Szkoła Główna Gospodarstwa Wiejskiego
w Warszawie
Instytut Inżynierii Środowiska

mgr inż. Karolina Kais

# Usługi ekosystemowe alei Warszawy

## Ecosystem services of Warsaw's avenues

Rozprawa doktorska
Doctoral thesis

Rozprawa doktorska wykonana pod kierunkiem
dr hab. inż. arch. kraj. Marzeny Suchockiej
Katedra Architektury Krajobrazu,
Instytut Inżynierii Środowiska,
SGGW w Warszawie

Warszawa rok 2025

**Oświadczenie promotora rozprawy doktorskiej**

Oświadczam, że niniejsza rozprawa została przygotowana pod moim kierunkiem i stwierdzam, że spełnia warunki do przedstawienia jej w postępowaniu o nadanie stopnia naukowego doktora.

Data 29.10.2025 Czytelny podpis promotora Monika Szczałba

**Oświadczenie autora rozprawy doktorskiej**

Świadoma odpowiedzialności prawnej, w tym odpowiedzialności karnej za złożenie fałszywego oświadczenia, oświadczam, że niniejsza rozprawa doktorska została napisana przeze mnie samodzielnie i nie zawiera treści uzyskanych w sposób niezgodny z obowiązującymi przepisami prawa, a w szczególności z ustawą z dnia 4 lutego 1994 r. o prawie autorskim i prawach pokrewnych (tj. z dnia 28 października 2022 r., Dz. U. z 2022 r. poz. 2509 ze zm.)

Oświadczam również, że przedstawiona rozprawa nie była wcześniej podstawą żadnej procedury związanej z uzyskaniem stopnia naukowego doktora.

Oświadczam ponadto, że niniejsza wersja pracy jest identyczna z załączoną wersją elektroniczną.

Przyjmuję do wiadomości, że rozprawa doktorska poddana zostanie procedurze antyplagiatowej.

Data 29.10.2025 Czytelny podpis autora rozprawy Karolina Kaś

## Spis treści

## Streszczenie

Usługi ekosystemowe są to korzyści, które czerpane są z natury przez ludzi, a zaliczają się do nich również usługi regulacyjne, które obejmują działania na rzecz regulacji klimatu i jakości powietrza. Drzewa miejskie tworzą zaś największy segment miejskich terenów zieleni, co jednocześnie wskazuje na ich duży potencjał w regulacji procesów środowiskowych oraz stanowi znaczący element strategii mitygacji zmiany klimatu. Efektywne planowanie nasadzeń miejskich napotyka istotne bariery, w tym niedostateczną świadomość społeczną dotyczącej usług ekosystemowych ale również niewykorzystanie potencjału drzew w procesie zarządzania miastem. Prowadzenie badań nad efektywnością usług ekosystemowych napotyka również na problemy wynikające z różnic w metodykach prowadzonych badań.

Niniejsza rozprawa ma charakter dokumentacyjny i analityczny oraz stanowi próbę uzupełnienia wiedzy w zakresie oceny świadomości mieszkańców w zakresie świadczonych usług ekosystemowych, ilościowego świadczenia usług ekosystemowych na przykładzie wybranych alei miasta Warszawy, , a także porównania metod fitofiltracji cząstek stałych. Analiza świadomości społecznej wykazała, że mieszkańcy zidentyfikowali funkcje ekosystemowe drzew, jednocześnie wskazując na najważniejszą ich funkcję - poprawę powietrza. Jednocześnie stwierdzono większą świadomość mieszkańców dot. usług ekosystemowych na obszarze o większym zadrzewieniu. Ponadto opracowano analizę stężenia poziomu $PM_{2.5}$ z podziałem na godziny szczytu oraz godziny poza szczytem natężenia ruchu samochodowego, a także z podziałem na obszary o kontrastującym pokryciu koronami drzew (TCC). Po przeprowadzonym monitoringu wykazano, że przekroczenia normy jakości powietrza WHO $PM_{2.5}$ (15 µg/m³) występowały 1,5 razy częściej na ulicach z 6% pokryciem koron drzew w porównaniu z ulicami z ponad 30% TCC. Wykazano również, że model jest statystycznie istotny, co oznacza że jeden z predyktorów TCC lub średnice pni drzew mają istotny wpływ na poziomy usuwania $PM_{2.5}$. Przeprowadzono analizę pochłaniania $PM_{2.5}$ oraz $PM_{10}$ za pomocą dwóch metod - metody i-Tree Eco oraz metody laboratoryjnej. Wyniki ujawniły istotne rozbieżności pomiędzy wartościami modelowymi a laboratoryjnymi. Porównanie średniej rocznej akumulacji $PM_{10}$ mierzonej metodami laboratoryjnymi wykazało, że *Tilia sp*. osiągnęła 24%, *Fraxinus sp*. 47,6%, *Aesculus sp*. 50,77%, a *Quercus robur* 23,4% wydajności wychwytu $PM_{10}$ oszacowanej przez model i-Tree Eco. W przypadku wychwytu $PM_{2,5}$ wartości uzyskane obiema metodami były bardziej spójne. Ponadto drzewa rosnące

w trudniejszych warunkach środowiskowych wykazywały mniejszą średnicę na wysokości pierśnicy (DBH) i niższą wydajność usuwania $PM_{10}$ i $PM_{2,5}$ zgodnie z obiema metodami.

Wyniki badań przedstawione w niniejszym studium dokumentują stan od roku 2021 do 2025. Opracowanie jest istotnym głosem w dyskusji o możliwościach oceny zanieczyszczeń powietrza, a przedstawione analizy dostarczają argumentów o istotności rozwoju nasadzeń miejskich.

## Abstract

Ecosystem services are benefits that people derive from nature, including regulatory services such as climate and air quality regulation. Urban trees constitute the largest segment of urban green areas, which also indicates their great potential in regulating environmental processes and constitutes a significant element of climate change mitigation strategies. Effective urban planting planning faces significant barriers, including insufficient public awareness of ecosystem services, but also the failure to exploit the potential of trees in the urban management process. Research into the effectiveness of ecosystem services also encounters problems resulting from differences in research methodologies.

This dissertation is documentary and analytical in nature and attempts to supplement knowledge in the field of assessing residents' awareness of ecosystem services, the quantitative provision of ecosystem services using the example of selected avenues in the city of Warsaw, as well as comparing methods of phytofiltration of solid particles. The analysis of public awareness showed that residents identified the ecosystem functions of trees, while pointing to their most important function, which is air improvement. At the same time, greater awareness of ecosystem services was found among residents in areas with more trees. In addition, an analysis of PM2.5 concentrations was developed, broken down by rush hour and off-peak hours of traffic, as well as by areas with contrasting tree canopy cover (TCC). The monitoring showed that exceedances of the WHO PM2.5 air quality standard (15 μg/m$^3$) occurred 1.5 times more frequently on streets with 6% tree canopy cover compared to streets with over 30% TCC. The model was also shown to be statistically significant, meaning that one of the predictors, TCC or tree trunk diameter, has a significant impact on PM2.5 removal levels. An analysis of PM2.5 and PM10 absorption was carried out using two methods: the i-Tree Eco method and a laboratory method. The

results revealed significant discrepancies between the model and laboratory values. The results revealed significant discrepancies between model and laboratory values. A comparison of the average annual PM10 accumulation measured by laboratory methods showed that *Tilia sp.* achieved 24%, *Fraxinus sp.* 47.6%, *Aesculus sp.* 50.77%, and *Quercus robur* 23.4% PM10 capture efficiency estimated by the i-Tree Eco model. For PM2.5 capture, the values obtained by both methods were more consistent. In addition, trees growing in more challenging environmental conditions showed smaller diameter at breast height (DBH) and lower PM10 and PM2.5 removal efficiency according to both methods.

The results of the study presented in this paper document the situation from 2021 to 2025. The study is an important voice in the discussion on the possibilities of assessing air pollution, and the analyses presented provide arguments for the importance of developing urban plantings.

# 1. Wstęp

## 1.1. Usługi ekosystemowe świadczone przez drzewa

Usługi ekosystemowe definiuje się jako warunki i procesy zapewniane przez naturalne ekosystemy i ich gatunki w celu utrzymania i wzbogacenia życia ludzi (Daily, 1997). Usługi ekosystemowe można zdefiniować także jako korzyści czerpane bezpośrednio i pośrednio z funkcji ekosystemów przez członków społeczności (Reid, Constanza, 1997). Ze względu na stale rosnącą populację miejską (FAO, WUP, ONZ) i ograniczone tereny zielone, funkcje ekosystemów miejskich, które tworzą połączenie między miastami a biosferą, poprawiają zdrowie publiczne mieszkańców, zmniejszają poziom hałasu, oczyszczają systemy kanalizacyjne i zmniejszają miejski dług ekologiczny (Gómez-Baggethun, 2013; Langemeyer, 2016; Haase, 2014) stały się zagrożone (Kim, 2021).

Wyróżnia się następujące usługi ekosystemowe:

- usługi podstawowe takie jak: tworzenie gleby, fotosynteza i produkcja pierwotna, cykl biochemiczny;
- usługi zaopatrujące: żywność, woda, leki, trwałe materiały, itp.;
- usługi kulturowe: rekreacja, inspiracja kulturowa, relaksacja;
- usługi regulacyjne: regulacja klimatu, oczyszczanie gleb, powietrza i wody, łagodzenie ekstremów pogodowych (Daily, 1997).

Zielona infrastruktura, która zapewnia mieszkańcom aglomeracji miejskich usługi społeczne i środowiskowe w celu poprawy jakości ich życia, służy jako generator usług ekosystemów miejskich (La Rosa, 2013; Jennings, 2016; Jim, 2009; Benedict, 2012; Ahern, 2007). Ponadto zielona infrastruktura, jako jeden z głównych elementów społecznych i ekologicznych systemów miejskich, staje się coraz ważniejszym punktem odniesienia w dyskusjach na temat zrównoważonego rozwoju i planowania urbanistycznego (Khelfi, 2008; EEA, 2012; Jasiński, 2021; Pappa, 2021).

