : x_i \preceq x_j\}$. The model was trained with 70% of the randomly arranged data from the oil viscosity experimental measurements and tested on the remaining 30%. It yields new interpolated $\hat{y}_i$ values by solving the solver :

$$\min \left\{ \sum_{i=1}^n (\hat{y}_i - y_i)^2 : \hat{y}_i \leq \hat{y}_j, \forall (i, j) \in I \right\} \quad (E_4)$$

The estimator minimizes the cumulative squared error while imposing the constraint that the fitted values remain monotonic (specifically, non-decreasing) with respect to the specified partial order. The trained model can interpolate oil dynamic viscosity values with a precision up to 0.01 Pa. s.

III. Results and Discussions

III.1. PM trapping on passive filter

The PM specific trapping mass expressed as the total PM mass captured per unit surface area of the filter media (g PM. m^{-2}) over time, is shown in Fig. 2A. The estimation of trapped PM quantity indicated that the trapped PM mass increases steadily with exposure time, reaching approximately $84 \pm 6 \text{ g. m}^{-2}$ after 14 weeks. However, a slight decrease in trapped PM mass is observed during subsequent tests conducted at 16 and 18 weeks. This decline may be attributed to the drying of the oil layer after 14 weeks, which diminishes its ability to provide a stable anchoring surface for PM capture under outdoor conditions. Additionally, prolonged exposure may lead to physical detachment of trapped PM from the filter surface, as the surface is too charged and closely to the clogging state (Fig. 2B).

Granulometric analyses reveal that fine and ultrafine particles constitute a relatively small proportion of the total particle volume (Fig. 2C). This observation can be attributed to their smaller surface areas when compared to fine or coarse particles, with surface areas of $0.03 \mu\text{m}^2$ for ultrafine particles, $19.6 \mu\text{m}^2$ for fine particles ($0.1 \mu\text{m}$) and $314 \mu\text{m}^2$ for coarse particles ($2.5 \mu\text{m}$, and $10 \mu\text{m}$), assuming perfect sphericity. However, ultrafine PM, despite their limited volume contribution is present in significantly higher quantities due to its small size (Fig. 2D), which is a critical factor for toxicity (Chan et al., 1980; Peters et al., 1997), as these particles can penetrate deep into the respiratory system, and diffuse into alveoli where the body's clearance mechanisms are significantly less efficient.

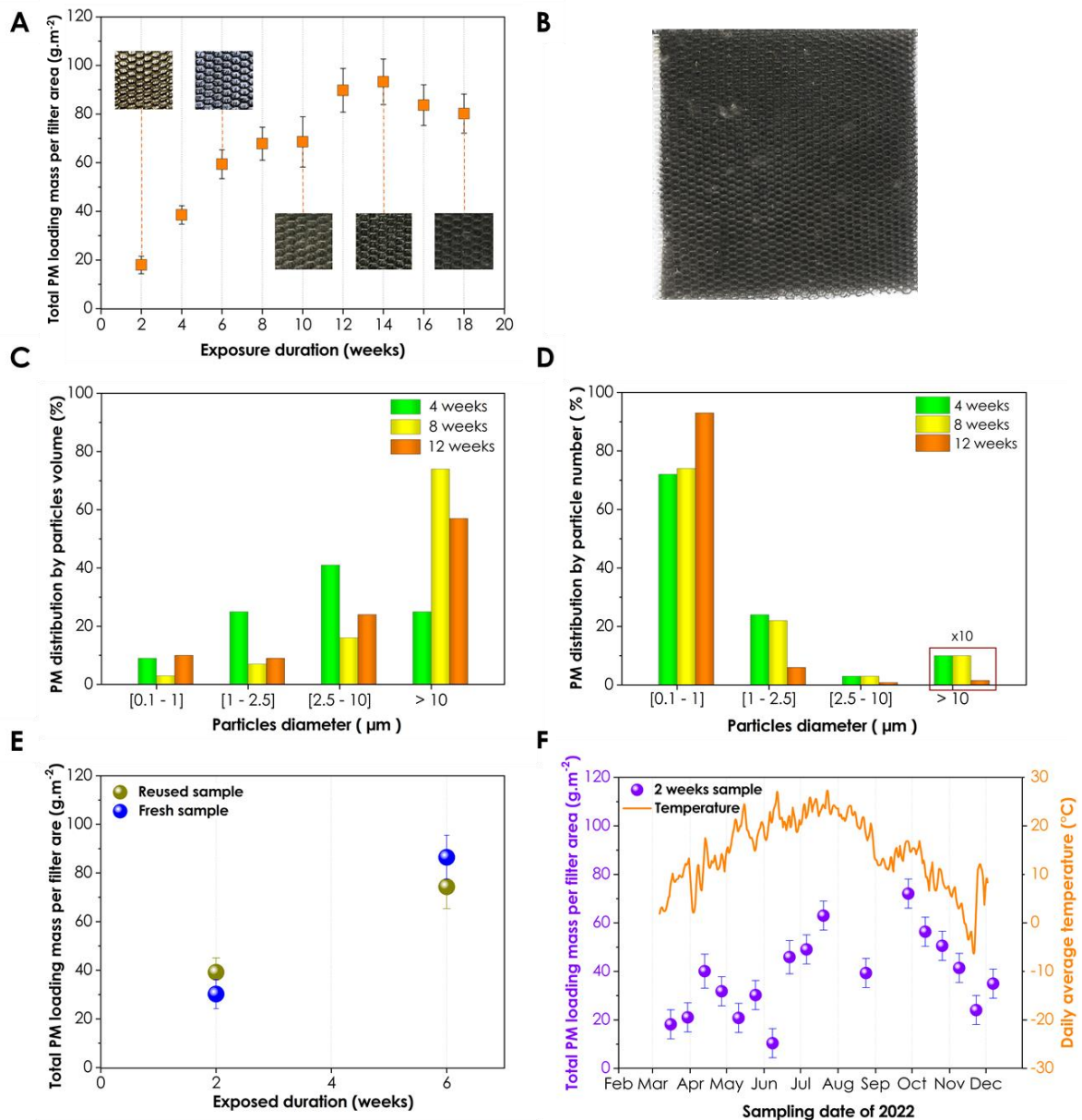


Figure 2 | PM trapping efficiency as a function of time of exposure. (A). The average PM in weight trapped per unit surface area of the filter as a function of time of exposure next to a city exit highway. Inset: Digital photos of the filter color as a function of time of exposure (after 2, 6, 10, 14, and 18 weeks). | **(B).** Digital photo of filters exposed 16 weeks at the RM35 prototype. | **(C, D).** Average distribution of the trapped PM, expressed in terms of particle size distribution in % of particles volume and number, after 4, 8, 12 weeks of time of exposure, respectively. | **(E).** Comparison of captured PM loading mass between the fresh and regenerated media showing the complete retention of the efficiency which confirms the possible reuse of the filter for several trapping processes. | **(F).** PM loading variations with temperature monitoring. The experiments were carried out at different periods with different weather conditions from March to December 2022. Each sample was exposed around 2 weeks.

Reusability is also essential to minimize waste generated by used filters. In our study, the washed and dried filter support was recoated with an oil layer and subsequently retested for passive trapping over the same duration, under comparable weather conditions and traffic density. The results clearly demonstrate that the PM loading and retention capacity of the reused filter are comparable to that of fresh media (see Fig. 2E). This potential for reuse underscores the filter's advantages, as a single-use design, such as those based on electrospun webs (C. Liu et al., 2015), which are neither environmentally sustainable nor economically attainable. Unlike traditional filters that collect contaminants horizontally, our fabric design captures particles in a vertical plane, preventing surface clogging and maintaining their structural integrity during prolonged use. Additionally, the fabric design can incorporate a secondary layer, particularly suited for liquid-based coatings, to maximize PM retention. In our experiments, deodorized olive oil has been chosen as the coating substrate on the surface and infiltrates the interconnection of each fiber within the filter media (Fig. 1H). The coated oil layer keeps PM stucked on the Aero structure but also prevents incoming particles from rebound and resuspension by wind. The high porosity of the filter, measured at $90.5\% \pm 2\%$, using a pycnometer (Semnani, 2017), combined with its special geometry, help to retain the filter thickness overlong periods of both static and dynamic loading, which can minimize the increase in pressure drop until clogging state.

Microscopic images of PM captured on the media filter were analyzed using SEM, with results shown in Figures 3A to 3K. After 2 or 4 weeks of exposure, PMs trapped number was not sufficient to cover most parts of filter surface (Fig. 3A to 3C). Captured PMs with diameter ranging from PM_1 to PM_{10} and larger are kept on the fiber thank to the oil coating layer (Fig. 3B and 3C). Increasing the time of exposure leads to a rapid coverage of the filter surface by large aggregates, phenomenon which could be generated through merging of smaller PM into secondary particles with greater size (Fig. 3D), despite many small PMs are still being observed on different parts of the sample (Fig. 3E and 3F). Prolonged exposure up to 8 weeks leads to a high coverage of the filter surface by PMs, as evidenced in Figure 3G. However, according to the results presented in Figure 2A, the filter displays the capacity of PM trapping up to 14 weeks. The distribution of the PMs size mapped by SEM can also be estimated by statistical counting, which reconfirmed the granulometric analysis and confirmed the capacity of PM capturing on the filter media.

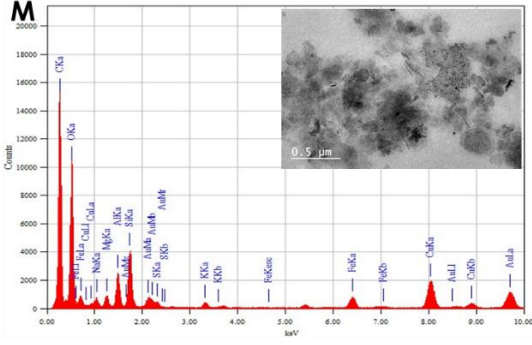
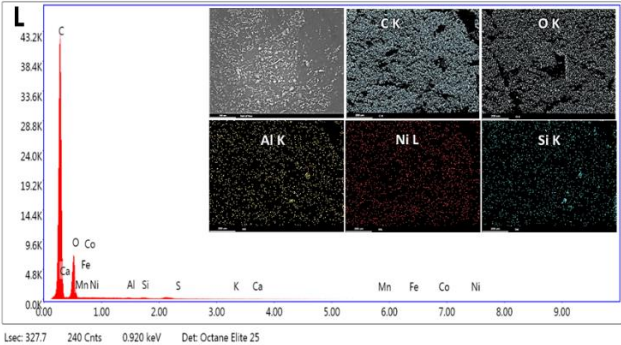
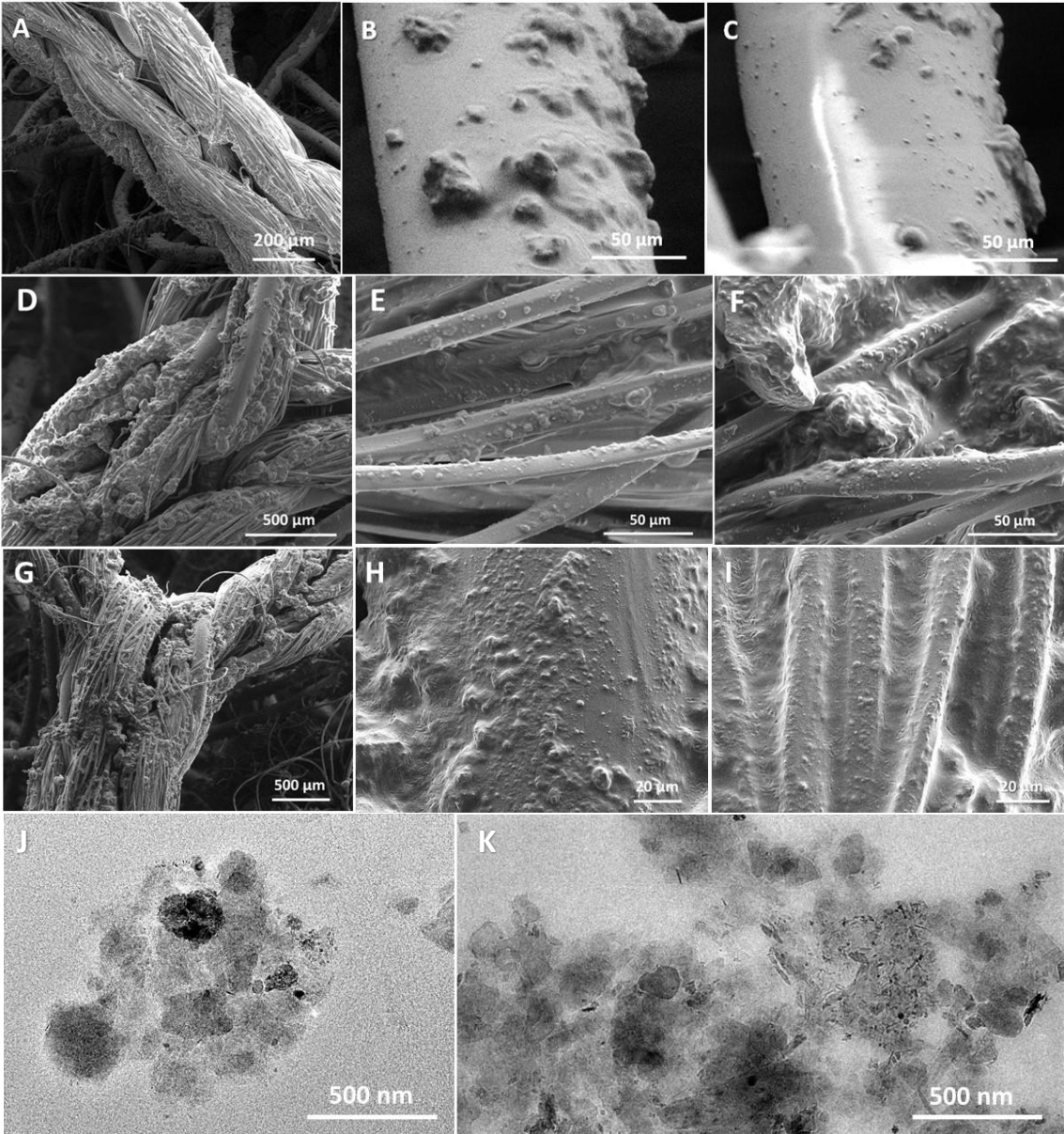


Figure 3 | Representative SEM and TEM micrographs of the trapped PM on the structured filter as a function of time of exposure. | (A to C) 2 weeks, (D to F) 4 weeks, and (G to I) 8 weeks. The as-received filters were dried at 60 °C in an oven for overnight in order to reduce the wetness of the oil thickness on the top surface of the samples before the SEM analysis. The trapped PM started to aggregate from each other as a function of time of exposure leading to the formation of medium to large patches on the surface of the filter. | (J, K) TEM micrographs of the PM₁ recovered from the washing suspension of the filter after 8 weeks of exposure. | (L, M) EDX analysis indicates that these particles are mostly constituted by carbon and oxygen but different elements such as Si, S, Al, Fe, Ni, Co are also detected.