Drzewa na poboczach dróg, w parkach, ogrodach, pozostałych lasach i na budynkach tworzą największy segment miejskich terenów zielonych (Feng, 2013; Jim, 2017). Badania pokazują, że drzewa wzbogacają krajobraz i odgrywają ważną rolę w procesie ograniczania niekorzystnego wpływu osiedli mieszkaniowych na środowisko (Seamans, 2013). Korzyści te określane są jako usługi ekosystemowe świadczone przez drzewa i zapewniają inne korzyści – ekonomiczne, zdrowotne, społeczne i wizualne, ale także regulację procesów środowiskowych (Roy, 2012). W praktyce drzewa i inne elementy zielonej infrastruktury w miastach są wykorzystywane do zarządzania systemem wód opadowych (Day, 2008; Xiao, 1998), zapewniają rozwiązania problemów z nieprzepuszczalnymi powierzchniami i przechwytują wodę deszczową zanim dotrze do systemów kanalizacji deszczowej (Villareal, 2004). Są one również przydatne w procesie obniżania poziomu zużycia energii – drzewa rosnące na południe i zachód od domów przyczyniają się do obniżenia kosztów chłodzenia budynków (Donovan, 2009). Według innych autorów drzewa pozytywnie wpływają również na zdrowie publiczne, podnosząc jakość powietrza, zachęcając mieszkańców do aktywności fizycznej, obniżając poziom stresu i poprawiając relacje społeczne (Hystad, 2014). Badania wykazały, że mieszkańcy dzielnic z lepszym dostępem do parków i terenów zieleni uprawiają więcej sportów (Coombes, 2010; Hansmann, 2007). Udowodniono, że większa liczba terenów zieleni wpływa pozytywnie na odbywanie spacerów po okolicy (Frank, 2005), a drzewa i dostęp do nich przyczyniają się do niższego poziomu stresu (Roe, 2011; Stigsdotter, 2010; van der Berg, 2010). Niezależne badania wykazały, że kobiety mieszkające w pobliżu drzew (w promieniu 50 metrów) rzadziej rodziły dzieci o niskiej masie urodzeniowej (Donovan, 2011; Laurent 2013). Jednocześnie należy zauważyć, że drzewa, które zapewniają usługi ekosystemowe, mogą również uszkadzać elementy infrastruktury i powodować alergie (Duan, 2015). Odpowiednie planowanie urbanistyczne zgodne ze zrównoważonym rozwojem powinno uwzględniać korelacje między stosunkiem mieszkańców do terenów zieleni a ich wpływem na rozwój i zarządzanie zieloną infrastrukturą miejską (Donzelli, 2021; Foszcz, 2021; Kurt, 2016; Fantke, 2014).

## 1.2. Świadomość społeczna w zakresie korzyści środowiskowych świadczonych przez drzewa

Drzewa w miastach mają różne znaczenie dla społeczeństwa. Niektórzy mieszkańcy miast uważają je za okazję do pozostania w kontakcie z naturą, podczas gdy inni postrzegają je jako uciążliwość (Roy, 2012). Relacje między środowiskiem naturalnym a ludźmi mogą być rozpatrywane na podstawie wielu teorii psychologii środowiskowej (Holahan, 2003); teoria planowanego zachowania Ajzena, teoria wartości-wiary-normy Sterna (Ajzen, 1991; Stern 1999] i teoria hierarchii poznawczej Rokeacha mają tu znaczenie (Baur, 2016; Milfont, 2010). Homer i Kale, w oparciu o wymienione tu modele, stworzyli swój model wartości, postaw i zachowań, który można zastosować w dyskursie środowiskowym (Milfont, 2010; Homer 1988). Postawy są zdefiniowane w modelu jako pozytywne i negatywne (zróżnicowane jako preferencja, sympatia lub niechęć) wobec pewnych obiektów, w tym między innymi drzew (Jones, 2012; Balram, 2005, Kaltenborn, 2002). Dane pokazują, że ludzie mają bardzo pozytywny stosunek do drzew w miastach (Salmond, 2016; Tzoluas, 2007; Schroeder, 2006; Taylor, 2015; De Vires, 2013; Peckham, 2013; Heynen, 2016; Tallis, 2009), co w połączeniu z modelem hierarchii wartość-postawa-zachowanie znajduje zastosowanie w badaniach nad potencjalnymi zachowaniami w przestrzeni miejskiej, gdzie określone postawy mieszkańców wpływają również na decyzje dotyczące zielonej infrastruktury (Heberlein, 2012). Prowadzono liczne badania na temat świadomości dotyczącej usług ekosystemowych. Analiza opinii mieszkańców San Juan w Puerto Rico pokazuje, że mieszkańcy miasta są w stanie zidentyfikować liczne usługi ekosystemowe świadczone przez tereny zieleni miejskiej (López-Marrero, 2011; Santiago, 2015). Wyniki ankiet przeprowadzonych w Puerto Rico pokazują, że postrzeganie usług ekosystemowych może różnić się na małych obszarach (López-Marrero, 2011). Badanie przeprowadzone w Holandii dotyczące terenów zieleni przyulicznej wykazało ich pozytywny wpływ na ogólny stan zdrowia i zdrowie psychiczne mieszkańców (De Vries, 2013). Badania przeprowadzone przez Peckham i in. (2013) pokazują, że mieszkańcy Halifax i Calgary prezentują różne postawy i sposoby postrzegania drzew miejskich. Podczas dojazdów do pracy niektórzy mieszkańcy korzystali z terenów zieleni miejskiej, a także wielu z nich wymieniało śpiew ptaków jako czynnik uspokajający. Wyniki badań dotyczących świadomości społecznej nt. usług ekosystemowych wpływają na proces podejmowania decyzji przez decydentów (Laurans, 2014), jednak zagadnienie to ciągle nie jest zbadane wystarczająco aby dawać podstawy do racjonalnych decyzji, które będą skutkowały wyższym poziomem usług ekosystemowych świadczonych przez drzewa miejskie (*urban forest*).

## 1.3. Problem zanieczyszczenia powietrza

Kwestie zanieczyszczenia powietrza są szeroko dyskutowane zarówno w debacie publicznej, jak i w nauce. Wynika to ze zjawiska ciągłego wzrostu problemów środowiskowych w konsekwencji intensywnego rozwoju gospodarczego. Jak wiadomo, urbanizacja zapewnia liczne korzyści społeczne, jednak można ją uznać za istotny czynnik odpowiedzialny za problemy środowiskowe (Pishgar-Komleh, 2020; Ünal, 2019). Powszechne przekształcanie terenów zielonych w betonowe place, osiedla mieszkaniowe czy centra handlowe przekłada się na coraz mniejszą ilość terenów zielonych w miastach, a w konsekwencji potęguje zjawisko smogu i wzrost zanieczyszczenia powietrza w miastach. Postępowanie tego procesu wiąże się z licznymi problemami zdrowotnymi (EEA, 2012; Jasiński et al., 2021; Pappa & Kioutsioukis, 2021). Według badań ekspertów zanieczyszczenie powietrza stanowi istotny problem, a wiele substancji wymienionych w dyrektywach Rady Europejskiej: 96/62/WE i 1999/30/WE, 2002/3/WE, 2008/50/WE (Rada Unii Europejskiej, 1996, 1999, 2002, 2008), które znajdują się w powietrzu, osiąga stężenia niebezpieczne dla życia i zdrowia ludzi (Bates, 2005; Zanobetti & Schwartz, 2012).

Jak wskazują badania, pył zawieszony (PM) ma najbardziej szkodliwy wpływ na zdrowie publiczne i środowisko (Russell & Brunekreef, 2009). Wynika to z wielkości cząstek - dlatego pył antropogeniczny jest uważany za największe zagrożenie dla zdrowia ludzkiego (CAFE, 2004). Wdychanie PM powoduje, że cząsteczki gromadzą się w tkance płucnej i dostają się do krwiobiegu, co z kolei prowadzi do wyższego ryzyka chorób układu krążenia i płuc (Cen, 2015), przewlekłej obturacyjnej choroby płuc i raka płuc (Jeong, 2013). Badania pokazują, że zachorowalność na raka płuc w Pekinie wynosiła 1,055 dla mężczyzn i 1,149 dla kobiet, a wzrost zachorowalności był spowodowany wzrostem poziomu PM2,5 o 10 mg -3 (Guo i in., 2014). Wdychanie pyłu powoduje również pogorszenie stanu zdrowia w chorobach układu oddechowego, takich jak astma (Bond i in., 2013; Brauer i in., 2007) i prowadzi do infekcji dróg oddechowych u dzieci (Bond i in., 2013). Badania epidemiologiczne wykazały również, że pył zawieszony, zwłaszcza PM2.5, może nawet prowadzić do przedwczesnej śmierci (Heal et al., 2012). Należy podkreślić, że zanieczyszczenie powietrza negatywnie wpływa na zdrowie ludzi nie tylko poprzez jego wdychanie, ale także poprzez wchłanianie przez skórę w wyniku kontaktu z zanieczyszczoną wodą lub żywnością (Cunningham i in., 2005).

Warto również wspomnieć, że kwestia zanieczyszczenia powietrza i jego wpływu na zdrowie doprowadziła do znacznego wzrostu kosztów opieki zdrowotnej (M. S. Ho & Nielsen, 2007; Matus et al., 2012) i pomimo rozwoju medycyny, nadal stanowi zagrożenie dla zdrowia publicznego. Źródłem zanieczyszczeń antropogenicznych są przede wszystkim aglomeracje miejskie (Dominick i in., 2012; Gulia i in., 2015; Zhang i Witlox, 2020) z intensywnym ruchem drogowym, dużą liczbą domów i gospodarstw domowych oraz procesami przemysłowymi na dużą skalę (Querol i in., 2008), dlatego bezpośredni wpływ zanieczyszczenia powietrza na zdrowie ludzi obserwuje się na obszarach przemysłowych i zurbanizowanych.

Szacuje się, że postępująca migracja z obszarów wiejskich do miejskich przyczyni się do wzrostu liczby ludności miejskiej i osiągnie 60% w 2030 r. (Bureau, 2007), 70% w 2050 r. w skali światowej (FAO, 2009) i 82% w UE (WUP, 2018). Jak powszechnie wiadomo, urbanizacja zapewnia wiele korzyści społecznych; można ją jednak uznać za istotny czynnik odpowiedzialny za problemy środowiskowe, takie jak Miejska Wyspa Ciepła (UHI) (Aslam i in., 2021; Branea i in., 2016; Huang i in., 2019; Pishgar-Komleh i in., 2020), spowodowane głównie zmianami w użytkowaniu gruntów i ekspansją budownictwa mieszkaniowego (Perpina Castillo i in., 2019; Tu i in., 2016). Zostało to również potwierdzone przez badania przeprowadzone przez WHO, które wykazały, że w ponad 3000 miast zanieczyszczenie powietrza na zewnątrz wzrosło o 8% na całym świecie w ciągu ostatnich pięciu lat (WHO, 2022).