The EDX results confirm the presence of carbon as the main constituent with some trace of metal (oxides) in the sample (Fig. 3L and 3M). While carbon elements represent particles resulting from the road degradation and tire fragments (often accompanied by sulfur). The metal elements are belonging to the degradation of tires and brake components (Beji et al., 2021). These results are logically fall in line with the prototype study conducted in the city center, as presented by Trinh et al. (2024). In fact, the traffic circulation in the city center is limited at 50 km. h⁻¹ with frequent stop-and-start conditions in the reason of nearby red lights, which makes metal particles appearing more frequently. In contrast, vehicles circulating on the RM35 ring road are limited to a speed of 70 km. h⁻¹ and generally do not stop (except for traffic jam or other disturbances), which tends to reduce the metal PM emission. Higher speed circulation degrades tires and roads more quickly, producing more debris which contain high C elements. Moreover, the action of braking at high speeds could degrade more significantly the wear of the brake pads, and generating more particles compared to braking at lower speeds (Beji et al., 2020). This phenomenon explains the presence of metal particles trapped by the filter of the RM35 prototype, even if the traffic is fluid in normal condition.

The weather monitoring experiment recorded unstable variation in the quantity of PM mass captured by media exposed 2-weeks during the experiment period (Fig. 2F). Precisely, the trapped PM mass varied from 10 to 72 g. m⁻² of media, with the increasing trends observed in the months of March, April, July, September (peak), and December. These variations are most likely related to the tendency of temperature during the same period. Studies (Banks et al., 2022a; Barmpadimos et al., 2012) revealed that temperature is the most important factor influencing the formation of PM and other atmospheric pollutants in urban areas. Furthermore, the trapped PM quantity is not perfectly correlated to temperature, i.e. the decrease of trapped PM quantity observed in May, June, and August, while the temperature remains high. Weather parameters such as traffic patterns, temperature fluctuations, wind velocity & direction,

atmospheric pressure and PM₁₀ concentration variations and hypothesis of their potential influences on PM formation and capture, will be discussed in the next sections. This comprehensive analysis aims to provide a deeper understanding of the complex interactions between meteorological factors and PM dynamics.

III.2. Weather parameters monitoring in Strasbourg City in 2022

For the reason that data was collected from various sources and faced multiple challenges (data disruptions, technical issues, weather disturbances, etc.), the conversion of weather monitoring data from lower frequencies to daily averages, provided coherence and comparability between different parameters. However, this approach has a limitation of overlooking short-term, localized weather variations that can have a substantial impact on the data. Assuming traffic peaks in the morning and late afternoon could result in higher PM deposition on the filter if wind direction and velocity are favorable. The synchronization of one or more parameters can significantly influence other parameters and, consequently, the quantity of PM trapped. Figure 4A illustrates the daily average values of each parameter over the experimental period, providing a visual representation of the trends and variation observed.

In 2022, the traffic velocity passing the portion of RM35 ring road (section next to Glacier park) was limited at 70 km. h⁻¹, accounting for 70,500 ± 16,300 vehicles per day on average, only for the Colmar-Strasbourg lane. Data missing from November to December is due to sensor malfunction and repair. Under normal circulation conditions, the traffic flow was high from Monday to Friday, then decreased on the week-ends. Pollution peaks are often observed during rush hours, particularly early in the morning and later in the evening. Throughout the year, the traffic distribution remained relatively stable, except for the months of August and December. During these two months, the average traffic volume dropped down to around 55,000 vehicles per day, for the reason of summer and winter vacations. As traffic is the main emission source of our captured PM, this deficit of traffic might be the main reason for the declination of trapped PM mass during August 2022 (Fig. 2F). The annual PM₁₀ concentration map for Strasbourg (Fig. 4C) showed higher level PM₁₀ pollution on the main axis of traffic circulation compared to the background pollution levels in the city. It confirms again the high

level of PM_{10} generated by traffic, even after the reduction of the speed limit, and the restriction of heavy-duty vehicles (HDV) in this section of the ring road.

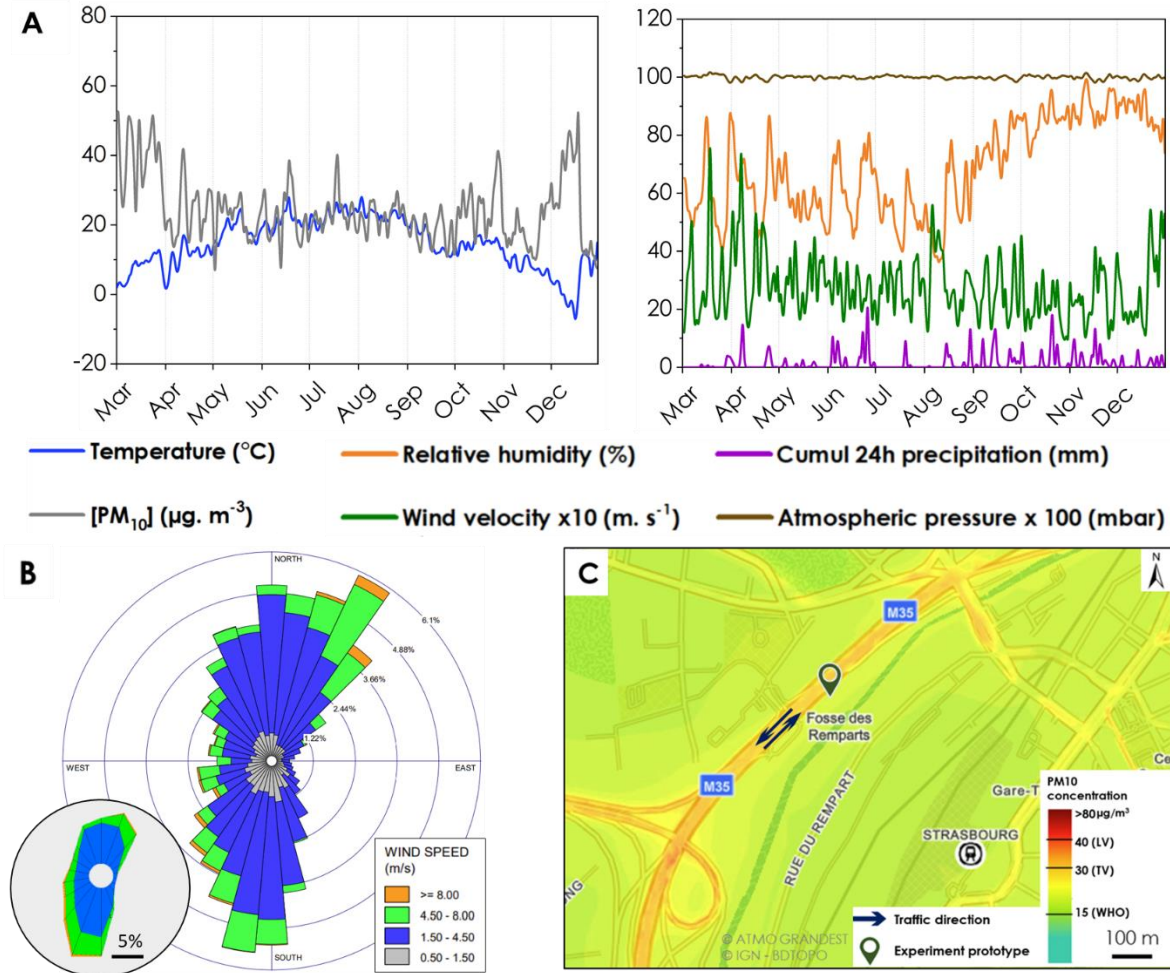


Figure 4 | Weather monitoring of the city of Strasbourg, France from March to December 2022. **(A)** Daily average evolution of recorded parameters during the studied period. Every hourly intervals or shorter data collected were converted into daily averaged value, except for precipitation which take the total quantity of daily rainfall. | **(B)** Wind rose graph of natural wind at 10 m altitude of Strasbourg (only from March to December 2022), hourly data retrieved from MétéoFrance, specifically from Entzheim weather station (48,55°N ; 7,63°E). Inset: Historical wind roses for the city of Strasbourg covering the period from 1991 to 2010. Main wind directions are on the NNE-SSW axis. | **(C)** 2022 annual average PM_{10} concentration map (in $\mu g \cdot m^{-3}$) in the experimental zone. WHO: World Health Organisation recommendation value; TV: Targeted value (European Commission's objective); LV: Limited Value for harmful effects on human health.

In 2022, the city of Strasbourg registered $+1.7^{\circ}C$ higher temperature than the average of 1991- 2020 period. During this study, the average temperature recorded was $15 \pm 7^{\circ}C$. The temperature steadily increased from March to August, then continuously decreased and

reached some negative temperature days in December, in addition to the cool periods in Mars and early April. The positive temperature noted in the latter half of December, coincided with a rebound in the quantity of PM mass captured. In general, the temperature variations in the study period follow the generic daily cycle (warmer at daylight and colder at night) and the seasonal cycle (hot in summer, moderate in spring and fall, cold in winter). Under normal conditions (stable traffic debit, absence or limited dispersion due to wind and rainfall), the concentration of PM₁₀ pollution remained relatively stable from April to October. But in the cold periods during March, November and December, the daily average of PM₁₀ concentration increased rapidly and can reach over 60 $\mu\text{g. m}^{-3}$, knowing that 40 $\mu\text{g. m}^{-3}$ is the limited value of daily PM₁₀ average recommended by WHO (WHO, 2021). As PM concentration is usually matched with positive temperature trends, data (Fig. 4A) shows the fluctuation of PM₁₀ in positive temperature (April to October) and a negative correlation during colder months (March, November and December). Similar trends have been also observed in other studies (Barmpadimos et al., 2011, 2012; Fameli et al., 2023), for the reason that residential PM emission from human activities during winter (wood heating, steam boiler heating). Moreover, the combination of pollutants with the low temperature at the ground level can create a temperature inversion layer (G.-X. He et al., 2013), which worsens the PM pollution as the inversion layer prevents the dispersion of PM to higher altitude.

Wind flow velocity and direction at a given location can have strong temporal variation due to changes in weather conditions and the movement of air masses. In general, the natural wind data for Strasbourg in 2022, as registered by the weather station, recorded an average wind velocity of 2.74 m. s⁻¹, and major wind frequencies come from the S-SW and N-NE directions (Fig. 4B). Furthermore, the wind flow direction in Strasbourg during the prototype experiments can be categorized into 2 distinct periods: summer (from March to August) and winter (from September to December). During the summer months, wind flows principally from the N-NE direction, regrouped from gentle breezes (<1, 1-2 m. s⁻¹) to medium winds (ranging from 2 to 8 m. s⁻¹). However, winter winds had more fluctuations, with the dominant flow coming from S to SE direction, also regrouped from gentle to medium wind speeds. These data align with the recorded wind in Strasbourg from 1991-2010, where the dominant wind directions remained aligned along the NE-SO axis. Our prototype position is strategically designed to maximize contact with the natural airflow, aligning with the traffic circulation of the RM35 ring road (Fig. 1A to 1C and Fig. 4C).

During the experiment, the Entzheim weather station of Strasbourg recorded high levels of relative humidity (%RH) and significant amounts of precipitation (Fig. 3A). From March to July 2022, the %RH fluctuated between 40% and 100 %, with strong variations between days and months. High temperatures can lead to abnormal quantities of precipitation, especially in the months of March, May, and June. Moreover, from August to December, the daily %RH values were relatively high, often exceeding 80 % during many days. The reason is probably linked to the abundant precipitation which may have less intensity than during the summer period, but last longer, through several consecutive days. In high humidity and absence of rainfall, particularly with the increase of temperature, PM and other pollutants can easily form and remain suspended in the atmosphere very long time, if they are not captured or transported. Meanwhile, the %RH during the fall and winter periods of 2022 were often accompanied by rainfall, which can effectively cleanse PM from the air by wet deposition procedure. Thus, PM₁₀ concentrations and PM mass capture declined in June and October, mainly because of this wet deposition.

From March to December of 2022, the average atmospheric pressure in Strasbourg was 1017 ± 7 hPa. The variation in atmospheric pressure can reach up to 50 hPa within a 24h period. Although atmospheric pressure does not have remarkable fluctuations, and does not directly engage into PM formation, transport, or dilution, a permanent observation on this parameter is still necessary, in order to assess other parameters such as temperature and wind velocity, which are crucial in air pollution study.