## 1.4. Rośliny a zanieczyszczenie powietrza

W związku z tym, wraz ze wzrostem zanieczyszczenia powietrza w aglomeracjach miejskich, kwestia pokrywy koron drzew (TCC) na obszarach miejskich zyskuje na znaczeniu (Akbari i in., 2001), ponieważ zapewnia mieszkańcom liczne funkcje ekosystemu (Escobedo i in., 2011), w tym filtrację powietrza atmosferycznego i zbieranie (zatrzymywanie) substancji toksycznych (Greksa i in., 2019; Sawidis i in., 2011). Badania pokazują, że obecność roślin jest prawdopodobnie jednym z najskuteczniejszych sposobów eliminacji pyłu zawieszonego ze środowiska (Przybysz i in., 2018; Xu i in., 2020). Drzewa miejskie poprawiają jakość powietrza, ułatwiając osadzanie się różnych gazów i cząstek stałych ze względu na dużą powierzchnię liści, a także poprzez ich wpływ na mikroklimat i turbulencje powietrza (Grote i in., 2016). Zanieczyszczenia są usuwane przez rośliny na dwa sposoby - jeden z nich polega na gromadzeniu osadów na powierzchni roślin, a drugi oznacza, że zanieczyszczenia są pochłaniane przez aparaty szparkowe (Weyens i in., 2015). Liście i kora filtrują powietrze, a w przypadku zanieczyszczenia powietrza ozonem, drzewa rozkładają go na gaz za pomocą emitowanych przez siebie substancji (Janhäll, 2015; Kurpius & Goldstein, 2003). Badania pokazują, że drzewa usunęły około 300 ton zanieczyszczeń powietrza w rejonie Christchurch w Nowej Zelandii w ciągu roku (Cavanagh, 2008). W Wielkiej Brytanii ustalono, że posadzenie drzew na jednej czwartej dostępnego obszaru miejskiego może prowadzić do zmniejszenia stężenia PM10 o 2 do 10% (McDonald i in., 2007). Wielkość absorpcji zanieczyszczeń zależy od trzech różnych czynników (Wesely i Hicks, 2000). Jednym z tych czynników jest ruch powietrza w koronie drzewa, drugi obejmuje przenoszenie powietrza przez warstwę przylegającą do powierzchni drzewa, a trzeci koncentruje się na zdolności absorpcyjnej danej powierzchni, w zależności od przewodnictwa szparkowego (Wesely i Hicks, 2000). Gazy gromadzą się głównie na powierzchni liści (Grote et al., 2016).

Gatunki drzew, których aparaty szparkowe są otwarte dłużej, pochłaniają zanieczyszczenia skuteczniej niż rośliny izohydryczne, które zamykają aparaty szparkowe wcześniej ze względu na niską dostępność wody (Dizengremel i in., 2009). Przeprowadzono wiele badań w zakresie efektywności pochłaniania PM2,5 przez drzewa w celu oceny prędkości sedymentacji (Vd, cm s-1) (Freer-Smith i in., 2005), powierzchni pokrycia cząstek (%) (L. Wang i in., 2015), liczby cząstek (%) (L. Wang i in., 2015), 2015), liczba cząstek (mm-2) (Neinhuis & Barthlott, 1998), prędkość sedymentacji magnetycznej (Mitchell et al., 2010) i objętość sedymentacji (mg cm-2 lub ug cm-2) (Sgrigna et al., 2015). Prędkość sedymentacji PM10 na roślinach wahała się od 0,01 do ok. 10 cm s-1 (Litschke & Kuttler, 2008), jednak badania wykazały, że dokładność modeli była stosunkowo niska (G. Chen et al., 2017). Różnice między modelami i pomiarem Vd zależą od interakcji między drzewem a atmosferą, procesów fizycznych i chemicznych, które obejmują absorpcję PM2.5 oraz wrażliwość modelu na różne parametry warstwy granicznej roślin i warunki początkowe (Selmi i in., 2016).

Zmienne, które wpływają na wartość Vd to, oprócz tych wymienionych wcześniej, rozmiar i gęstość cząstek zanieczyszczeń (Gallagher i in., 1997), zmienne meteorologiczne, takie jak opady (David J. Nowak, Hirabayashi i in., 2013), wiatr (K. Paul Beckett i in., 2000) oraz struktura korony drzewa (David J. Nowak, Greenfield i in., 2013). Wartość absorpcji zanieczyszczeń zależy od trzech różnych czynników (Wesely & Hicks, 2000). Jednym z nich jest ruch powietrza w przestrzeni korony drzewa, drugim jest transfer powietrza przez warstwę przylegającą do powierzchni drzewa, a trzeci odnosi się do zdolności absorpcyjnej powierzchni i zależy od przewodnictwa szparkowego (Wesely & Hicks, 2000).Osadzanie się zanieczyszczeń w postaci cząstek stałych zachodzi głównie na powierzchni liści (Grote i in., 2016).Ultrastruktury kryształów wosku w znacznym stopniu przyczyniają się do adsorpcji PM poprzez ich działanie na powierzchnię kontaktu między PM a powierzchnią liścia (Wang i in., 2018).

Przeprowadzono również badania, które wykazały, że cząsteczki sadzy o wielkości submikronowej mogą być usuwane ze środowiska przez aparaty szparkowe roślin (Tao i in., 2022). Niemniej jednak gatunki drzew, które utrzymują otwarte aparaty szparkowe dłużej, pochłaniają zanieczyszczenia bardziej efektywnie niż gatunki izohydrotyczne, które zamykają aparaty szparkowe wcześniej z powodu zmniejszającej się dostępności wody (Dizengremel i in., 2009).

Pomimo faktu, że właściwości powierzchni drzew powodują zatrzymywanie cząstek zanieczyszczeń (Beckett i in., 1998), należy podkreślić, że funkcja ta różni się w odniesieniu do zdolności pochłaniania pyłu z powietrza przez różne gatunki drzew (Beckett i in., 1998; Litschke i Kuttler, 2008).

Zatrzymywanie pyłu i jego skuteczność zależy od takich warunków, jak mikromorfologia liści (wosk, trichomy, szorstkość), gęstość liści i rodzaj korony (Beckett i in., 2000; Burkhardt, 2010; Freer-Smith i in., 2005; Kardel i in., 2011; Prusty i in., 2005; Rai i in., 2009; Räsänen i in., 2013; Sæbø i in., 2012; Sgrigna i in., 2015). Badania pokazują, że drzewa iglaste są bardziej skuteczne w absorpcji PM10 niż drzewa liściaste (Beckett i in., 1998).

Ponadto gatunki liściaste można podzielić na te o liściach szorstkich i gładkich - gatunki drzew o liściach szorstkich są bardziej wydajne w pochłanianiu PM2,5 (K. Paul Beckett i in., 2000; Hwang i in., 2011). Dlatego też - ze względu na fakt, że sadzenie drzew jest uważane za metodę łagodzenia zanieczyszczenia powietrza w miastach - należy stosować najbardziej wydajne gatunki, aby zmaksymalizować ich zdolność do pochłaniania pyłu (Chen i in., 2017). Absorpcja PM2,5 zależy nie tylko od drzew, ale także od obecności innych określonych gatunków w sąsiedztwie (Sæbø i in., 2012). Oprócz drzew, zmniejszenie objętości pyłu i filtrację cząstek na obszarach miejskich można również przypisać strefom zieleni w postaci pasów (zieleń naturalna lub nasadzona) (Wang, 2011).

Badania przeprowadzone przez Yin i innych (2011) przetestowały zdolność roślin do usuwania PM2.5 z powietrza w mieście. Według ich analiz, stężenie PM2.5 spadło o 9% na obszarach zalesionych sąsiadujących z obszarami miejskimi (Yin i in., 2011). Świadomości tak istotnej roli drzew prawdopodobnie brakuje jednak w wielu krajach - na pewno w Polsce, gdzie coraz powszechniejsze jest usuwanie zieleni z przestrzeni publicznych i zastępowanie jej betonem (Mencwel, 2020).

## 1.5. Narzędzia wykorzystywane do pomiaru zdolności drzew do usuwania zanieczyszczeń powietrza

Narzędzie wykorzystywane do pomiaru skuteczności lasów miejskich, takie jak Urban Forest Effects (UFORE), służy do pomiaru danych w terenie wraz z cechami obszaru, takimi jak pokrycie terenu, woda, krzewy, pokrywa roślinna, trawa, gleba, liczba budynków, ilość betonu i nieprzepuszczalnych materiałów (Bass, 2001). Narzędzie to zostało opracowane, aby pomóc badaczom i organom zarządzającym w ocenie funkcjonalności lasów miejskich i ich struktury w oparciu o dane terenowe, ustalenia meteorologiczne i zanieczyszczenia stwierdzone na miejscu (Nowak & Crane, 2000). Model UFORE umożliwia obliczanie określonych parametrów na podstawie pomiarów stanu zdrowotnego drzew (ubytki w koronach, uszkodzenia drzew) oraz biomasy liści, powierzchni liści i pokrycia terenu. Parametry generowane w modelu UFORE to: całkowity zmagazynowany węgiel i węgiel netto sekwestrowany w drzewach miejskich, wpływ drzew na zużycie energii w budynkach i emisję dwutlenku węgla, szacowany ranking wpływu gatunków na poprawę jakości powietrza, usuwanie zanieczyszczeń przez drzewa miejskie i związana z tym poprawa jakości powietrza (ozon, dwutlenek siarki, dwutlenek azotu, tlenek węgla, pył zawieszony PM10) (Nowak & Crane, 2000).

Dodatkowo model zawiera również komponent służący do obliczania ilości zanieczyszczeń usuwanych przez rośliny (Hirabayashi i in., 2012). Narzędzie i-Tree Eco zostało opracowane na podstawie modelu przygotowanego przez Nowak i Crane (2000). I-Tree Eco to oprogramowanie opracowane przez Służbę Leśną Stanów Zjednoczonych (USFS) i jest dostępne jako narzędzie otwartego oprogramowania (*open source)*. Analizuje ono strukturę drzew miejskich pod kątem ich przynależności gatunkowej i stanu zdrowotnego w celu oszacowania wartości usług ekosystemowych świadczonych przez drzewa (Nowak & Crane, 2000). Analizy przeprowadzone przy użyciu tego narzędzia pokazują, że na poziomie grupy drzew czynnikami przyczyniającymi się do usuwania zanieczyszczeń są gęstość nasadzeń, całkowita powierzchnia liści, ich fenologia i rozmieszczenie przestrzenne (Brantley i in., 2014; Hagler i in., 2012; Nowak, Greenfield i in., 2013). Na poziomie pojedynczych drzew najważniejszymi cechami są charakterystyka liści i wzór wzrostu, które określają możliwości usuwania PM2,5 przez dany gatunek. Największe korzyści środowiskowe i krajobrazowe uzyskano, gdy gęstość korony i wskaźnik powierzchni liści (LAI) wynosiły odpowiednio około 50-60% i 1,5-2,0.

Biorąc pod uwagę, że według Organizacji Narodów Zjednoczonych (ONZ) ponad połowa światowej populacji zamieszkuje obszary miejskie, istotną kwestią staje się zatem przeprowadzenie badania rzeczywistych pomiarów zanieczyszczenia powietrza w aglomeracjach miejskich, a przede wszystkim porównanie jego stężeń na obszarach pokrytych roślinnością i tych, gdzie jest jej znacznie mniej. Badanie to jest o tyle uzasadnione, że z jego pomocą możliwe będzie nakreślenie skali rzeczywistego problemu i określenie stopnia zagrożenia dla zdrowia ludzi związanego z obecnością rzeczywistego zanieczyszczenia powietrza.

Laboratoryjne metody szacowania akumulowanych zanieczyszczeń koncentrują się na strukturze i morfologii powierzchni liści (np. trichomów, warstwy wosku, gęstości aparatów szparkowych). Metody te są stosowane do oceny adsorpcji zanieczyszczeń w mniejszej skali czasowej i przestrzennej; analizy grawimetryczne i chemiczne pozwalają określić masę i zawartość pierwiastków w osadzanych materiałach, podczas gdy techniki mikroskopowe i spektroskopowe (np. spektroskopia w podczerwieni z transformacją Fouriera za pomocą mikroskopu skaningowego elektronowego i spektroskopia rentgenowska z dyspersją energii) umożliwiają szczegółową wizualizację i identyfikację cząstek powierzchniowych oraz rozkładu zanieczyszczeń. Wymienione metody są skomplikowane i wymagają wysokich umiejętności analitycznych, dlatego nie są wystarczająco często wykorzystywane do zarządzania drzewami miejskimi. Brakuje analiz ułatwiających ich wdrożenie w realizacji procesu decyzyjnego włodarzy.

## 1.6. Działania polityczne mające na celu poprawę jakości powietrza

Niektóre miasta w Polsce wdrożyły inicjatywy sadzenia drzew, takie jak program Platanus w Szczecinie (Association of the Szczecin Metropolitan Area, 2019), mający na celu sadzenie drzew oczyszczających powietrze lub aplikacja "Milion drzew" używana w Warszawie, która umożliwia mieszkańcom miasta zgłaszanie miejsc, w których brakuje drzew (Zarząd Zieleni Warszawy, 2019). Podobne programy, takie jak inicjatywy ponownego zalesiania i kampanie ochrony lasów miejskich, zostały również wdrożone w innych miastach na całym świecie (Green Forest Fund Forest Donation, 2019; Lawton, 2021; Ripple Africa Inspiring Commuties, 2021). Celem tego typu działań jest zwiększenie odsetka zadrzewienia, jak w przypadku kampanii "Milion drzew" w Nowym Jorku (Rae, 2010) lub inicjatywy Melbourne mającej na celu osiągnięcie poziomu 40% zadrzewienia.

W badaniu Baldera z zespołem. (1997) za optymalną gęstość drzew uznano 100 drzew na kilometr drogi; w rzeczywistości sadzenie drzew w miastach jest promowane jako rozwiązanie miejskie (Han, 2021), które zmniejsza degradację środowiska spowodowaną rozwojem miast. Celem tych działań jest zwiększenie zrównoważonego rozwoju obszarów miejskich, złagodzenie i dostosowanie się do zmian klimatycznych oraz poprawa zdrowia i samopoczucia ludzi (Roy, 2012; Andersson-Sköld, 2015).

Analizując wybrany temat badawczy zidentyfikowano lukę badawczą tj. brak wystarczających informacji do skutecznego zarządzania zielenią miejską w zakresie oczyszczania powietrza przez drzewa.

## 2. Cel badań i hipotezy badawcze

Niniejsza rozprawa doktorska ma na celu weryfikację następujących założeń badawczych:

1) Istnieje niska świadomość społeczna na temat funkcji drzew w mieście i ich udziału w pochłanianiu zanieczyszczeń miejskich,
2) Pokrycie koronami drzew (TCC) ma istotny wpływ na pochłanianie zanieczyszczeń w miastach,
3) Lokalizacje o różnych wartościach pokrycia koronami drzew będą różnić się pod względem wysokich poziomów zanieczyszczenia, sklasyfikowanych jako poniżej 15 $\mu g/m^3$ oraz powyżej 15 $\mu g/m^3$, a skuteczność usuwania zanieczyszczeń związana jest ze średnicą drzew,
4) Wyniki uzyskane przy użyciu modelu i-Tree Eco mogą różnić się z wynikami uzyskanymi metodą laboratoryjną,
5) Wyniki uzyskane metodą i-Tree Eco mogą mieć ograniczoną możliwość wykazania różnic w skuteczności fitofiltracji powietrza przez różne gatunki roślin ze względu na nieuwzględnianie lokalnych warunków siedliskowych i stężeń zanieczyszczeń.

Weryfikacja hipotezy badawczej została dokonana poprzez realizację trzech wymienionych poniżej zadań badawczych, na które składały się:

1) Analiza świadomości społecznej wraz z zestawieniem z analizą usług ekosystemowych świadczonych przez drzewa,

2) Analiza empiryczna zanieczyszczeń powietrza na wybranych alejach Warszawy wraz z zestawieniem z analizą pochłaniania zanieczyszczeń świadczonych przez drzewa na wybranych alejach,
3) Porównanie metod oceny fitofiltracji cząstek stałych.

## 3. Zarys rozprawy doktorskiej wraz z wykazem publikacji naukowych

Rozprawa doktorska została przygotowana w postaci zbioru trzech opublikowanych i powiązanych ze sobą tematycznie artykułów naukowych. Każda z publikacji rozwiązywała jedno spośród trzech wskazanych w rozdziale 2. zadań badawczych, realizując postawione cele badawcze. Poniżej przedstawiono trzy publikacje naukowe wchodzące w skład rozprawy doktorskiej:

1. **Kais, K.**; Gołaś, M.; Suchocka, M. Awareness of Air Pollution and Ecosystem Services Provided by Trees: The Case Study of Warsaw City. Sustainability 2021, 13, 10611. (IF = 3,889) https://doi.org/10.3390/su131910611
2. **Kais, K.**; Gołaś, M.; Suchocka, M.; Ziemiański, M.; Kalaji, H. M. The Role of Urban Trees in PM2.5 Mitigation: Air Quality Assessment and Absorption Capacity Comparison in Warsaw Alleys. JSPAE 2025, 4, 75–94 (SCOPUS: 2024 SJR = 0,525) https://doi.org/10.56946/jspae.v4i2.730
3. **Kais, K.**; Suchocka, M.; Balcerzak, O.; Przybysz, A. Street Trees as Sustainable Urban Air Purifiers: A Methodological Approach to Assessing Particulate Matter Phytofiltration. Sustainability 2025, 17, 7451. (IF = 3.3) https://doi.org/10.3390/su17167451

Koncepcja rozprawy doktorskiej polegała na zastosowaniu skonsolidowanego podejścia obejmującego analizę świadomości społecznej, analizę zanieczyszczeń znajdujących się na wybranych alejach warszawskich i porównanie ich z możliwościami pochłaniania zanieczyszczeń przez wybrane drzewa, a także porównanie metod, które służą do oceny wartości świadczonych usług ekosystemowych - pochłaniania zanieczyszczeń przez drzewa. Podejście to obejmowało w pierwszym kroku wyznaczenie lokalizacji odcinków alei o podobnym natężeniu ruchu samochodów oraz strukturze ulicy, opracowanie ankiet świadomości społecznej, a następnie analizę ich wyników. W przeprowadzonej ankiecie świadomości społecznej zadano pytania dotyczące usług zaopatrujących, kulturowych oraz regulacyjnych. Na podstawie uzyskanych wyników ankiet uzyskano informacje, że świadomość mieszkańców na temat zdolności drzew do pochłaniania pyłów była raczej niska, co wskazało kierunek dalszych badań. Tematem szczegółowych analiz były zaś regulacyjne usługi ekosystemowe, wśród których wybrano usługi oczyszczania powietrza. W związku z powyższym w kolejnym etapie wykonano inwentaryzację dendrologiczną wraz z analizą pochłaniania zanieczyszczeń na zinwentaryzowanych odcinkach metodą i-Tree Eco na podstawie analizy parametrów wielkościowych i gatunkowych drzewostanu oraz przeprowadzono analizę empiryczną zanieczyszczeń powietrza. W ostatnim etapie porównano wyniki badań laboratoryjnych pochłaniania pyłów zawieszonych wraz z analizą poziomu zanieczyszczeń absorbowanych przez drzewa za pomocą i-Tree Eco. Artykuł nr 1 prezentuje wyniki badań podstawowych obejmujących dokumentację stanu świadomości społecznej w zakresie usług ekosystemowych świadczonych przez drzewa, a artykuły nr 2 i nr 3 prezentują wyniki badań stosowanych.


Rysunek 1. Struktura rozprawy doktorskiej (D1 – artykuł 1, D2 – artykuł 2, D3 – artykuł 3)

W każdym z artykułów byłam pierwszym i wiodącym autorem, a w skład moich zadań wchodziła: konceptualizacja, opracowanie metodyki, prace terenowe, pozyskanie danych, przeprowadzenie analiz, przygotowanie tekstu publikacji wraz z jego edycją i recenzją, a także przygotowanie materiałów graficznych wizualizujących wyniki badań. Ponadto w każdym artykule byłam autorką korespondencyjną.