III.3. Model results and data analysis

III.3.1. Correlation matrix

As this work includes field work in outdoor sites, samples and in-situ data were collected and analysed every two weeks. This exposure duration assures the continuity of sample collection and analysis while simultaneously acquiring weather data through in-situ sensors. However, the results obtained from the captured PM mass quantification (see part III.1) were not sufficient to build up a comprehensive weather model, as the experimental period is probably shorter than those in other studies (Barmpadimos et al., 2011; Feng & Wang, 2012). Moreover, weather data were averaged over a period of 24h. For the reason that our sensors were calibrated and regularly combined with data collected from various sources, every parameter in the database needed to have an aligned interval. The current daily averaged

database (see part III.2) can more or less reveal the tendency of weather variation and build a regression model for PM₁₀ prediction based on other parameters. The model results yield linear or polynomial regression, with 70-30 ratio of unshuffled train-test data. Yet, the correlation coefficient (R^2) returned values of only ≤ 0.5 for each degree of regression. The regression model results concluded to be insignificant to show. The correlation matrix is then considered more suitable to reveal the connection between parameters (a value of 1 indicates a perfect positive correlation, and -1 a perfect inverse correlation).

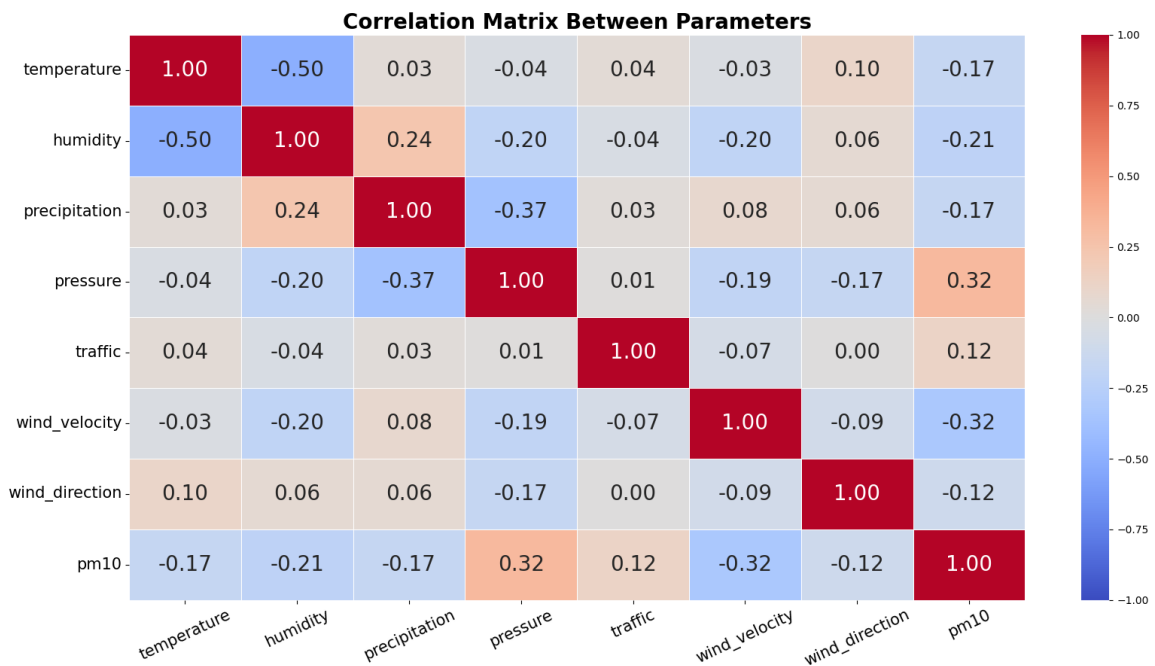


Figure 5 | Correlation matrix between various weather parameters variation. Daily (24h averaged) data registered from 02/03/2022 to 31/12/2022

As the correlation matrix reveals the interconnections between each pair of parameters, no strong correlation could be found, no matter positive or negative relationship. The highest absolute Pearson coefficient ($r = -0.5$) comes from the relation of temperature and humidity. Strasbourg is located in a semi-continental climate zone., where under normal conditions, high temperatures in summer accelerate water evaporation, leading to increased high relative humidity. But the year 2022 recorded an unusually high level of %RH during winter despite the decrease of temperature (Fig. 4A), which confirms the report of Copernicus Marines Service (Copernicus, 2022). High %RH in low temperature conditions can favorise PM condensation and liquid particles formation. Atmospheric pressure and wind velocity have weak connections with PM₁₀ concentration, with coefficients of +0.32 and -0.32, respectively. As discussed in the Introduction part (see part I.5 and I.6), stable atmospheric pressure can

keep PM at the ground level and prevent them from being transported away. Otherwise, wind plays as a PM disperser, high wind speeds can dilute PM concentration in a location, and deposit PM in another. The negative correlation reflects a link between wind velocity and PM₁₀ concentration. Still, the correlation coefficients for every couple of parameters remain too low to have a solid conclusion about the correlation between them. More accurate data on longer measurement periods or smaller inquisition intervals (hourly or minute instead of daily) should be completed to construct the weather model.

III.3.2. Oil viscosity interpolation and impact to trapped PM quantity

Adhesion forces of particles on fibers can vary depending on the viscosity of the coating layer (T. K. Müller et al., 2014; Zimon, 1982). The interest of coating a viscous oil layer on the fibers before exposure is for increasing its capacity of particles capturing and retention. A modification in viscosity can affect the capillary forces, which are crucial to prevent the particles from falling off the fiber due to gravity or air flow movement (Dörmann & Schmid, 2015; Kralchevsky & Denkov, 2001; Mead-Hunter et al., 2013). Oil viscosity should not be either too low or too high, and preferably remain stable facing open air oxidation. Laboratory test results (Trinh et al., 2024) certified the stability of the reference olive oil, even after being exposed to 60°C for a long period (> 1 month). For the reason that weather monitoring samples using fresh oil for the coating layer are replaced every 2 weeks, the following model results will only consider fresh oil viscosity, neglecting the aging effect and the dryness of oil during the first two weeks of exposure.

As the reference oil and mostly vegetable and mineral oils are Newtonian fluids, meaning their viscosity remains unchanged under varying shear rates (Kassi, 2019; Ramírez-Tortosa et al., 2006), the most effective parameter to viscosity remains temperature. Consequently, oil viscosity increment is proportional to the declination of the temperature (Sánchez-Rubio et al., 2006). The tested olive oil has higher viscosities at negative temperatures compared to other vegetable oils, but is more stable in the operational zone (from 0 to 40°C, with an annual average of 13°C), and also more stable after the aging process. For lower temperatures (< 0°C), the viscosity of olive oil increases quickly, which may affect its capacity of particles trapping (Fig. 6A). The experimental results are adequate to the theoretical calculations following the Walther equation about oil viscosity as a function of temperature. Simple supervised learning model interpolates the logarithmic evolution of viscosity. It can yield up to 0.01 Pa.s of exactitude for the dynamic viscosity of the reference oil, at any given

temperature within the range of -15 to 80 °C ($R^2 > 0.99$). This model was used to interpolate oil viscosity during the experimental period, based on the variation of daily averaged temperature (Fig. 6B).

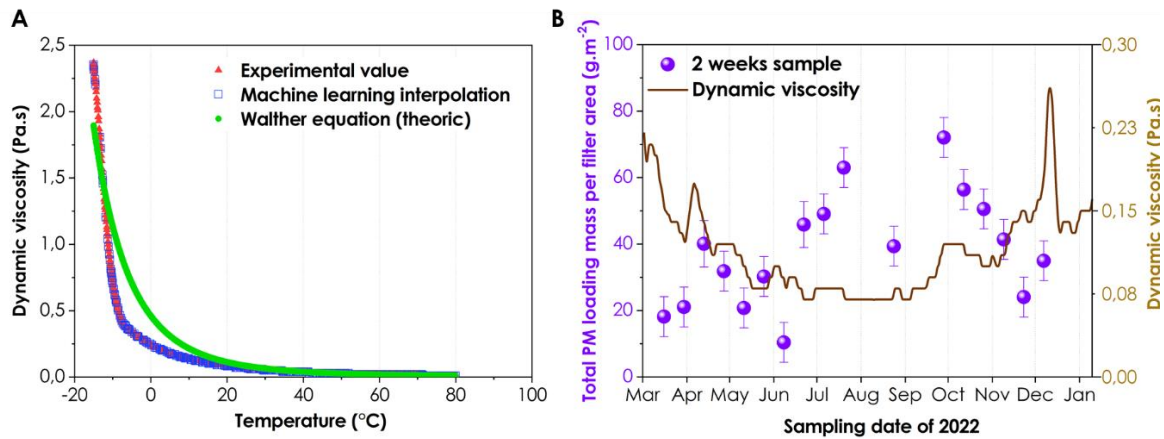


Figure 6 | (A) Dynamic viscosity as a function of temperature. Red triangle displays measured results on TA Instrument DHR3 rheometer; blue squares are interpolated values from experimental results; green line indicates theoretical values, calculated from Walther equation. | (B) Trapped PM mass of weather monitoring, each sphere correspond to 2 weeks consecutively exposed at RM35 prototype. Yellow line displays the variation of oil viscosity in function of outdoor temperature during the experimental period.

Interpolation model shows strong variations of the coating oil viscosity during the experimental campaign conducted from March to December 2022. Dynamic oil viscosity tends to remain low in summer (high temperature), then rapidly increases in winter and spring (low temperature). Fresh oil viscosity values had tripled, from 0.08 Pa.s in July to 0.25 Pa.s in December 2022. High values of viscosity were also observed in March and the beginning of April, coinciding with episodes of cooler temperature (Fig. 4A). Moreover, the peak of viscosity observed in December 2022 corresponds to an exceptionally cold period (for the last recent years in Strasbourg) with daily average temperature falling under zero. Regarding the complexity of explaining the evolution of trapped PM mass by PM₁₀ concentration monitoring, temperature may not directly impact the trapping quantity by its influence on PM formation.

Still, temperature effect on oil viscosity variation may cause the gap in trapped PM quantities observed during different periods of 2022 (Fig. 6B). Precisely, for the same exposure duration and position on the prototype, trapped PM quantity gradually increases from March to July, then decreases from September to December. These trends are nearly

coincident with the evolution of temperature as discussed before (Fig. 2F). With the interpolated viscosity values, the explanation of PM trapping evolution can be closely related to oil viscosity which varies with temperature. Warmer weather favors PM capturing by keeping the low viscosity of the coating layer, also accelerating the oil oxidation process. In contrast, the higher viscosity in low temperature conditions makes the PM capturing process less efficient, resulting in lesser PM captured during winter and spring, even if the PM_{10} concentrations are higher than in summer. The abnormal months of April, June and August where the PM trapped mass do not follow the explained trends, can be clarified by the dispersion parameters (Fig. 4A). Indeed, strong wind activities during March and April, along with high precipitation in June, dissipate the PM in the air, thereby explaining the lower quantities of PM captured despite the rise of the temperature. In addition, the month of August is one of the hottest months of that year, but the PM quantity captured stays only in the middle. It turns out that the traffic circulation in that period dropped by around 20 000 vehicles per day lesser than the average of that year, probably due to the summer vacation. Nevertheless, oil viscosity should be closely monitored for efficient oil selection, in order to adapt to the weather conditions of the target location.

IV. Conclusion and perspectives

Fine particulate matter (PM) from road traffic remains a significant public health concern in urban settings. This study presents a field evaluation of a passive air filtration system designed for deployment in high-traffic areas. The filter consists of a highly porous polyester fiber matrix coated with a thin layer of vegetable oil and was installed along a busy ring road in Strasbourg, France. Over a 14-week period, the device successfully captured up to 84 ± 6 g. m⁻² of particulate matter. Chemical analysis identified tire and pavement wear as the primary sources of collected particles, with minor contributions from metal particulates likely originating from braking at higher speeds. Variability in captured PM levels was linked to local meteorological conditions. Importantly, the filter system demonstrated consistent performance across multiple regeneration cycles, indicating sustained trapping efficiency. These passive, energy-free units represent a scalable and practical solution for mitigating PM exposure, particularly in sensitive environments such as schools, hospitals, parking structures, and subway stations.

Upcoming tests can be performed using the same material but with thicker fabric and higher density of fibers. Furthermore, pressure drop across the filter should be regularly controlled for assuring the adequate airflow circulation during the exposure duration. As PM accumulation can lead to cake filtration and air stagnation, this action can help to estimate the filter life and also necessary human and financial resources to replace a new one, wash and re-infiltrate oil on the regenerated filter structure. Oil selection can have other alternatives for adapting to different exposure conditions. For example water-soluble mineral oil can facilitate the washing step, or winterised oil having the waxes removed during refinement step, retarding the solidification of oil in negative temperature, etc.

Weather parameters can have strong influences on the capture and retention of particles. Studies of simulations and socio-economics impacts should be carefully performed before the installation of such devices on large scales. In order to acquire high quality and accurate numerical and/or data analysis models, weather monitoring data should be obtained using high quality, calibrated sensors, with no disrupted, high frequency of registered data (ideally hourly or every minute if possible). In many densely populated French cities, such as Paris, Lyon, and Strasbourg, systems of surveillance are deployed for continuously monitoring air quality, especially PM concentration and other air pollutants like NO_x and O_3 . Beside long term methods like Crit'Air norm to control vehicle emissions, public transports are free of charge during air pollution peaks (EMS, 2024). And these events can occur during favorite weather conditions (high temperatures, low wind speeds), or abnormal rises in emission sources like traffic circulation or household heating activities. In the context of climate changes and air pollution mitigation scenarios, weather influences should be observed closely alongside PM and other pollutant emission controls. This practice could help to build accurate scenarios and/or models of prediction or interpolation, helping to gain knowledge of outdoor air filtration and improve air pollution mitigation plan management.