# 4. Materiały i metodyka

## 4.1. Obszary badawcze

Badania przeprowadzone w ramach artykułów będących częścią rozprawy doktorskiej zostały wykonane na terenie Warszawy, w trzech wybranych lokalizacjach, które spełniały założenia badań w różnych skalach czasowych. Prace nad dokumentacją zanieczyszczeń powietrza prowadzono przy ulicy Marszałkowskiej oraz Żwirki i Wigury (Artykuł 1 i Artykuł 2), następnie w celu przeprowadzenia szerszej analizy dołączono obszar ulicy Puławskiej (Artykuł 3). Obszary te wybrano pod kątem pokrycia koronami drzew (TCC) z podziałem na niskie, średnie oraz optymalne pokrycie koronami drzew, pod kątem geometrii ulicy (proste, bez zakrzywień, zakrętów), pod kątem natężenia ruchu ulicznego, a także obszary badawcze musiały spełniać warunek alei, lecz nie kanionu ulicznego.

Alejami zgodnie z definicją (Słownik Języka Polskiego, 2025) były Żwirki i Wigury, zaś ulica Puławska i Marszałkowska stanowiły aleje z częściowo obumarłymi lub wyciętymi drzewami ze względu na niekorzystne warunki siedliskowe.


Rysunek 2. Aleje badane w ramach rozprawy doktorskiej.

## 4.2. Świadomość zanieczyszczenia powietrza i usług ekosystemowych świadczonych przez drzewa

Badania przeprowadzone w ramach publikacji nr 1. stanowią ocenę świadomości społecznej na temat zanieczyszczenia powietrza i powiązania ich wraz ze znaczeniem drzew w procesie oczyszczania powietrza. Podstawowym celem badań było porównanie opinii mieszkańców dotyczących świadczonych przez drzewa usług ekosystemowych zgodnie z pytaniami przedstawionymi w ankiecie wraz z obiektywną oceną potencjalnej zdolności do pochłaniania zanieczyszczeń przez drzewa. Na podstawie przeprowadzonych badań stwierdzono, że przy zadrzewieniu uznanym za optymalne tj. powyżej 30% pokrycia koronami drzew na analizowanych alejach świadomość respondentów na temat oczyszczania powietrza była większa niż w przypadku oceny alei z mniejszym pokryciem koronami drzew. Ocena świadomości mieszkańców w zakresie usług ekosystemowych przeprowadzana była na podstawie ankiety przygotowanej przez Autorki publikacji. Analizy obejmowały przedstawienie ilościowe wyników badań społecznych i zestawienie ich z danymi na temat pochłaniania zanieczyszczeń na analizowanych alejach. Na podstawie zebranych danych terenowych dokonano digitalizacji danych dotyczących lokalizacji oraz parametrów drzew w oprogramowaniu QGIS 3.21, która umożliwiała wykonanie dokładnej analizy porównawczej obejmującej dwie badane lokalizacje wraz z zestawieniem ich z wynikami poszczególnych pytań ankietowych.

## 4.3. Ocena jakości powietrza i porównanie zdolności absorpcyjnych w warszawskich alejach

Badania przeprowadzone w ramach publikacji nr 2 obejmują terenową walidację poziomów narażenia mieszkańców na $PM_{2.5}$. Oceny wartości stężeń dokonano na podstawie przeprowadzonych badań terenowych wraz z użyciem czujników Temtop M2000 (wielofunkcyjny detektor jakości powietrza drugiej generacji z kolorowym ekranem TFT - EN60825-1W/A11US21CFR1040.10) - wszechstronnego miernika jakości służącego do pomiaru $PM_{2.5}$, $PM_{10}$, $CO_2$, HCHO, temperatury i wilgotności. Stężenia $PM_{2.5}$ monitorowano na wysokości 1m nad poziomem gruntu, którą uznano za przybliżoną strefę oddychania. Miernik wyposażony jest w czujniki laserowe, co zapewnia pomiary z dokładnością 0,1 μg/m3 dla pyłu PM2,5, w zakresie pomiarowym 0-999 μg/m3 z zakresem pomiarowym 0,1–10 000 μg/m3, rozdzielczością i czułością 1 μg/m3, przepływem powietrza 1 l/min i skalibrowany z wykorzystaniem pyłu drogowego z Arizony jako punktu odniesienia. Materiał referencyjny dotyczący pyłu (instrukcja obsługi Temtop M2000, 2022). Po włączeniu detektor był kalibrowany przez około 10 minut, a następnie umieszczany na zewnątrz na kolejne 10 minut w celu przewietrzenia. Każdy pomiar trwał minutę, podczas której obliczano i wyświetlano średnie stężenie PM2,5. W każdej lokalizacji monitorowanie trwało co najmniej 10 minut, a dane były rejestrowane co minutę, aby zapewnić dokładną wartość średnią. W razie potrzeby czas monitorowania był przedłużany do momentu ustabilizowania się odczytów. Aby zminimalizować wpływ zmieniających się warunków środowiskowych, całkowity czas monitorowania w każdej lokalizacji (ulicy) był ograniczony do 2 godzin. Ponadto protokół monitorowania wymagał wykonywania pomiarów w krótkich odstępach czasu podczas ruchu. Poziomy stężenia zanieczyszczeń powietrza były rejestrowane co minutę w okresie monitorowania, trwającym od 24 września 2021 r. do 8 października 2021 r., w dwóch odrębnych przedziałach czasowych: w godzinach szczytu oraz poza godzinami szczytu. Taki harmonogram zapewnił, że ocena uwzględniła warunki najbardziej istotne dla użytkowników, a także wpływ ekologiczny i zdrowotny miejskich terenów zielonych w ich najbardziej aktywnej fazie. Pomiary przeprowadzono we wrześniu i październiku, kiedy drzewa zazwyczaj zachowują pełne liście, co umożliwiło wiarygodną ocenę skuteczności usuwania $PM_{2,5}$. Ten czas pomiarów ułatwia również wykrycie różnic w żywotności między strefami o kontrastującym TCC, ponieważ wysokie pokrycie koronami drzew pomaga utrzymać aktywność fizjologiczną, podczas gdy obszary o niskim TCC mogą wykazywać wczesne objawy stresu, zmniejszające wydajność oczyszczania. Każdy czujnik był umieszczony w miejscach testowych na 60 minut w każdym okresie. Godziny szczytu zostały określone jako przedział czasowy między 16:00 a 18:00 od poniedziałku do piątku, natomiast okresy poza godzinami szczytu obejmowały pozostały czas, z wyjątkiem godzin między 8:00 a 10:00. Ponadto przeprowadzono dokładną analizę drzew w obszarze badań, co obejmowało dokumentowanie gatunków drzew i ich lokalizacji, a także pomiary dendrometryczne w tym średnicę pnia, całkowitą wysokość drzewa, wysokość drzewa żywego, podstawę korony, szerokość korony w kierunku północ-południe oraz wschód-zachód, procent utraty korony, stan zdrowia korony i nasłonecznienie korony. Pomiary drzewa uzyskano za pomocą miary oraz miernika laserowego Bosch GLM120. Dodatkowo do modelu włączono dane pogodowe i dane dotyczące jakości powietrza z bazy danych i-

Tree, w tym poziomy stężenia $PM_{2,5}$mierzone przez czujniki umieszczone w Warszawie. Model i-TreeEco wersja 6.0 stanowił wytyczne dla gromadzenia danych terenowych zgodnie z określonymi protokołami, opisanymi w instrukcji obsługi i-TreeEco (i-TreeEco User's Manual, 2019) zgodnie z zaleceniami oprogramowania. Baza danych i-Tree ułatwiła dostęp do danych meteorologicznych i informacji o jakości powietrza. Następnie, po wprowadzeniu wszystkich wymaganych danych, model został uruchomiony w celu wygenerowania szacunków dotyczących skuteczności drzew w usuwaniu zanieczyszczeń wzdłuż ulicy Marszałkowskiej oraz ulic Żwirki i Wigury. Ponadto, aby ustalić statystyczną istotność różnic w pomiarach jakości powietrza między odcinkami porośniętymi drzewami a odcinkami o niskim pokryciu drzewami, przeprowadzono analizę różnic w stężeniu PM2,5 przy użyciu oprogramowania R. Pomiary pokrycia koronami drzew zostały wykonane przy użyciu oprogramowania GIS i skorelowane z pomiarami terenowymi.

## 4.4. Metodologiczne podejście do oceny fitofiltracji cząstek stałych

Badanie przeprowadzone w ramach publikacji nr 3 stanowi analizę metod wykorzystywanych do oceny fitofiltracji cząstek stałych. Badanie składało się z dwóch odrębnych etapów. Pierwszy etap obejmował szczegółową inwentaryzację drzew o tożsamych dla Artykułu nr 2 parametrach, jednak badania wykonano na trzech odcinkach – ulicy Żwirki i Wigury, Marszałkowskiej oraz Puławskiej.