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CHAPTER 4

MOBILE PM TRAPPING





Passive mobile trap for fine particles capture in outdoor air for sectorial pollution analysis: a study case in Strasbourg city, France

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Abstract

A passive filtration system mounted on bicycles was tested for its ability to capture fine particles (PM) during travel in two sectors, urban and peri-urban, of the city of Strasbourg. The objective is to establish, in the medium term, a sectoral mapping of the city's air pollution in order to better adapt prevention methods by sector in order to lower the pollution level. Preliminary tests made it possible to define the optimal position of the filter on the mobile vector. The filters thus mounted were tested over the same period in two different sectors: an urban route passing through an area with high traffic and population density and a peri-urban route where traffic is lower. The results obtained showed that the quantity of PM captured is directly proportional to the concentration of PMs present in the area to be analyzed. Chemical analysis reveals that the chemical composition of the PMs, between the two profiles, is relatively similar, which highlights road traffic as the main source of pollution. This study made it possible to draw up an average map of pollution in two different sectors of the city. The studies will still need to be completed in order to obtain a complete map of the city's sectors, which will be used for future urban development. This study could also contribute to new strategies for reducing air pollution by integrating an innovative, scalable, and environmentally friendly air filtration method.

I. Introduction

Air pollution contributed by particulate matter (PM) has become a heavy burden in our modern society, causing around 8 million annual indirect deaths worldwide for both indoor and outdoor pollution (WHO, 2021). Nowadays, people spend most of their time in indoor spaces such as home or work-office, supermarket, transportation, etc. but outdoor activities are still mandatory for human health, both physically and mentally (Thompson Coon et al., 2011). For the well-being of citizens, and more specifically for vulnerable groups of people such as children, the elderly and immunocompromised patients, the lack of outdoor activities and exposure to any type of air pollution could be both harmful to health being (Mata et al., 2022; Pope, 2007). Furthermore, outdoor air quality can directly affect indoor air quality, through passive air exchange between the two environments and/or through the building ventilation system, which adds to the intrinsic pollution of the environment, cooking, cigarette smoke, etc. Reducing PM, in developed countries with a high concentration of industrial plants and road traffic, by sustainable and effective methods represents a great challenge to improve the quality of life and reduce the risk of respiratory diseases. In large cities, with usually high population density, in addition to the lack of green spaces, which play a role of passive trap, air pollution is aggravated due to many PM emission sources (Hama et al., 2021; Karagulian et al., 2015; Kumar et al., 2014), and especially by traffic through exhaust emissions (thermic vehicles) and non-exhaust emissions (both thermal and electrical vehicles). With the evolution of technologies and respect of stricter norms of exhaust emission limits for new and on-circulation vehicles, PM emission from the catalyst exhaust system could be greatly reduced, depending on the national policy and individual engagement (Allen & Barn, 2020; H. Zhang, Mao, et al., 2021). In addition, non-exhaust emissions consist primarily of particles from brake and clutch system degradation, which can release inorganic and metallic particles as small as a micrometer or even smaller, as well as carbon and other additives resulting from degradation generated during tire-to-road contact. To date, no large-scale solutions have been implemented to reduce these types of emissions. Electrical vehicles significantly contributes to the reduction of the exhaust emission on one hand, but generate more non-exhaust emission due to the battery weight, on the other hand (Timmers & Achten, 2016). Trees and vegetation are indispensable for urban management and air pollution mitigation plan as their can trap PMs through contact with the leaves surface. Many studies have examined the benefits of various tree species in PM trapping (Janhäll, 2015; Ysebaert et al., 2021). It turns out that they could have more or less efficiency in trapping PM, but they

cannot provide a radical solution of eradicating PM out of the ecosystem. In addition, the trapped PM on leaves surface could also be washed away during rainfall and the removed PM could follow the water cycle, rejoin the rivers or ocean and contribute to an increase of microplastic pollution, and finally, end up in the food chain. In addition, the efficiency of PM capture by trees is greatly reduced during the winter period, due to the absence of foliage, which offers a large contact surface with PMs. Otherwise, fibrous, bag filters are commonly used in the ventilation system for buildings or individual houses (Qiao et al., 2020). For the reduction of PMs in the outdoor environment, active filtration processes have been developed, such as forced convection by fans or by the generation of upward air flow by temperature difference between the low point (cold inlet) and the high point (hot outlet), or the use of electrostatic filters (Cao et al., 2018). As previously mentioned, these air filters offer relatively high efficiency in trapping particles in a dedicated area. This performance is significantly higher than that of passive trapping systems using trees and vegetation. However, their large-scale implementation remains difficult due to their relatively high installation, operation, and maintenance costs, as well as their significant energy consumption. In addition, most filter materials are generally not recyclable and could generate a large amount of waste once deployed on a large scale (J. P. Chen et al., 2017; Torres & De-la-Torre, 2021). However, innovative and more environmentally friendly methods for mitigating air pollution should be tested, with an optimization of the cost-benefit ratio, in order to make them more affordable and applicable in both developed and developing countries.

Bicycling has proved to be a sustainable transport method, which has many benefits to the health and greatly reduces air pollution in the city compared to other transports such as personal cars. This type of displacement is receiving more and more public interest in European cities where urban management tends to expand bicycle lanes. Despite these measures, traffic density and air pollution remain a major challenge for authorities in many large cities, particularly due to the movement of workers from the suburbs to the city center, where company headquarters are located. Today, road traffic remains one of the main sources of fine particle emissions in urban areas, alongside pollution from winter home heating. Air pollution, originating from road emissions, reaches its peak on the road itself and its surroundings, degrading air quality and the health of local residents. This pollution is dispersed over long distances by natural factors and can impact a large segment of the population (Finkelstein et al., 2004; Pant & Harrison, 2013). Indeed, depending on the design of the buildings, road, street, and PM transportation factors (wind, rain), these particles could

be diffused far away from the emission source, and even combined with the weather and other pollutants, forming secondary pollution (Guo et al., 2014). It is expected that secondary PM display higher treat compared to the primary ones because such secondary PM carries adsorbed species, which could be inorganic or organic compounds having different level of toxicity when integrated human system. As bicycle lanes are usually localized side-by-side with the traffic circulation roads, bikers could be exposed to high levels of pollution. In movement, the air around the cyclist creates a resistance, combined with the natural wind and other vehicles' motion, forming a wind load on the cyclist (Lubitz & Rubie, 2018). This air flux can be heavily charged with particles when cycling near the road as discussed above. In their study (Samad & Vogt, 2021), the authors tested a novel mobile air quality measurement method by using sensors attached on a bicycle. In fact, this method is very flexible and adaptive to mapping the spatial distribution of pollutants in a large zone, in addition to the fixed measure stations. However, the chemical composition, which represents also an important treat for human health, is lacking in such investigation. The results confirm that the spatial variation between traffic road, side road, and green spaces could significantly influence the pollution measured, depending on the distance to the emission source. With the idea of mobile air filtration by attaching a device on the bike handle, the SmogFreeBicycle prototype was created by the Studio Roosegarde company (Roosegarde, 2017). In 2017, within the collaboration with the Chinese company Ofo, they tried to integrate this device on every shared bike in the city of Pekin, China. Their air filter is connected to the bike wheel to generate energy in the same time of pedaling, to powering a filtration device equipped with a cartridge filter inside, which generates a cleaner current of air to protect the cyclists during the ride. It is expected that mobile filtration could prevent the user to inhale outdoor PM during the ride. On the other hand, mobile filtration could also allow one to local analyze of the pollution at different areas of the city and to build up a general pollution map, which could help politics and environmental agency to the reduction of such pollution.

In this study, we experienced a potential method of mobile PM trapping by installing a passive, oil coated filter on the bike and to evaluate the trapping results at different areas across the city of Strasbourg. The washable, regenerable, oil coated material was previously described in our recent study (Trinh et al., 2024). This research proposes a new, eco-friendly method of PM trapping in urban environment, and can contribute to determining the type of PM pollution that people are in contact when they have outdoor activities. The results, if relevant, can be further extended to the entire city in order to build up an accurate map of

urban and peri-urban pollution based on traffic. It is expected that the combination of such mobile trap and fixed analyzer could allow one to determine, with more accuracy, the degree of pollution (quantity, average size, and most importantly the chemical composition) for different sectors and the associated density of the population, within the city, which could help to implement sectorial specific remediation solutions. The results could also be used for the implementation of new filtration systems, preferentially the passive ones, which can reduce such pollution close to the emission point.

II. Materials and methods

II.1. Passive filter

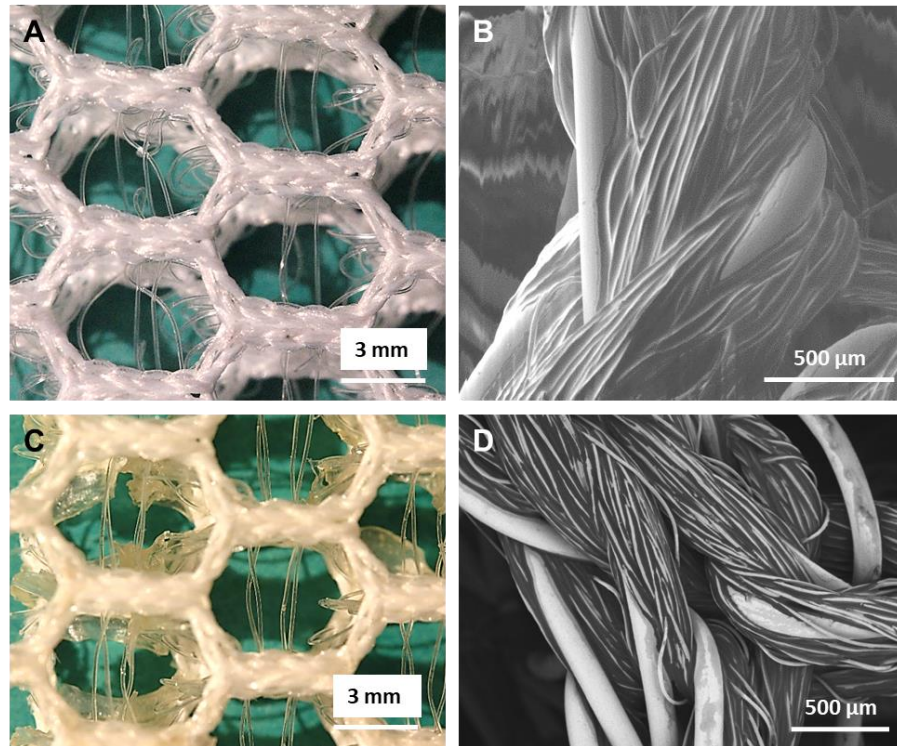


Figure 1 | **A, B.** Digital photo and microscopic magnification of filter structure without coating layer. | **C, D.** Digital photo and microscopic mangification of filter structure after coated an oil layer

The filter media is composed of polyester fibrous matrices structured to provide a large exposure surface (Fig. 1A), thus maximizing the contact between polluted air and the fibers, while facilitating the passage of air with low pressure drop. The polyester matrix is coated with a thin layer of oil (Fig. 1C), by soaking followed by draining under protection in order to reduce the deposition of particles in the ambient air, and which acts as a fixative for the

capture of PMs (Trinh et al., 2024). The representative SEM micrographs of the uncoated and oil-coated filters are presented in Fig. 1B and D. The filters used have dimensions of 22 x 22 (cm). The filters are installed in their metal frames, and fixed on the bicycle frame, which acts as a filtration vector.

II.2. Mobile air filtration on different positions of the bike

According to the annual average PM₁₀ pollution map of Strasbourg city in 2022 (Fig. 2A), the most polluted section is the ring road where high traffic circulation is observed. The city center also has a high level of PM concentration, especially in cold seasons when residential heating is abundant, in addition to various other human activities. The traps were installed on two bicycles that traveled on different sections of the road to analyze the PM pollution in two different areas of the city. The first bicycle, labeled VH, followed a trajectory mainly in the peri-urban area with relatively low traffic (Fig. 2B). The second bicycle, labeled VQ, mainly covered the city center and the edges of the roads with high traffic as shown in Fig. 2C. The passive filter device, which is similar to that described in previous work (Trinh et al., 2024), is installed on the bicycle frame with different configurations as shown in Fig. 2D and 2E. The tests were carried out over a relatively long period, from 2022 to 2024, and is divided into several campaigns lasting approximately two months each. Initially, two filters were installed on both bikes, on the front and side of the VH, which were exposed for 29 days, from 08/23/2022 to 09/21/2022, and covered 70 km. Further tests were carried out during 2024. After the exposure duration, both samples were collected at the same time, and then analyzed separately for comparing their performances.

II.3. Mobile air filtration by similar installation but different routes

We have two different profiles of trajectories that correspond to two sectors in the city with different traffic. The first bike covers an area of the northwest suburb, and occasionally the north ring road (Avenue des Vosges), labeled VH (Fig. 2B). The second bike covers the south section of Strasbourg, and a part of the city center near the main central station, labeled VQ (Fig. 2C). After arriving at each location, the bike is stored in covered or isolated areas, which allow the avoiding contact with wind, rainfall and other PM emission sources, in order to reduce, as much as possible, the cross-pollution. The experiments were only carried out during days without rain (weather check every day) to avoid splash water and possible dirt projection from under the bike, as well as rainwater from above that could partly remove the

oil layer and the trapped PMs deposited on it. The samples always have the same exposed duration, which facilitates the comparison between the PM deposited from the targeted areas.

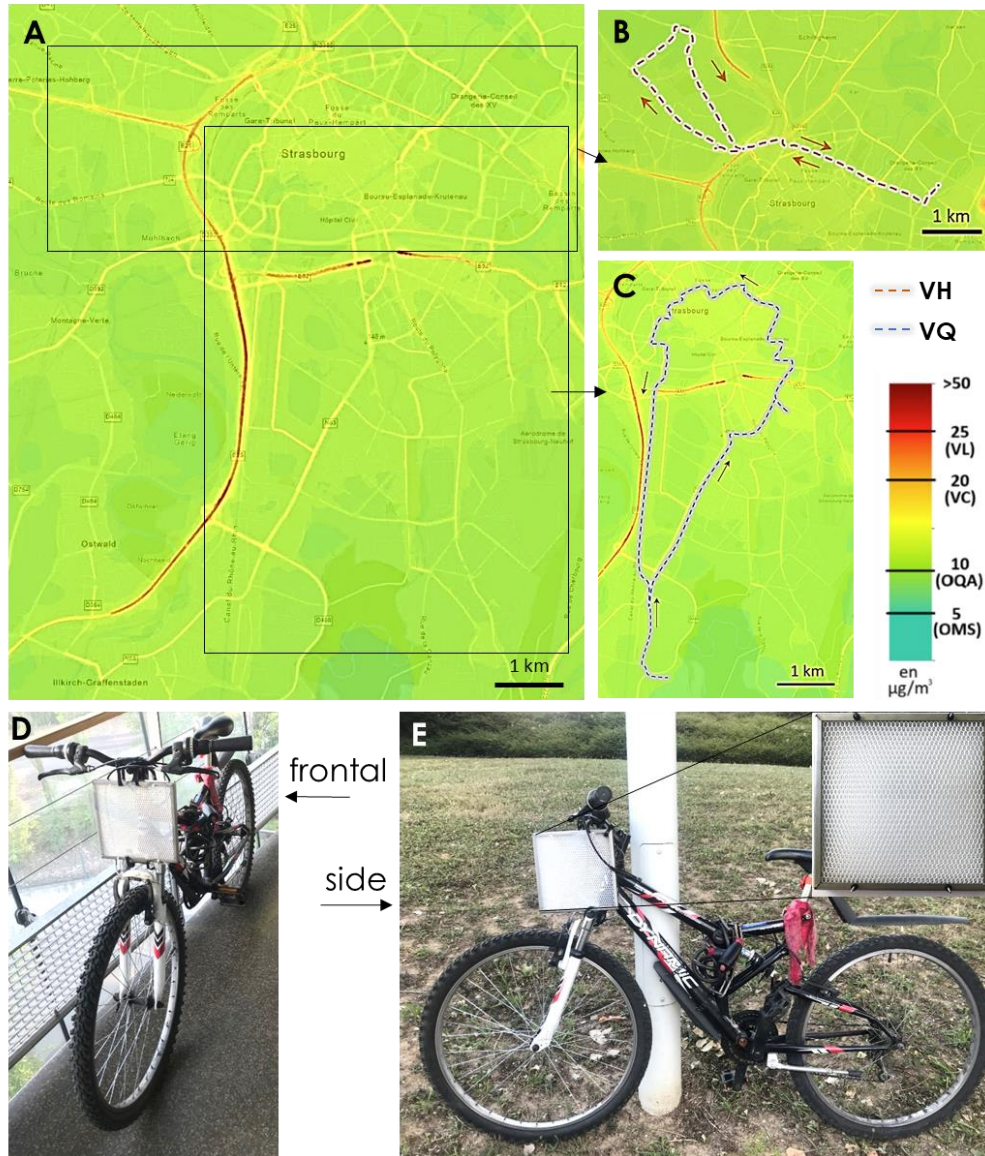


Figure 2 | **A.** Map of annual averaged concentration of PM_{10} in 2022 of Strasbourg city, France (Source: ATMO Grand Est) | **B.** VH's trajectory, mostly concerned by peri-urban zone. | **C.** VQ's trajectory mostly covered the city center and near the high traffic axis. | **D.** Frontal installation of the passive trap on VH. | **E.** Side position of the passive trap on VH. The safe PM concentration recommended by the WHO is presented in the inset of Fig. 1C. After experimental observations, only side configuration was retained for both VH and VQ. | Abbreviation: OMS: Safe PM concentration recommended by WHO; OQA: EU air quality objective; VC: Target value of Europe Union; VL: Threshold value recommended by WHO; VQ: Urban trajectory; VH: Peri-urban trajectory).

The PM and oil can be extracted from the filter structure material by soaking the sample in a solution of 5–10 % detergent (Alcohol C₉-C₁₁ ethoxylated, KOH) mixing with distilled water at 80 °C, followed by 15 min ultrasonication (Trinh et al., 2024). The resulting suspension containing the PM and oil was filtered on a Nitrocellulose membrane filter with a pore size of 0.45 µm, followed by a washing step with ethanol to remove the remaining oil inside the filtered solid. The solid, after drying in an oven at 60 °C for overnight, was weighted in order to determine the trapping efficiency of the filter.

The spent filters are analyzed with different characterization techniques. Scanning electron microscopy on two microscopes with different spatial resolution Tescan VEGA III and Gemini SEM 500. Tescan VEGA III was mostly used to determine the gross morphology of the spent filter while the Gemini SEM 500 was used for high-resolution morphological analysis and for measuring the PM size distribution, and also to analyze the chemical composition of the filtered particles. Beside the statistical analysis of particle size on microscopic images, the particle's granulometric estimation was analyzed by the MALVERN Mastersizer 3000 with 150-200 mL of homogenous washing solution. The particle size distribution determined by this technique is more accurate and comes in complementary with that determined by SEM.

III. Results and discussions

III.1. Filter position, side vs frontal, and PM trapping efficiency

During the period of this study, the weather in the city of Strasbourg was quite stable with the following data: average daily temperature around 19 ± 4 °C, a relative humidity (RH) of around $69 \pm 11\%$, an atmospheric pressure at around $99,827 \pm 380$ Pa, a total precipitation accumulation of 74 mm over 4 days, and the wind speed, at 10 m height, is around 2.6 ± 1 m. s⁻¹ and mainly oriented in the NE-SW direction. The data are extracted from the Eintzheim weather station (Info Climat, 2025). As oil viscosity change is directly dependent on the temperature, higher temperature could reduce the oil viscosity and vice versa (Sánchez-Rubio et al., 2006). The relatively steady temperature, during the exposure period, allows the coating oil layer to maintain a stable viscosity, not too low or not too high and loses the ability of capturing particles. Moreover, low humidity accompanied by low atmospheric pressure can limit the formation of secondary liquid particles, which could display different adsorption

behavior. As our filter captures PM by the mechanism of dry deposition on a viscous coating layer, liquid and solid nucleus particles with liquid cover could quickly evaporate after being captured, or have less chance to be trapped because the liquid layer limits at the PM-oil coating contact surface. It should also be noted that during the evaluation period, precipitation remains close to the annual average values and, therefore, the amount of PM present in the air is quite representative compared to that existing annually. However, in order to reduce external errors, the experiment was not carried out during rainy days to avoid contact with rainwater, which can wash away the oil layer and the particles on it. In general, these weather conditions can be considered as adequate for PM trapping.

The spent filter was removed and three small pieces, located at the border and the center, were taken from the filter and analyzed by SEM for the determination of the PMs trapped and also for the statistical analysis of the PMs particle size. The micrographs of frontal position (Fig. 3 A-C) and side position (Fig. 3 D-F) indicate that fine particles of various sizes are presented on the filter surface, with relatively similar amount of PM captured on each m² of filter per kilometer, i.e. 1.3 and 1.9 mg of PM_{total} . m⁻². km⁻¹, for frontal and side position filters, respectively. As two samples were exposed to the same level of pollution and in the same exposure duration, the gap of captured PM mass between two samples indicates that the PM trapping performances are slightly different, probably due to the difference of the filter position on the bike. The average daily PM₁₀ concentration value recorded at the nearest ATMO Grand Est station (RM35 Rempart near Glacis park) is $20 \pm 5 \mu\text{g. m}^{-3}$. The elemental analysis of the PM trapped on both filters is displayed in Fig. 3G and 3H and confirms similar nature of the trapped PM, which is mostly constituted by carbon and oxygenated elements. Some metallic elements are also detected but in a much smaller amount compared to the formers.

The PM₁₀ concentration value did not exceed the threshold value recommended by WHO, and stayed within the European air quality target (Commission Welcomes Provisional Agreement for Cleaner Air in the EU, 2024). Regarding the ratio of PM₁₀ by PM_{total} measured by granulometric technique as around 40 % (Fig. 4D), we estimated that for each m² of filter will be able to catch approximately 5 -7 % of the non-exhaust PM₁₀ emission for each km of a light duty vehicle (LDV - which releases 44 mg of PM₁₀ for each km) (Y. Wang et al., 2017). These results are quite positive, since this is not a much polluted period when the traffic is nearly absent and the PM₁₀ concentration is just a little bit higher than the background pollution level of Strasbourg ($17 \mu\text{g. m}^{-3}$).

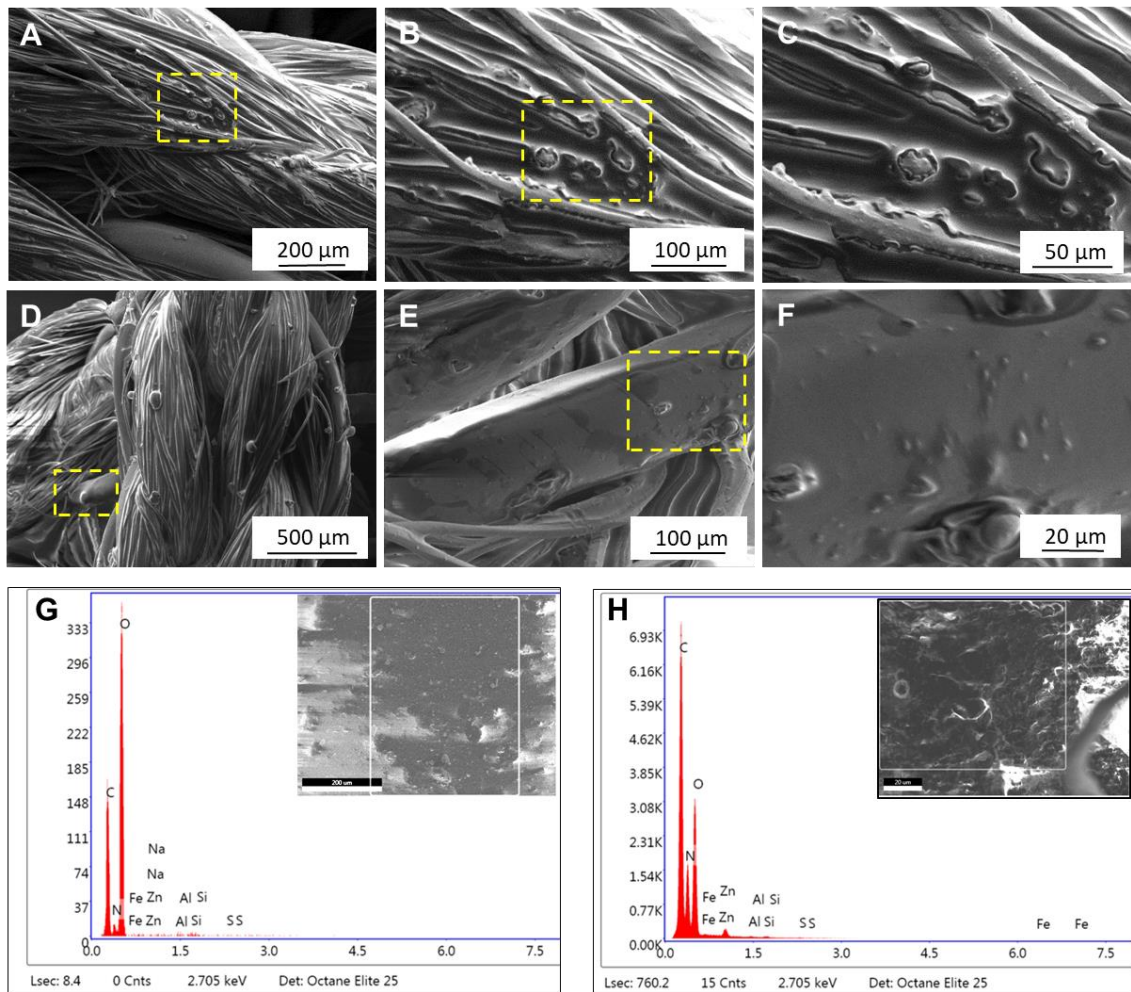


Figure 3 | A-C. SEM micrographs of the filter at frontal position of VH, exposed 29 days from 23/08/2022 to 21/09/2022, 70 km travelled. | D-F. SEM micrographs of the filter at the side position of VH with the same exposed duration and distance travelled with the side filter. | G-H. EDX analysis of chemical components of particles captured by frontal position filter (G) and side position (H).

The frontal position filter has more marks of impact of particles on the oil layer, indicating that the particles which come in contact with the fiber surface were at high velocity. At such high speed displacement, particles could present less time of contact with the oil layer, thus, reducing the probability to be captured. In addition, as the particle rebound is higher as a function of the inertial impact of particles on the fiber which thus reducing the amount of trapped particle on the filter surface (Boudina et al., 2020; Kasper et al., 2010). On the other hand, the side position filter surface remains smoother and finer particles are observed on its surface, which correspond to a slower deposition with weaker impactation of PM on the oil layer compared to that was observed on the frontal filter. The orientation of the filter in the

side position, at the same time, reduces the drag force created by the rebound of air current after the first contact with the filter surface (screening effect), and increases the contact time of air flow with the filter superficial (as air slides across the filter length).