Drugi etap obejmował badania laboratoryjne, które oceniały zdolność absorpcji pyłów zawieszonych przez liście drzew, z wykorzystaniem tych samych próbek, które pobrano wcześniej z analizowanych lokalizacji. Pobrane wyniki służyły do porównania danych uzyskanych metodą i-Tree Eco i analizy ich podobieństwa. Zgodnie z pomiarami przeprowadzonymi przez Urząd Miasta Stołecznego Warszawy wybrane obszary charakteryzują się podobnym natężeniem ruchu i mają porównywalną geometrię tj. są to odcinki proste bez zakrętów i łuków. Ponadto wszystkie aleje biegną z północy na południe, a na tej podstawie założono, że warunki związane z ruchem powietrza są podobne we wszystkich lokalizacjach. Wykonano ocenę nierozpuszczalnych w wodzie pyłów zawieszonych. Zebrano materiał roślinny z lokalizacji analizowanych przez i-Tree Eco w lipcu 2023 roku. Zbiór poprzedzono sześcioma dniami bez opadów i silnych wiatrów oraz w czasie okresu z wysokim stężeniem pyłów zawieszonych, co zapewniło wystarczającą liczbę zanieczyszczeń zdeponowanych na liściach do analizy. Pobrano próbki liści o powierzchni 500 $cm^2$ wraz z ogonkami liściowymi z całego obwodu rośliny i gałęzi 1,5 do 2,0 m nad ziemią. Dla każdego gatunku i lokalizacji zebrano materiał z czterech pojedynczych drzew, gdzie każde drzewo stanowiło replikę biologiczną. Kolejnym krokiem było płukanie przez 60 sekund w 200 ml wody destylowanej (woda PM zmywalna z powierzchni liści), a następnie przez 45 sekund w 100 ml chloroformu (PM zatrzymywany w wosku liściowym). Przeprowadzono sekwencyjne frakcjonowanie. Roztwory płuczące filtrowano przez poszczególne filtry papierowe zgodnie z przyjętą metodyką. Ponadto wykorzystano próbki ślepe zgodnie z procedurą do walidacji wyników. Powierzchnię liści próbek mierzono za pomocą systemu analizy obrazu wyposażonego w kamerę CCTV Vista Protos i z użyciem oprogramowania Skye-Leaf v2 - oba systemy wyprodukowane przez firmę Skye Instruments Ltd. Przeprowadzono również analizy statystyczne z wykorzystaniem oprogramowania statystycznego IBM SPSS v30.

# 5. Wyniki i dyskusja

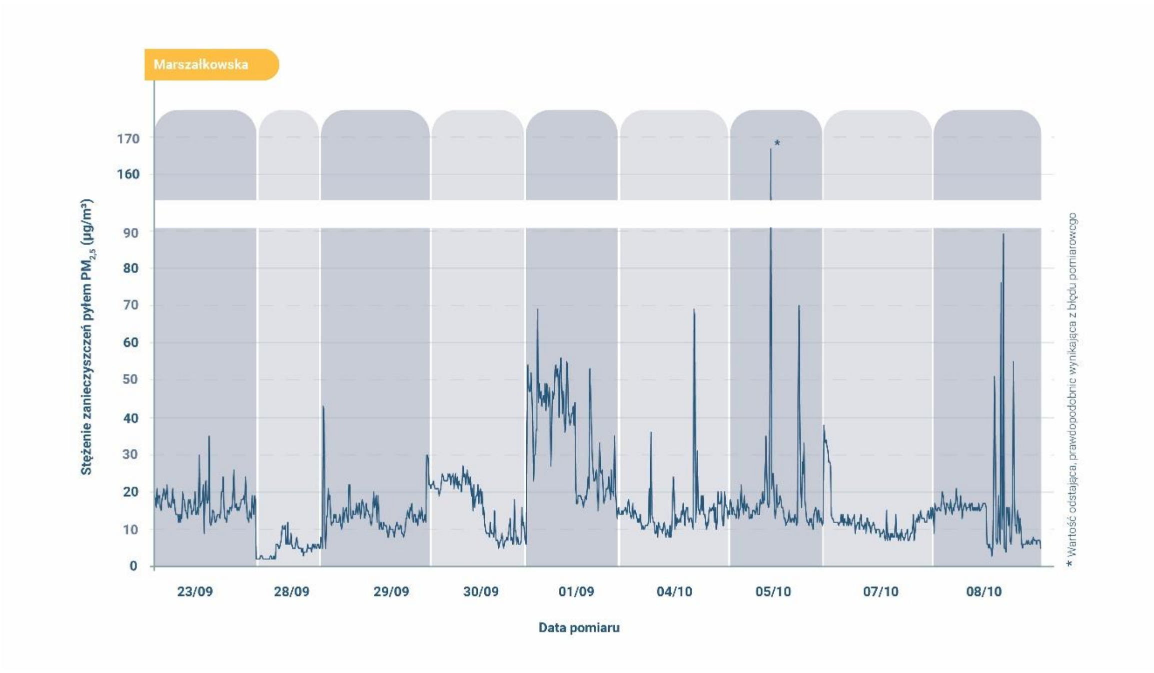
## 5.1. Świadomość zanieczyszczenia powietrza i usług ekosystemowych świadczonych przez drzewa

Badanie terenowe przeprowadzono wśród 271 respondentów - mieszkańców 18 dzielnic Warszawy. Grupę badawczą stanowiło 137 mężczyzn i 134 kobiety w wieku od 18 do 75 lat. Łącznie 7% respondentów pracowało lub posiadało wykształcenie wyższe w zakresie ochrony środowiska. Respondentom zadawano pytania dotyczące usług ekosystemowych wyróżniając usługi zaopatrujące np. odnawialne źródła energii, usługi regulacyjne np. regulacja klimatu, oczyszczanie powietrza, zapobieganie powodziom, usługi kulturowe np. obecność parków, terenów rekreacji, terenów zieleni, a także usługi podstawowe np. regulacja cykli hydrologicznych. Badanie wykazało, że prawie 75% respondentów jest zaniepokojonych zanieczyszczeniem powietrza w Warszawie, chociaż nie postrzegają go jako wysoce niepokojącego. Wśród osób, które wskazały brak obaw lub niski poziom obaw najliczniejszą grupę (ponad 81%) stanowił osoby w wieku od 18 do 25 lat. Mieszkańcy Warszawy wskazali również na złą jakość powietrza w mieście, choć średnio nie określili oni jakości powietrza w stolicy jako bardzo złej. Przeanalizowano również percepcję mieszkańców Warszawy dotyczącą wpływu na zanieczyszczenie powietrza takich działań jak: spalanie węgla brunatnego, plastiku, płyt wiórowych i innych nieodpowiednich materiałów w centralnym ogrzewaniu, spalanie odpadów w domowych piecach, eksploatację elektrociepłowni, emisję spalin z ruchu drogowego oraz emisję spalin generowaną przez zakłady produkcyjne (kominy). Od 30 do prawie 90% oceniło wpływ powyższych czynników jako szkodliwy dla jakości powietrza. Podjęto również próbę oceny działań, które przyczyniają się do redukcji zanieczyszczeń powietrza takich jak filtry kominowe, odnawialne źródła energii, pasy zieleni oddzielające tereny przemysłowe, obecność parków i lasów miejskich, terenów zieleni i zieleni przyulicznej, popularyzacji korzystania z transportu zbiorowego oraz ekologicznych środków transportu. Respondenci ocenili pozytywnie popularyzację indywidualnych, ekologicznych środków transportu oraz obecność parków i lasów miejskich. W przeprowadzonym badaniu oceniano również świadomość wpływu zanieczyszczenia powietrza na zdrowie. Na podstawie przeprowadzonej ankiety można stwierdzić, że respondenci nie widzą żadnej zależności pomiędzy obecnością zanieczyszczenia powietrza a zdrowiem - 75,28% uszeregowało ją na poziomie 2 lub niższym. Ocenie podlegał również aspekt oceny zdolności drzew do pochłaniania zanieczyszczeń powietrza $PM_{10}$ i $PM_{2,5}$. Ponad połowa ankietowanych (57,2%) oceniła zdolność drzew do pochłaniania zanieczyszczeń jako bardzo niską lub zerową. Wśród respondentów, którzy wskazali brak tej zdolności, najliczniejszą grupę stanowili ludzie w wieku 18-25 lat. W związku z niską świadomością dotyczącą zdolności drzew do pochłaniania zanieczyszczeń do dalszych badań wytypowano tę usługę ekosystemową.

## 5.2. Ocena jakości powietrza i porównanie zdolności absorpcyjnych w warszawskich alejach

Przeprowadzone badania dostarczyły danych dotyczących poziomów stężenia zanieczyszczeń na odcinkach alei zlokalizowanych przy ul. Marszałkowskiej oraz Żwirki i Wigury. Przegląd wyników stężeń PM przedstawiono na Rysunkach X i Y.


Rysunek 3. Przegląd stężeń zanieczyszczeń odnotowanych przy ul. Żwirki i Wigury.




Rysunek 4. Przegląd zanieczyszczeń odnotowanych przy ul. Marszałkowskiej.

Monitorowanie odbywało się jednocześnie w dwóch lokalizacjach, a w tabeli nr 2 i nr 3 przedstawiono całkowite przekroczenia poziomów $PM_{2,5}$ z podziałem na czas godzin szczytu i poza godzinami szczytu. Przekroczenia limitów $PM_{2,5}$ o wartościach wyższych niż 15 μg/m3 odnotowano 1,5 razy częściej na ulicy o niskim pokryciu koronami drzew. Ponadto przekroczenia limitów $PM_{2,5}$ o wartościach wyższych niż 15 μg/m3 występowały 3,5 razy częściej w tym samym obszarze, a przekroczenia limitów o wartościach wyższych niż 25 μg/m3 występowały 14 razy częściej. Wyniki przedstawiono w Tabeli 1. oraz Tabeli 2.

| | Czas trwania zarejestrowanych poziomów zanieczyszczenia poniżej 15 μg/$m^3$ [w minutach] | | | Czas trwania zarejestrowanych poziomów zanieczyszczenia powyżej 15 μg/$m^3$ [w minutach] | | |
|---|---|---|---|---|---|---|
| Data | Poza godzinami szczytu | W godzinach szczytu | Łącznie | Poza godzinami szczytu | W godzinach szczytu | Łącznie |
| 24.09.2021 | 14 | 22 | 36 | 40 | 32 | 72 |
| 27.09.2021 | 35 | 83 | 118 | 17 | 2 | 19 |
| 28.09.2021 | 0 | 52 | 52 | 60 | 5 | 65 |
| 29.09.2021 | 0 | 49 | 49 | 60 | 10 | 70 |
| 30.09.2021 | 48 | 5 | 53 | 8 | 50 | 58 |
| 01.10.2021 | 16 | 32 | 48 | 34 | 20 | 54 |
| 04.10.2021 | 63 | 33 | 96 | 9 | 20 | 29 |
| 05.10.2021 | 3 | 56 | 59 | 43 | 2 | 45 |
| 06.10.2021 | 3 | 52 | 55 | 44 | 12 | 66 |
| Średnia (z odchyleniem standardowym) | 20,22±23,15 | 42,67±22,56 | 62,89±26,37 | 35,00±19,84 | 17,00±15,81 | 53,11±18,66 |

Tabela 1. Przegląd zarejestrowanych zanieczyszczeń przy ul. Marszałkowskiej.

| | Czas trwania zarejestrowanych poziomów zanieczyszczenia poniżej 15 µg/m$^3$ [w minutach] | | | Czas trwania zarejestrowanych poziomów zanieczyszczenia powyżej 15 µg/m$^3$ [w minutach] | | |
|---|---|---|---|---|---|---|
| Data | Poza godzinami szczytu | W godzinach szczytu | Łącznie | Poza godzinami szczytu | W godzinach szczytu | Łącznie |
| 24.09.2021 | 66 | 64 | 126 | 2 | 0 | 2 |
| 27.09.2021 | 63 | 61 | 124 | 0 | 0 | 0 |
| 28.09.2021 | 66 | 65 | 131 | 0 | 0 | 0 |
| 29.09.2021 | 62 | 62 | 124 | 0 | 1 | 1 |
| 30.09.2021 | 0 | 0 | 0 | 65 | 63 | 128 |
| 01.10.2021 | 0 | 58 | 58 | 66 | 8 | 74 |
| 04.10.2021 | 65 | 65 | 130 | 0 | 0 | 0 |
| 05.10.2021 | 60 | 66 | 126 | 8 | 0 | 8 |
| 06.10.2021 | 66 | 65 | 131 | 0 | 0 | 0 |
| Średnia (z odchyleniem standardowym) | 49,78±28,30 | 56,22±21,24 | 105,56±45,84 | 15,67±28,37 | 8,00±20,79 | 23,67±45,95 |

Tabela 2. Przegląd zarejestrowanych zanieczyszczeń przy ul. Żwirki i Wigury.

Przy uwzględnieniu warunków takich jak podobny poziom natężenia ruchu oraz identyczne gatunki drzew w obu lokalizacjach, można wywnioskować, że główną przyczyną różnicy w poziomach stężenia zanieczyszczeń jest gorszy stan drzew przy ulicy Marszałkowskiej. Gorszy stan drzew przy ulicy Marszałkowskiej może być spowodowany trudnymi warunkami siedliskowymi - drzewa rosną tam w wyznaczonych miejscach wyciętych w chodniku (1,9 x 1,9 m), co powoduje niedostateczny dostęp do wody i niewystarczającą przestrzeń dla rozwoju systemu korzeniowego. Trudne warunki siedliskowe powodują również niskie pokrycie koronami drzew, które w tym obszarze wynosi 6%. Średnia szerokość korony w kierunku północ - południe przy ul. Żwirki i Wigury wynosi 7,71 m, zaś przy ulicy Marszałkowskiej 3,42 m. W przypadku szerokości korony wschód-zachód uzyskano wyniki 7,78 m przy ulicy Żwirki i Wigury oraz 3,18 m przy ul. Marszałkowskiej.

Przeprowadzono również analizy statystyczne na podstawie zebranych danych terenowych. Test rozkładu Shapiro-Wilka, który obejmował poziomy stężenia $PM_{2,5}$ na drogach o niskim i wysokim poziomie wykazał znacząco odbiegające od normy wzorce rozkładu ($p < 0,05$). Przeprowadzono również test Manna-Whitneya w celu oceny sumy rang. Test wykazał istotną różnicę ($W = 341450$, $p < 0,05$) między poziomami stężenia na ulicy pokrytej drzewami, a ulicą o niskim pokryciu drzewami. Mediana poziomów stężenia $PM_{2,5}$ wynosiła 14 µg/m3 w segmencie ulicy o niskim pokryciu drzewami i 10 µg/m3 w alei pokrytej drzewami. Dodatkowo przeprowadzono test tabeli ANOVA. Tabela ANOVA sprawdza ogólną istotność modelu. Statystyka F wynosząca 120,103 przy wartości p mniejszej niż 0,001 wskazuje, że model jest statystycznie istotny, co oznacza, że co najmniej jeden z predyktorów ma znaczący wpływ na poziomy wartości usuwania $PM_{2,5}$. Wzrost średnicy o jedną jednostkę wiąże się ze wzrostem wartości usuwania $PM_{2,5}$ o 0,244, przy stałych pozostałych zmiennych. Dla całkowitej wysokość drzewa współczynnik wynosi 1,142 ($p < 0,001$), co wskazuje na silny pozytywny wpływ na wartość usuwania $PM_{2,5}$. Wzrost wysokości drzewa o jedną jednostkę powoduje wzrost wartości usuwania $PM_{2,5}$ o 1,142. Dla wartości procent braków w koronie w: Współczynnik wynosi -0,148 ($p < 0,001$), co oznacza, że wyższy procent braków w pokryciu korony zmniejsza wartość usuwania $PM_{2,5}$. Każdy 1% wzrost procentu braków w koronie powoduje spadek wartości usuwania $PM_{2,5}$ o 0,148. Wszystkie zmienne prognostyczne są statystycznie istotne na poziomie 0,001, co potwierdza ich silny wpływ na model. Powyższe wyniki przedstawiono w Tabeli 3.

| Model | | Suma kwadratów | df | Średnia kwadratów | F | Odchylenie standardowe |
|---|---|---|---|---|---|---|
| 1 | Regresja | 3956,983 | 3 | 1318,994 | 120,103 | <,001b |
| | Reszta statystyczna | 1691,262 | 154 | 10,982 | | |
| | Łącznie | 5648,244 | 157 | | | |
| a. Zmienna zależna: $PM_{2.5}$ | | | | | | |
| b. Predyktory: (stałe), ubytek korony, wysokość drzewa, średnica | | | | | | |

Tabela 3. Wyniki testu ANOVA dla modelu regresji przewidującego stężenia PM2,5 przy użyciu procentowego ubytku korony, wysokości drzewa oraz średnicy pnia jako predyktorów.

## 5.3. Metodologiczne podejście do oceny fitofiltracji cząstek stałych

Najwyższe wartości całkowitego pochłaniania $PM_{10}$ odnotowano w sierpniu z podziałem na ulice: Żwirki i Wigury - 2,264 kg, Puławską - 1,474 kg oraz Marszałkowską - 1,097 kg. Najwyższe wartości pochłaniania pyłu $PM_{2.5}$ odnotowano we wrześniu na ulicy Puławskiej - 0,288 kg, a w październiku na ulicach Żwirki i Wigury - 0,399 kg i Marszałkowskiej - 0,128 kg.

Dominującym gatunkiem na analizowanych alejach była lipa drobnolistna (*Tilia cordata*). Poniżej przedstawiono wartości usuwania zanieczyszczeń $PM_{10}$ i $PM_{2,5}$ z podziałem na inwentaryzowane aleje oraz porównanie usuwania $PM_{10}$ i $PM_{2,5}$ według gatunków drzew przy zastosowaniu metody laboratoryjnej oraz i-Tree Eco. W lokalizacji przy ul. Puławskiej najbardziej efektywnym gatunkiem jest *Fraxinus sp.*, który jest gatunkiem dominującym na tym obszarze i odpowiada za pochłanianie 81,3% zarówno $PM_{10}$ jak i $PM_{2,5}$. Gatunkiem pochłaniającym najmniej PM w tej lokalizacji jest *Robinia sp.*. Pochłania ona zaledwie 0,001% obu rodzajów PM. W przypadku lokalizacji przy ul. Żwirki i Wigury drzewa gatunku *Tilia cordata* odpowiadają za 100% pochłaniania obu rodzajów pyłów zawieszonych.

Przeprowadzono również porównanie poszczególnych ulic i gatunków, aby zidentyfikować najbardziej efektywną lokalizację, a także obliczono średnią pojemność absorpcyjną pojedynczego drzewa.

Analiza metodą i-Tree Eco wykazała, że najbardziej efektywne są drzewa przy ul. Puławskiej ze średnią 119,0 g $PM_{10}$ na drzewo oraz z całkowitym poborem 9280,9 g $PM_{10}$ na ulicę, a także odpowiednio 11,7 g $PM_{2,5}$ na drzewo oraz z całkowitym poborem 914,3 $PM_{2,5}$ na ulicę. Kolejną lokalizacją pod względem efektywności jest Żwirki i Wigury ze średnią 63,3 g $PM_{10}$ na drzewo oraz z całkowitym poborem 10 071,5 g $PM_{10}$ na ulicę, a także odpowiednio 9,7 g $PM_{2,5}$ drzewo oraz z całkowitym poborem 1540,9 $PM_{2,5}$ na ulicę. Najmniej efektywną lokalizacją pod kątem absorpcji pyłów jest ul. Marszałkowska, gdzie średnia dla jednego drzewa wynosi 11,0 g $PM_{10}$ przy całkowitej absorpcji 1097,7 g $PM_{10}$ na ulicę oraz dla $PM_{2,5}$ są to wartości 1,28 g na drzewo przy całkowitej absorpcji 128,20 g $PM_{2.5}$/ulicę.

Przedstawiono również analizę zdolności każdego gatunku do pochłaniania zanieczyszczeń. Analiza znajduje się na Rysunku 5 wraz z podziałem na metody.

| | metoda empiryczna - g/drzewo (osobnik) | | iTree Eco - g/drzewo (osobnik) | | metoda empiryczna (%) | | iTree Eco (%) | | metoda empiryczna g/drzewa (suma dla gatunku) | | iTree Eco g/drzewa (suma dla gatunku) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $PM_{10}$ | $PM_{2,5}$ | $PM_{10}$ | $PM_{2,5}$ | $PM_{10}$ | $PM_{2,5}$ | $PM_{10}$ | $PM_{2,5}$ | $PM_{10}$ | $PM_{2,5}$ | $PM_{10}$ | $PM_{2,5}$ |
| Tilia cordata | 15,1 (±1,82) | 2,54 (±0,30) | 11,08 | 1,29 | 100 | 100 | 100 | 100 | 1 494,9 | 251,4 | 1 096,9 | 127,7 |
| Fraxinus | 548,2 (±54,5) | 246,7 (±24,7) | 127,90 | 12,60 | 82,6 | 87,9 | 81,3 | 81,3 | 32 343,8 | 14 555,3 | 7 546,1 | 743,4 |
| Aesculus hippocastanum | 550,5 (±65,1) | 120,6 (±11,5) | 116,56 | 11,49 | 12,2 | 6,34 | 11,0 | 11,3 | 4 954,5 | 1 085,4 | 1 049,0 | 103,4 |
| Quercus robur | 292,9 (±31,0) | 122,5 (±22,1) | 134,8 | 13,3 | 1,44 | 1,43 | 3,0 | 2,9 | 585,8 | 245,0 | 269,6 | 26,6 |
| Tilia cordata | 60,9 (±5,32) | 24,0 (±2,10) | 19,65 | 1,95 | 0,30 | 0,28 | 1,0 | 0,4 | 121,8 | 48,0 | 39,3 | 3,9 |
| Populus alba | 432,7 (±37,4) | 148,2 (±7,77) | 147,70 | 14,60 | 1,07 | 0,87 | 2,7 | 2,8 | 865,4 | 296,4 | 295,4 | 29,2 |
| Acer platanoides | 264,1 (±22,2) | 176,1 (±14,8) | 96,60 | 9,50 | 0,65 | 1,03 | 0,01 | 0,01 | 528,2 | 352,2 | 193,2 | 19,0 |
| Acer negundo | 625,1 (±74,4) | 341,0 (±40,6) | 125,10 | 12,30 | 1,54 | 1,99 | 1,0 | 1,3 | 625,1 | 341,0 | 125,1 | 12,3 |
| Robinia | 41,6 (±8,60) | 20,8 (±3,64) | 7,90 | 0,80 | 0,10 | 0,12 | 0,001 | 0,001 | 41,6 | 20,8 | 7,9 | 0,8 |
| Tilia cordata | 120,5 (±7,61) | 30,4 (±1,92) | 53,86 | 8,24 | 100 | 100 | 100 | 100 | 19 159,5 | 4 833,6 | 8 563,7 | 1 310,2 |