There are differences in the results of PM granulometric estimation between two methods: direct measurement via SEM images and granulometric analysis. For both side and frontal position samples (Fig. 4A), the PM₁ ratio observed on the SEM images is less than 10%, according to statistical SEM analysis, of the total number of PM measured. Thus, the estimated particle volumes are over 90% for particles > 10 µm, for samples in both positions (Fig. 4B). On the contrary, the number of PM₁ harvested in the washing solution and passed the granulometric analyzer display a high proportion compared to those observed for the other sizes, cf. Fig. 4C (over 80% of particles in side position samples, and more than 60% of particles in frontal position samples). As a result, the volume of particles that diameters are greater than 10 µm for both positions reaches only 60 ± 5% of the total PM volume (Fig. 4D). As our filters are covered by an oil layer, the smallest particles could be buried under the coating layer, especially under the zones with high density of fibers, containing more oil than the sparse ones. Such problem can explain the deficiency of % PM₁ in the SEM images analysis results. Another hypothesis is advanced on the fact that the oil layer plays the role of an adhesion surface that favors the formation of agglomeration (Corn, 1961), or that can strengthen the dendritic evolution in dry deposition which is, in absence of the coating layer, dependent on the connection between particles (Kanaoka et al., 2001). After the washing step, most of the particles, including the ones which could be buried inside the coating oil film, are removed from the fibers. For that reason, the ratio of PM₁ in granulometric analyzer results is much higher than the previous method. Moreover, the oil-adhesion connection and agglomeration of particles can be broken down by the effect of surfactant and ultrasonic waves (Trinh et al., 2024). For now, we expected that most of the agglomerations were formed after the deposition of PM on the oil layer, despite the fact that some aggregation could be generated directly between the different primary PM. Still, as the granulometric analyzer has taken into account not only the particles present on the surface but also the hidden ones, granulometric results are more reliable than SEM images analysis to access the trapped PM distribution.

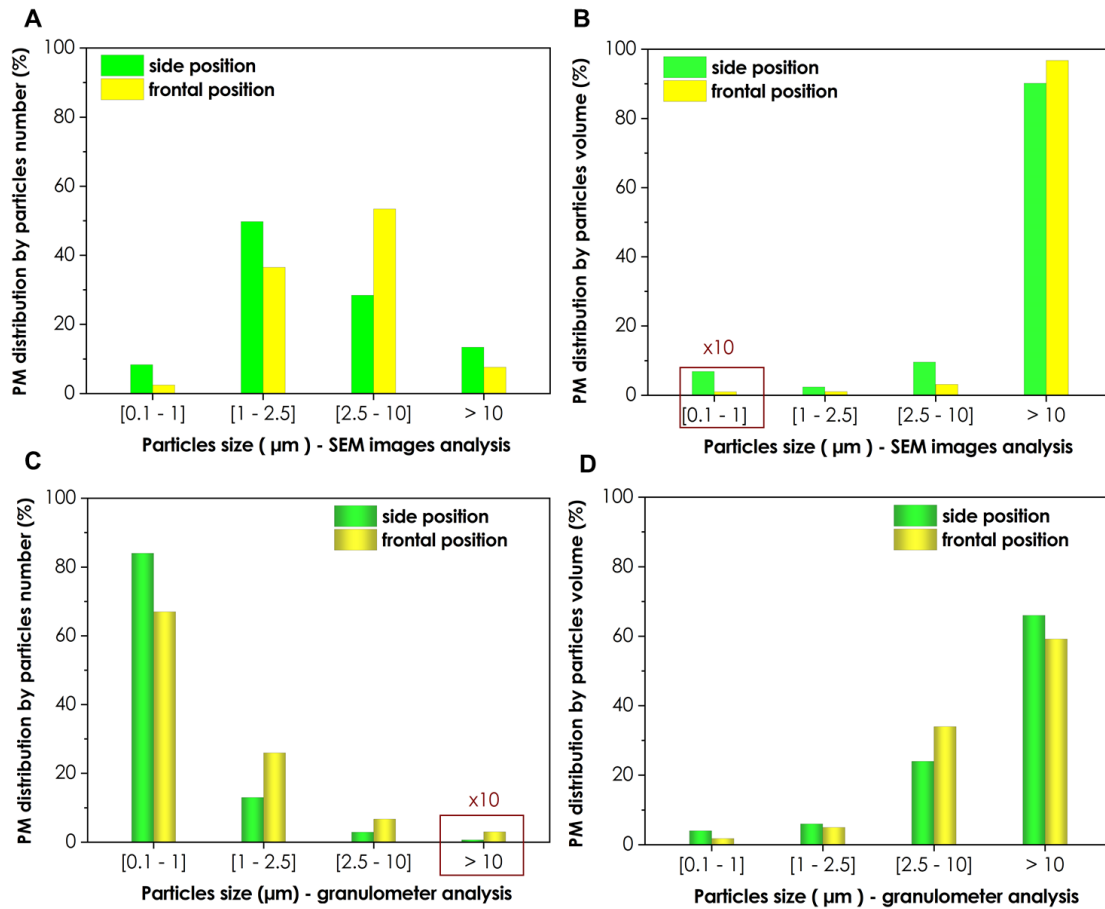


Figure 4 | A and B. Distribution of captured particle size by particles number (A) and by particles volume (B). Statistical analysis from over 300 particles per sample, retrieved from different SEM images. Particle size was measured by ImageJ software. | **C and D.** Distribution of captured particle size by particles number (C) and by particles volume (D). Particles were harvested from washing solution and passed through the granulometric analyzer.

For both granulometric methods, the results clearly evidence that the side position captured more fine and ultrafine particles than the frontal position (Fig. 4A-D). Precisely, for the same trajectory and exposure duration, granulometric results indicate that the number of PM₁ captured at the side position is about 17% higher than the frontal one. Similar tendency was also observed for PM_{2.5} on the side position, while bigger PMs appearing more frequently in the frontal position. For the reason that the air flow slides alongside the length, instead of directly colliding with the filter surface, more contact time and less turbulence conditions allow smaller particles to deposit by interception, even diffusion (Mohammed et al., 2022; Ounis et al., 1991) on the surface of the side position filter. These differences in deposition mode favor the capture and retention of small particles, which are the most harmful ones, in side position, as particles have more time to deposit, and avoid being released by the collision of the fast air flow with the filter. The results thus obtained clearly highlight the advantages

of using a filter in a side position compared to one in a frontal position. For the following experimentation, tests will be carried out on filters fixed in a side position on the frame of the bicycle.

III.2. Different profiles of mobile PM trapping

Samples collected from both trajectories profiles, i.e. peri-urban for VH, and city center and high traffic roads for VQ, give clear evidence for the capacity of the filter to capture PM_{10} , $PM_{2.5}$, and most importantly, PM_1 (Fig. 5A - 5F). Particles deposition on the different filter surfaces display homogeneous arrangements, with a higher PM captured apparent density on VQ compared to VH. In comparison to the previous study of the fixed prototype for capturing PM in outdoor urban air (Trinh et al., 2024), VH and VQ samples do not have the deposition of large particles and aggregation like the fixed prototype's samples. The explanation of such results could be attributed to the side position of the filter and also to the mobility of this later during the experimentation where the particles were deposited with higher velocity but in a parallel direction with respect to the filter surface. With a Reynold regime more laminar than turbulence one, particles follow the air flow lines and deposit on fiber mostly by interception or diffusion deposition (Hinds, 1999), explaining the well-organized deposition of PM on both profiles. It should also be noted that the deposition of PMs in this study is carried out in a dynamic mode, and not static as for the fixed prototypes, and can be considered more realistic because it remains close to the dynamic movement of a moving pedestrian, despite the latter being at a lower speed.

As the filter is installed on the bike frame (1 - 1.2 m above the ground), the PMs captured on the filter can represent the PMs inhaled by pedestrians and cyclists. Children with their shorter size and higher breathing rates expose them to greater concentrations of vehicle emissions (J. Gao et al., 2022). Also in this group of age, short-term exposure to air pollution may also trigger allergies, including allergic rhinitis, eczema and conjunctivitis (A. C. Wu et al., 2021). The high deposition rate of PM, particularly fine and ultrafine PMs, on the given height can represent an important nuisance for the respiratory system of children. Moreover, high population density is usually found in the city center where there is a higher traffic frequency than peri-urban, increasing the exposure to PM and other air pollution. The PM particle size density remains similar, except for $PM_{2.5}$, on both filters, i.e. VH and VQ, according to the results presented in Fig. 5G and 5H. Indeed, the granulometric analysis of particles collected yielded quite similar granulometric in particle numbers between two

profiles (Fig. 5G), and both profiles have a high proportion of PM_1 (around 90% of the total particles number). The same tendency is observed in the particle's volume results (Fig. 5H), with no differences in particle volume between two profiles. Such phenomenon can be easily understanding by the fact that small PMs are more prone to be transported by wind, due to their low weight density, compared to the bigger ones. The results presented in Fig. 5G also show that the concentration of $PM_{2.5}$ is higher in the urban area, with dense traffic, compared to that of the peri-urban area, i.e. ca 3 times. These results can be explained by the fact that $PM_{2.5}$ are heavier and therefore more difficult to be transported, as is the case with PM_1 , by the wind out of the emission area, and consequently, their local concentration remains high. As passive trapping is not selective and depends on the relative concentration of different PM inside the aerosols, it is normal to find more $PM_{2.5}$ trapped on the filter in urban areas. Similar observation can be made for the other PMs with larger size, i.e. PM_{10} and $PM_{>10}$ (Fig. 5G and 5H).

On the other hand, the mass of the PM captured varies in a relatively large range between peri-urban and urban locations, which is due to the PM released at a proximity with emitting sources. The PM recovered after washing and drying reveals that for the same period and exposure duration, VH captured 2 - 4 times less of total PM mass than VQ. On average, by each m^2 of filter and each km of exposure, the quantity of total PM mass captured by VH reaches about $2 \pm 0.3 \text{ mg} \cdot m^{-2} \cdot km^{-1}$, while the quantity on VQ is amounted to about $8 \pm 3 \text{ mg} \cdot m^{-2} \cdot km^{-1}$. As described in the previous section, traffic in the peri-urban area is relatively low and therefore results in a lower concentration of PM emitted at the proximity of this area, which explains the low mass of PM captured. In the case of areas located near busy traffic routes, e.g., avenue du Rhin and avenue de Colmar, as the quantity of PM emitted is proportional to the traffic density, higher PM is expected compared to that of peri-urban areas. These explanations allow one to assess the relatively large difference in the mass of PM captured between the two routes. In addition, the dense building and road configuration of urban area can limit PM dispersion, leading to high PM concentration stagnation in stable atmospheric conditions (Reiminger et al., 2023; Y. Wang et al., 2017). In peri-urban profile, where the buildings are more scattered and PM less concentrated, PM in suspension can be easily dispersed by wind, which explains the deficit in quantity of captured PM in peri-urban profile compared to urban profile.

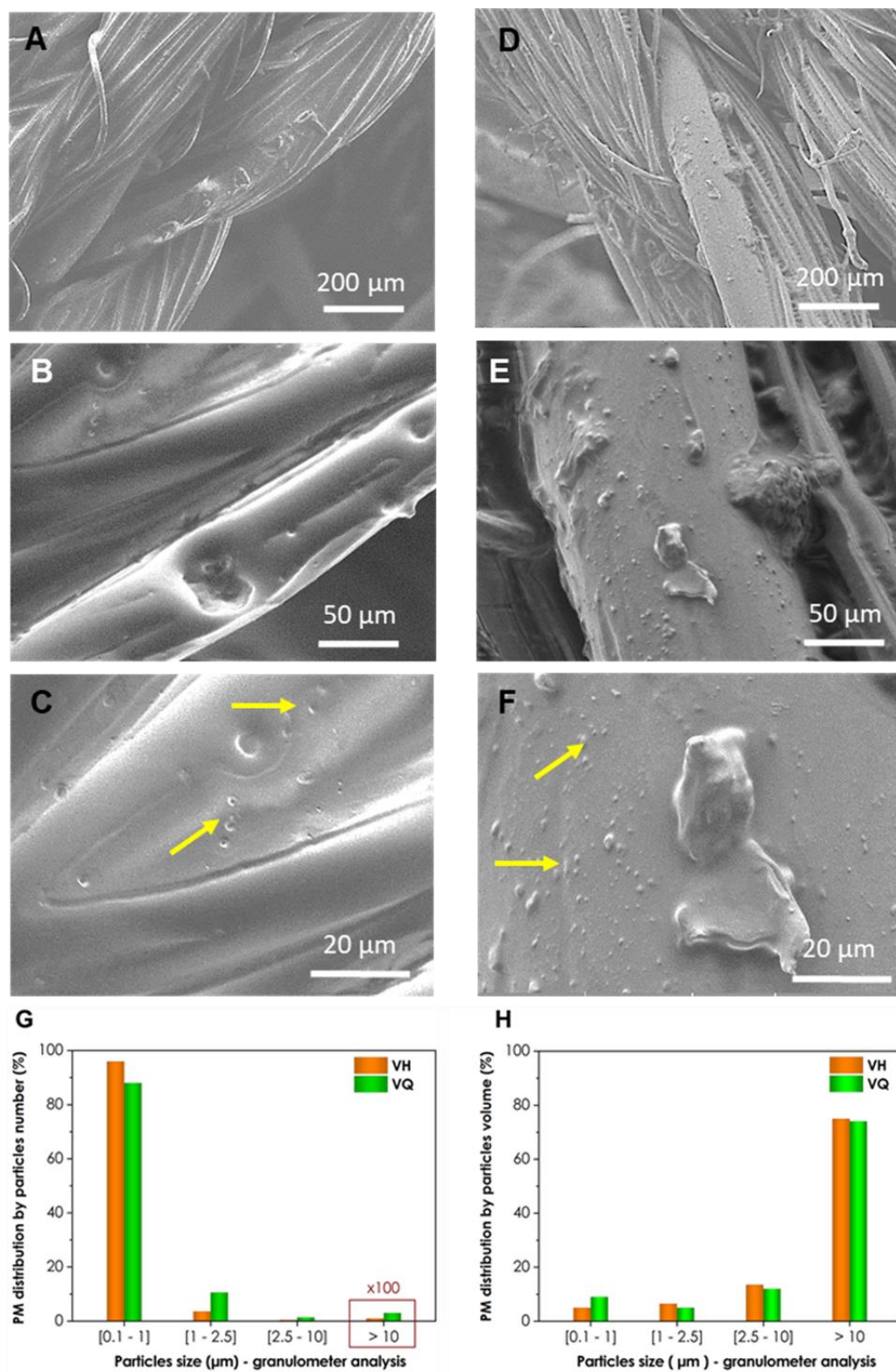


Figure 5 | **A-C.** SEM micrographs of the filter at side position of VH, exposed 31 days from 04/03/2024 to 04/04/2024. | **D-F.** SEM micrographs of the filter at the side position of VQ, also from 04/03/2024 to 04/04/2024. | **G-H.** Comparison of particle size distribution of VH and VQ, by particles number (G) and by particles volume (H). Particles were harvested from the washing solution and passed through the granulometric analyzer.

Although PM emissions may vary depending on vehicle generation, engine power, road type, traffic density, etc., the similarities observed between the deposition pattern and distribution of PM may reflect the same origin and the same mechanisms of PM deposition on the filters. Regarding the origin, the test period is in summer, and therefore the PM emission is not affected by other emission sources such as district heating and weather phenomena. Indeed, in winter, a decrease in temperature at ground level can cause the formation of an inversion layer, especially during sunny weather: in this situation, a layer of cold air forms near the ground and warm, while hot lighter air rises above it. This layer blocks the cold air at the ground, preventing the dispersion of pollutants from human activities and thus, contributes to an increase of the pollution near the ground. Regarding the mode of deposition of PM on filters, passive trapping does not allow the selection of particles to be captured, as in the case of electrostatic filtration where certain particles can be differently charged, and consequently, the distribution of particles thus trapped is directly proportional to those present in the immediate environment. Hankey et al. (Hankey & Marshall, 2015) monitored PM pollution of on-bike exposure near traffic emission sources. They find out that black carbon and PM_{2.5} are the main particulate matter contribution near the road, and drop half of their concentration shortly after moving away from their sources.

Elemental mapping indicates that the chemical composition of the PMs trapped on VH sample is quite similar compared to that obtained on the VQ (Fig. 6A and 6B). On both samples, EDX analysis reveals high concentrations of C and O, with minor contributions of K, Ca, Na, Mg, Si, N and also traces of metal particles like Fe, Al on both PM profiles (Fig. 6C). In their studies (Hankey & Marshall, 2015; Pant & Harrison, 2013; Wypych, 2014), the authors have reported that black carbon of soot particles, bitumen and tires abrasion are the main contributors to the particulate emissions from traffic. As both VH and VQ circulate on the bike lanes of the city of Strasbourg, they have mostly the same road configuration and distance to the road. The speed limit and vehicle circulation mode are similar (50 km. h⁻¹, stop and restart at the traffic lights,...) between the two trajectories, and for these reasons, the two PM profiles do not have much differences in physical aspects. The difference in total mass of PM trapped on the filters can be caused by the difference in PM concentration of near source emission (traffic flux), and the influence of road configuration to PM dispersion mechanism between two trajectories. Such results could be attributed to the higher traffic in the case of VQ, which contributes to a higher emission of metallic or heteroelements.

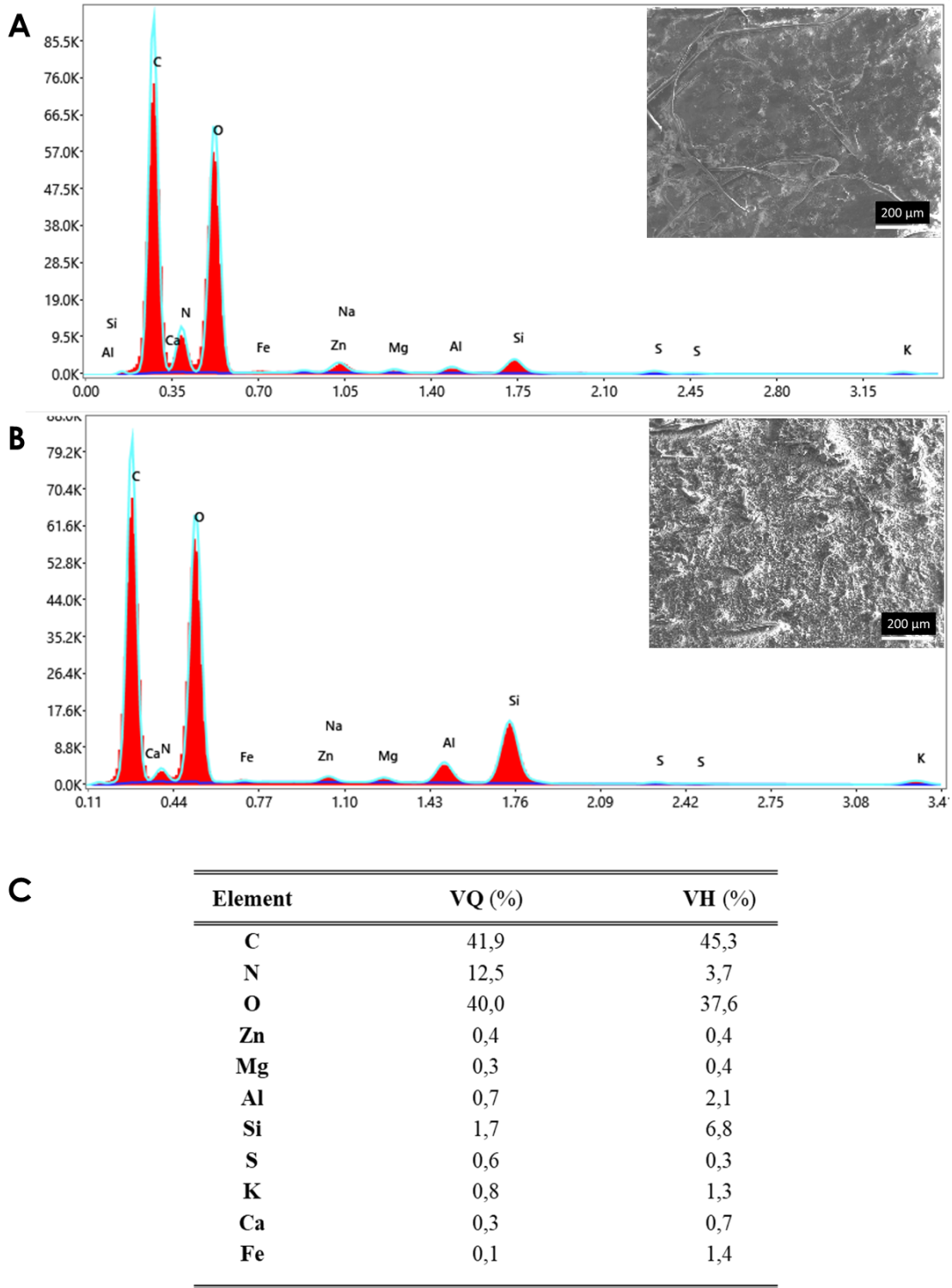


Figure 6 | A, B. EDX analysis of chemical components of particles captured by VQ (A) and VH (B) filters. Inset: images of the scanning zone of analyzed particles, harvested in the washing solution and filtered on the paper filter. | **C.** EDX analysis results of chemical components of particles captured by VQ and VH filters.

Without measures for the pollution mitigation, these emissions can contribute to the episodes of pollution peak, where PM from traffic combines with adequate weather and other emission sources such as biomass burning, construction, etc. (Ehrnsperger & Klemm, 2022; Guo et al., 2014). In normal conditions, carbon is not considered as toxic for human health. But a long and repetitive exposure to carbon particles from traffic emission can trigger many risks of respiratory system issues, especially young children with an incomplete immune system, resulting in several diseases even at young age (Aithal et al., 2023). In addition, during their travel from the emission sources carbon particles can trap other elements, i.e. VOCs, steam aerosol with dissolved chemical compounds, to generate secondary PM which could pose a more serious treat upon inhalation. Furthermore, the presence of the minor elements found in two profiles can be explained by the existence of PM from natural sources. Silicate dust is abundant in nature, it can contain alkaline minerals, salts, and other elements depending on their origins. Studies (Middleton & Kang, 2017; Z. Wang et al., 2024) proved that wind activities can transport and deposit dust thousand kilometers away from their sources. Their existence in both profiles, with the similar proportion indicate that they are in the same wind regime, without anomaly in natural PM deposition. Nitrogen is also present in both profiles, with proportion equivalent to silicon. This element can be linked to NO_x , a secondary pollution, generated by combustion activities and a major contribution to the destruction of ozone layer (Hossain et al., 2021). Last but not least, metal particles found on the filter can be attributed to the degradation of brake, clutch pads during the stop and start of vehicles (Piscitello et al., 2021). Intra-city streets have many traffic lights, which require vehicles to slow down, brake, and restart frequently over short distances. While comparing urban and peri-urban trajectories, the PM composition did not have much variation in chemical element, but the quantity and proportion between elements can be varied by different factors, such as local traffic density. These chemical analysis results align with the findings of our fixed prototype (Trinh et al., 2024), confirming the presence of PMs with different chemical composition found in the outdoor urban environment, for both fixed and mobile trapping methods.

IV. Conclusion and perspectives

In this study, we tested a new concept of mobile trapping PM in urban and peri-urban areas by passive filter fixed on bicycle frame. Both trajectories exposed at the same period and exposure duration, with the same position on the bike. However, the proportion of $\text{PM}_{2.5}$

trapped in urban area remains higher than that trapped in peri-urban one. On average, mobile trap exposed in urban area can capture up to 2-4 times more of total PM mass compared to peri-urban one. Such results are due to the large concentration of PM issued from high traffic density in the city centers and also to the infrastructure configuration which contributes to the stagnation of the emitted PM in urban area. According to the results obtained, for every kilometer exposed, each m² of filter can capture up to 5 - 7 % of non-exhaust PM₁₀ emission of a LDV. In urban area, the amount of PM_{2.5} is higher compared to that trapped in peri-urban one, which could be attributed to the lower dispersion of such PMs by natural factor. Furthermore, we also find significant differences in terms of chemical composition between the two profiles investigated due to a higher traffic and low dispersion of the emitted PMs. The PMs are constituted principally by carbon and oxygen, with minor contribution of natural elements and traces of metal particles in the case of peri-urban area, while the later elements increase for the urban sector. These major elements, C and O, have origin from particles issue from the degradation of the tires and road surfaces, while natural-abundant elements from dusts and wind deposit, and metal particles from non-exhaust traffic emission. The other elements are emitted from brake and clutch and steadily increase with the increasing of traffic in the sector. The metallic elements, despite only contribute to a small fraction of the suspended PMs, are expected to have a high impact on the human health as their can be further reacted upon inhalation to generate secondary products with more harmful effect. The results of this study have highlighted particle pollution in various sectors of the city.

The advantage of this type of measurement lies in the fact that it is carried out on a larger geometric scale compared to fixed measuring stations where only particles within a restricted radius were measured. This type of measurement can be extended to the entire city in order to draw up an accurate map of urban and peri-urban pollution based on traffic and to implement remediation solutions based on the sectors and the associated population. In order to improve air quality in urban areas, the mobile PM trapping solution can be considered in combination with other solutions such as the installation of fixed active/passive filters, and to reconsider urban planning compared to the current one in order to reduce the impact of this pollution on the population.

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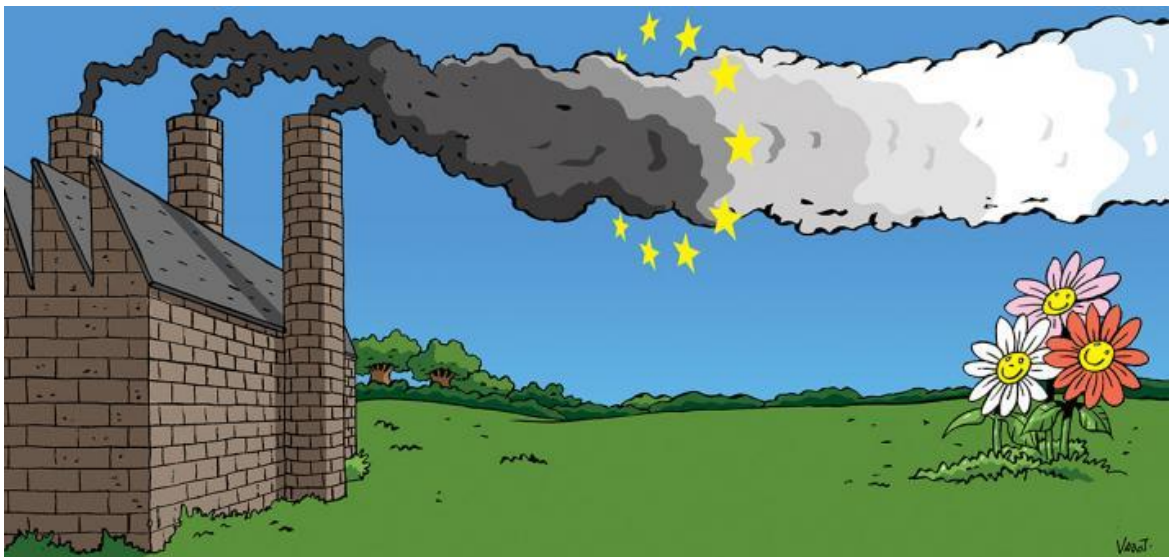
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CHAPTER 5

CONCLUSION AND PERSPECTIVES



I. Conclusion

Urban air pollution, particularly fine (PM_{2.5}) and ultrafine (PM₁) particles, remains a leading contributor to premature mortality and chronic diseases worldwide. Fine particle pollution from road traffic emissions is one of the most pressing environmental and public health challenges in contemporary urban environments. This thesis focuses on mitigating fine particle pollution near roadways through the development and field application of a passive outdoor air filtration system. This work integrates multidisciplinary approaches, including environmental engineering, materials science, meteorological monitoring data analysis, and CFD modeling, to test a passive (no energy consumption), washable and regenerable, affordable, and scalable solution for reducing outdoor air particles. Currently, for indoor and industrial environments, technological advances allow the development of robust and highly efficient active filtration systems, offering a wide range of preferences. However, these active systems often have drawbacks that complicate their deployment in outdoor environments or those with limited available space, including high-energy consumption, high noise level, incompatibility with infrastructure and a significant carbon footprint (most filters are single-use). Moreover, existing regulatory efforts and strategies for PM reduction at source, although crucial, do not yet effectively and fully cover non-tailpipe emissions, such as those due to brake wear, tire abrasion and road surface degradation, especially with the increasing adoption of electric vehicles equipped with large batteries (the heavier the vehicle, the higher the non-tailpipe emissions). This research proposes and validates a passive air filtration solution, capable of capturing non-tailpipe PM emissions near the sources. This filter consists of a washable, oil-coated polyester fiber matrix offering low pressure drop and a high accessible geometric surface area. This filter has been tested in various outdoor environments under natural conditions without external energy input. The device has been designed to be both durable and adaptable, allowing deployment in diverse environments, such as busy urban roadsides to semi-enclosed infrastructures (car parks, underground public transport stations, etc.). The filter used is completely regenerable, thus offering an environmental alternative to disposable filters.

Field tests conducted in Strasbourg, France, demonstrated that the system positioned along a busy avenue, i.e. ADR, captured approximately $40 \pm 3 \text{ g. m}^{-2}$ while the system positioned along a busy road, i.e. RM35, could capture up to $84 \pm 6 \text{ g. m}^{-2}$ (all particle sizes combined) over a 14-week period. The difference in capture could be explained by the

difference in local PM concentration in the two areas. Particle size analysis identified a very wide range of particle sizes, depending on the exposure duration, exposure period, and location. On average, approximately 40% of the total trapped particle volume and more than 80% of the particle number are PM₁₀. Chemical characterization confirmed that most of the trapped particles originated from traffic sources other than exhaust gases, including tire and road wear, as well as metal fragments associated with braking activity. Even on highways, where vehicles travel at high speeds and stop less, traces of metal particles can also be found, as high-speed braking can generate more particles, due to the high friction force between the wheels and brake pads. The system maintained trapping performance after washing and regeneration, confirming its potential for long-term use with reduced environmental impact. In addition to filter recyclability tests and analysis of captured particles, this thesis also examined the influence of weather conditions on fine particle capture and filter behavior. Variables such as temperature, wind speed, and humidity appear to have a significant impact on the deposition rate and stability in terms of fine particle retention on the filter surface. Rain and wind can reduce the concentration of fine particles in the air, thus decreasing their concentration and, indirectly, the amount of fine particles captured on filters. Since oil viscosity changes with temperature, daily and seasonal variations in ambient temperature can strongly affect the properties of the oil layer and the overall filtration dynamics. These close links between fine particle trapping and meteorological parameters, during real-life tests, highlight the need to integrate real-time in situ meteorological data with CFD modeling in future outdoor filter deployment strategies. This integration will optimize positioning and adaptation to local atmospheric conditions, thus maximizing filtration performance and reducing maintenance frequency.

In addition to passive trapping with a fixed device, our study extends its scope to mobile passive filtration systems, such as filters mounted on bicycles, with a view to mapping pollution in different sectors of the city and also as a case study for pollution mitigation at the individual level. The results showed that the filters, mounted in a lateral position, present a significant efficiency for particle capture in urban and peri-urban environments. Although unbalanced in the amount of total particle mass captured due to the difference in particle concentration, mobile trapping in urban and peri-urban trajectories presents a very similar particle profile. For particle size analyses, a difference was observed for PM_{2.5} between urban and peri-urban environments, which can be attributed to problems of PM_{2.5} dispersion by wind. Regarding the chemical composition, the profile of the captured PM is similar between

the two areas, with more than 90% of particles consisting of carbon black. Traces of metallic particles and particles of natural origin were also observed in the chemical analysis of the residues after washing. The primary objective of this study is to draw up a more comprehensive map of air pollution in different sectors of the city, which can be used for the deployment of prevention measures to reduce the impact of this problem on the local population. It should be noted that the results obtained in this study could also serve as an initiative for individual strategies to reduce transport-related pollution, particularly in cities where cycling is encouraged for sustainability and health reasons.

In conclusion, this thesis investigates a promising solution for reducing air pollution by testing a passive filtration approach that is energy-free, reusable, and adaptable to various urban contexts. The prototype thus developed allows for detailed investigation of passive air filtration in larger-scale air quality management systems. Based on similar studies, we suggest that passive filters can be combined with other active or hybrid air filtration systems, and also as a device for sectoral pollution monitoring. The combination between these different systems can have a significant role in reducing human exposure to fine particle pollution, especially in vulnerable and highly exposed areas..

II. Perspectives

Further optimization of the filter structure, i.e. improving entanglement and higher exposure geometric surface area while preserving the low initial pressure drop, and oil formulation, i.e. higher stability as a function of time of exposure, will be necessary to improve the particle trapping efficiency. It is also possible to consider testing and using multi-layer filters after carefully evaluating the pressure drop change of the additional layers. It is important to note that the filter's washability and regenerability significantly reduce the issue of filter waste management, which is in line within the framework of the principles of circular economy and industrial sustainability. A life cycle analysis can also be performed to assess the filter's impact on the environment and contribute to the cost-benefit ratio. Nevertheless, reducing particle emissions at the source (as close as possible) remains and will continue to be the most effective and sustainable approach.

In terms of practical deployment, the use of CFD simulation and statistical models for data analysis can be applied to pre-deployment assessments of this type of passive process. The combination of these techniques and sectoral mapping, carried out by mobile means,

could help to better identify the sectors at risk for the implementation of the process. The combination of different data will help to determine the optimal quantity and positioning of filters, thus reducing testing and associated costs, and facilitating data-driven policy development. In addition, socio-economic and behavioral factors such as public awareness, institutional support, and cost-benefit analyses must be considered when implementing passive filtration technologies on a large scale in various urban and peri-urban sectors. The development of modular, user-friendly, and affordable filters would increase public acceptance and awareness of environmental protection. Future work should focus on scaling the system, optimizing materials for specific environmental conditions, and integrating advanced sensing and data analysis tools to build resilient and smart air filtration networks. These efforts will significantly contribute to creating cleaner, healthier, and more equitable urban environments. Finally, passive trapping systems could also be installed in high-pollution locations such as metro stations, where the concentration of metallic PM_{2.5}, resulting from train braking with the track, is extremely high, exceeding the WHO standards several dozen times. Indeed, active systems are difficult to implement in these locations due to limited access to electricity and space between platforms, not to mention noise pollution issues for users. Preliminary tests were conducted at the Aubervilliers metro station in Paris, France, and showed interesting results in terms of PMs capture and storage on the passive filter developed in this study.

To this end, in the introductory part of this work other technological advances, such as vacuum brake particle collectors (e.g., TAMIC by Tallano and solutions by Mann+Hummel), improved tire compounds, and abrasion-resistant road surfaces, are to be kept in mind and can also be considered to reduce particles at the source. Nevertheless, technology like the one developed by Tallano does not seem suitable for light cars but more efficient for public transport, i.e., buses, trams, metros. These technologies, along with urban greening, traffic policy reform, and industrial electrification, are essential complementary measures. Standards and regulations can also influence future industrial development and citizen behavior, such as the Euro 7 emission standards and WHO recommendations.

LIST OF PUBLICATIONS AND COMMUNICATIONS

Patent

1. Pham, C., Vieville, C., Hertel, N., Nhut, J.-M., Ba, H., Vigneron, F., Truong-Phuoc, L., Trinh, T.-H., & Pham-Huu, C. (2021). Dispositif passif de capture des microparticules en suspension dans l'air (Patent No. FR3128130). <https://data.inpi.fr/brevets/FR3128130>

Published articles

1. Trinh, T.-H., Pham, C., Nhut, J.-M., Vigneron, F., Vieville, C., Reiminger, N., Jurado, X., Ba, H., Romero, T., Truong-Phuoc, L., Hertel, N., Legorgeu, C., Vidal, L., & Pham-Huu, C. (2024). Washable oil-coated structured support for passive outdoor particulate matters trapping. *Sustainable Cities and Society*, 116, 105884. DOI: 10.1016/j.scs.2024.105884
2. Trinh, T.-H., Pham, C., Reiminger, N., Nhut, J.-M., & Pham-Huu, C. (2025). Filtration systems for particulate matter reduction in outdoor air: A review. *Journal of Environmental Management*, 390, 126263. DOI: 10.1016/j.jenvman.2025.126263

Submitted articles

1. Trinh, T.-H., Pham, C., Reiminger, N., Nhut, J.-M., Vigneron, F., Jurado, X., & Pham-Huu, C. (2025). Dispositifs pour la filtration passive des particules fines en milieu urbain et periurbain à Strasbourg, France. Submitted to *Techniques Sciences et Méthodes* journal.
2. Trinh, T.-H., Nhut, J.-M., Reiminger, N., Jurado, X., Vidal, L., Fabrice, V., Pham, C., Pham-Huu, C. (2025). Passive Technologies for Fine Particle Mitigation in Urban Environments: A Case Study in Strasbourg, France. Submitted to *Atmospheric Pollution Research* journal.
3. Trinh, T.-H., Maerklen, Q., Nhut, J.-M., Pham, C., Pham-Huu, C. (2025). Passive mobile trap for fine particles capture in outdoor air for sectorial pollution analysis: a study case in Strasbourg city, France.

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4. Trinh, T.-H., Nhut, J.-M., Reiminger, N., Jurado, X., Nguyen, H.-L., Vigneron, F., Vidal, L., Romero, T., Pham, C., Pham-Huu, C. (2025). Passive PM Capture by Reusable Oil-Coated Structure and weather impacts on PM trapping process (Case study on a busy ring road in Strasbourg City, France).

Conference and presentations

1. T.-H. Trinh, C. Pham, J.M. Nhut, F. Vigneron, C. Vieville, N. Reiminger, X. Jurado, H. Ba, T. Romero, L. Truong-Phuoc, N. Hertel, C. Legorgeu, L. Vidal, C. Pham-Huu. Oral presentation at 37^{ème} congres of aerosols CFA 2024, Paris, France at 19 and 20/03/2024. DOI : 10.25576/ASFERA-CFA2024-38764
2. J.M. Nhut, F. Vigneron, T.-H. Trinh, C. Pham, N. Reiminger, X. Jurado, T. Romero, N. Hertel, C. Pham-Huu. Oral presentation for TrapAparT report, 11/07/2022.
3. T.-H. Trinh. Oral presentation at the general assembly of ICPEES in 18/10/2022 and 22/11/2022.

Devices for passive trapping of fine particulate matters in outdoor air

Résumé

La pollution atmosphérique causée par des particules fines (PM) est devenue un enjeu important, spécialement dans des grandes villes où des activités humaines sont identifiées comme une source d'émissions majeures de PM. La réduction de PM devient la priorité dans le plan d'amélioration de la qualité d'air intérieur ainsi qu'extérieur. Dans ce travail, un nouveau concept de filtration passive de l'air dans les milieux extérieurs est développé et testé. Un matériel lavable et réutilisable est choisi, ses faibles pertes de charge assurent une circulation d'air continue et stable, en favorisant le contact du flux avec des fibres. Les prototypes expérimentaux à proximité des routes à haute densité de circulation trafic ont été déployés et utilisés pour étudier la captage des PM à longues durées. La couche d'envêtement a un rôle indispensable, à la fois en captage et en rétention des particules, avec une longue durée de 12 à 14 semaines d'exposition. Avec une installation facile et sans avoir besoin d'une source d'énergie pour fonctionner, l'appareil a la possibilité d'installer sur les transports, i.e. les vélos afin de capter des PM en circulant dans les milieux urbains. Les influences des différents paramètres météorologiques sur la quantité de PM total captée sont aussi discutées et extrapolées. La procédure est simulée par la computation du dynamique des fluides qui investigate des différents modèles et scénarios de filtration PM dans des milieux extérieurs.

Abstract

Particulate matter (PM) pollution has become one of the major atmospheric pollution, especially in big cities, where anthropogenic activities are, in most cases, the main PM emission source. As PM is one of the main causes of several respiratory diseases and chronic illnesses, PM reduction might be the priority in air pollution mitigation for both indoor and outdoor air. In this work, a new concept of passive outdoor air filtration was developed and tested. A layer of vegetable oil was coated on a washable and reusable filter structure, which has low pressure drop for favouring air circulation and the contact of air with the fibre. Experimental prototypes in proximity of high traffic city ring roads were successfully deployed and used for testing the long-term effects of PM trapping. The coating layer is certified to have a crucial role in PM captage and retention, and the optimised exposure duration can extend up to 12-14 weeks. With its simple mechanism, the filter device can also be installed on the bicycle for trapping PM while moving. The emphasis of the air filtration device with the natural aerodynamics of the air highlights the benefit of passive filtration with no electricity needed for the filter to function. Influences of weather aleatory and variation on PM captage are also discussed, while analysing weather data for extrapolating and optimising PM filtration. Computational fluid dynamics (CFD) can be used to simulate the procedure, and predict different scenarios of passive outdoor air filter deployment and scale-up.