Marszałkowska Puławska Żwirki i Wigury

Rysunek 5. Porównanie zdolności pochłaniania zanieczyszczeń przez poszczególne gatunki drzew.

Przeprowadzono również test Kruskala-Wallisa, który wykazał istotne różnice w wychwytywaniu $PM_{10}$ przez *Tilia cordata* w porównaniu z *Aesculus hippocastanum* oraz *Tilia cordata* w porównaniu z *Fraxinus excelsior,* a także istotne różnice w wychwytywaniu $PM_{2.5}$ przez *Tilia cordata* w porównaniu z *Fraxinus excelsior*.

Uzyskane wyniki w obu badaniach stanowiły podstawę analizy porównawczej obu metod. Porównując średnią roczną akumulację $PM_{10}$ dla poszczególnych gatunków drzew z gatunku *Aesculus hippocastanum*, średni wynik dla metody laboratoryjnej wynosi 59,2 g/drzewo, a dla i-Tree Eco 116,6 g/drzewo; dla gatunku *Fraxinus* średni wynik pobrania $PM_{10}$ dla metody laboratoryjnej wynosi 58,9 g/drzewo, a dla i-Tree Eco 123,7 g/drzewo. Dla gatunku *Quercus robur* średnia akumulacja obliczona metodą laboratoryjną wynosi 21,1 g/drzewo, a dla i-Tree Eco 90,0 g/drzewo. Ostatnim gatunkiem, dla którego wykonano porównanie, jest *Tilia cordata* — wynik średniej rocznej akumulacji metodą laboratoryjną wynosi 12,0 g/drzewo, a dla metody i-Tree Eco jest równy 43,6 g/drzewo.

Podobne porównanie przeprowadzono dla wychwytu $PM_{2,5}$. Wyniki uzyskane w porównaniu $PM_{2,5}$ były znacznie bliższe sobie niż w przypadku $PM_{10}$. W związku z tym dla gatunku *Aesculus hippocastanum* otrzymano następujące wyniki — średnia roczna akumulacja $PM_{2,5}$ uzyskana metodą laboratoryjną wyniosła 13,0 g/drzewo, natomiast metodą i-Tree Eco wyniosła 11,5 g/drzewo. Dla gatunku *Fraxinus* otrzymano średnią roczną akumulację $PM_{2,5}$ wyniesioną metodą laboratoryjną 13,8 g/drzewo, a metodą i-Tree Eco wyniosła średnio 12,2 g/drzewo. Dla gatunku *Quercus robur* otrzymano następujące wyniki — pobór $PM_{2,5}$ metodą laboratoryjną wynosi 8,8 g/drzewo, a metodą i-Tree Eco 8,9 g/drzewo. Ostatnim analizowanym gatunkiem była lipa drobnolistna *(Tilia cordata)* – wynik uzyskany metodą laboratoryjną wyniósł 3,0 g/drzewo, a metodą i-Tree Eco 6,5 g/drzewo.

## 6. Wnioski

W niniejszej rozprawie doktorskiej, poprzez realizację trzech odrębnych powiązanych tematycznie artykułów naukowych, dokonano pozytywnej weryfikacji postawionej hipotezy badawczej.

Główne wnioski rozprawy doktorskiej:

- Świadomość mieszkańców dotycząca zdolności drzew do pochłaniania pyłów była raczej niska, zaś w przypadku wskazywania konkretnych badanych lokalizacji mieszkańcy wskazali na wyższą świadomość wartości usług ekosystemowych oraz pochłaniania zanieczyszczeń przy zagęszczeniu drzew uznanym za optymalne.
- Wyniki wskazują, że skuteczność oczyszczania powietrza zależy od pokrycia koronami drzew, zaś pokrycie koronami drzew jest o 25% większe na ulicach o optymalnych warunkach siedliskowych dla drzew. Wzrost pokrycia koronami drzew (*tree canopy cover*) jest dodatnio skorelowany ze zwiększoną zdolnością wychwytywania $PM_{2,5}$ przez pojedyncze drzewo.
- Na ulicy z 6% pokryciem koron drzew i złymi warunkami siedliskowymi (drzewa w misach o maksymalnych wymiarach 1,9 x 1,9 m) odnotowano 1,5 razy częściej przekroczenia norm jakości powietrza WHO (15 $\mu g/m^3$), zaś drzewa przy ulicy o optymalnych warunkach siedliskowych są 14 razy bardziej efektywne w wychwytywaniu $PM_{2,5}$ niż drzewa rosnące w misach. Gatunek lipa drobnolistna *Tilia cordata* posadzony w dwóch różnych siedliskach wykazuje różną efektywność pochłaniania PM również ze względu na stan fitosanitarny roślin, który wpływa na ich potencjał wzrostowy, a tym samym na efektywność oczyszczania powietrza.
- Po analizie obu metod służących do oceny fitofiltracji można stwierdzić, że metoda i-Tree Eco jest ograniczona ryzykiem błędu, wynikającymi m.in. z braku uwzględnienia warunków lokalnych w szerszym kontekście lub możliwości popełnienia błędu przez pracownika terenowego podczas zbierania danych

inwentaryzacyjnych. Porównanie wyników uzyskanych obiema metodami wykazało istotne różnice w wynikach dla $PM_{10}$. Różnice te występują jednak w obu kierunkach, co oznacza, że nie potwierdza się reguła, zgodnie z którą i-Tree Eco zaniża lub zawyża wyniki w porównaniu z metodą laboratoryjną.

- Możliwe jest wykorzystanie zalet obu metod tj. porównanie wyników z oprogramowania i-Tree Eco wraz z wynikami uzyskanymi metodą laboratoryjną. Takie porównanie pozwala na uwzględnienie w analizie warunków lokalnych np. siedliskowych i pewną kalibrację modelu i-Tree Eco w pewnym zakresie.

## 7. Wpływ badań na rozwój dyscypliny naukowej inżynieria środowiska, górnictwo i energetyka

Niniejsza rozprawa doktorska rozszerza wiedzę w dyscyplinie inżynieria środowiska, górnictwo i energetyka w kontekście gospodarowania miejskim drzewostanem i jego pozytywnego wpływu na pochłanianie zanieczyszczeń powietrza. Praca ta dokumentuje wartości pochłanianych zanieczyszczeń powietrza $PM_{2,5}$ z uwzględnieniem $PM_{10}$ wraz z analizą istniejącego drzewostanu. Uzyskane wyniki posiadają wysoką wartość aplikacyjną w zakresie planowania zieleni miejskiej, ochrony środowiska oraz kształtowania polityki miejskiej dotyczącej jakości powietrza, a także zastosowania inżynierii środowiska w zakresie planowania gospodarki drzewostanem. Badania wskazują, że zwiększenie pokrycia koronami drzew, wynikające z zapewnienia im optymalnych warunków siedliskowych, prowadzi do istotnego wzrostu efektywności wychwytywania zanieczyszczeń pyłowych (PM2,5). Oznacza to, że wyniki mogą być wykorzystane przez samorządy i urbanistów przy planowaniu nasadzeń drzew, projektowaniu ulic oraz rewitalizacji przestrzeni miejskich, aby maksymalizować ich potencjał filtracyjny.

Ponadto praca uwzględnia aspekty społeczne związane ze świadomością mieszkańców na temat usług ekosystemowych świadczonych przez drzewa miejskie alejowe, które mogą służyć do dalszych wskazań w kierunku edukacji społeczności, która powinna być realizowana, aby lokalne społeczności wspierały inwestycje proekologiczne.

Rozprawa prezentuje również postęp metodyczny poprzez opracowanie porównania obecnie stosowanych metodyk w zakresie metod oceny fitofiltracji, umożliwiający połączenie podejść dwóch stosowanych podejść i poprawa ich funkcjonalności oraz dokładności w zakresie prowadzonych analiz. Przeprowadzone analizy pozostawiają możliwości do prowadzenia dalszych badań, w szczególności opracowania ulepszeń w zakresie metod szacowania wartości fitofiltracji. Możliwość kalibracji modelu i-Tree Eco przy użyciu danych lokalnych zwiększa dokładność szacunków usług ekosystemowych i może być wykorzystana do opracowania lokalnych strategii zarządzania zielenią miejską oraz oceny efektywności inwestycji proekologicznych. Istnieją możliwości prowadzenia dalszych badań w tym zakresie w celu uzyskania dokładniejszych danych dotyczących pochłaniania PM.

Rozprawa doktorska przedstawia praktyczne wnioski, które pozwalają na wdrożenie działań związanych ze zrównoważonym gospodarowaniem drzewostanem miejskim w celu maksymalizacji uzyskiwanych usług ekosystemowych oraz związanych z tym korzyści społecznych. W tym ujęciu przedstawione wyniki badań mają wartość poznawczą i utylitarną w zakresie nauk inżynieryjno-technicznych, nauk społecznych oraz nauk przyrodniczych.

## 8. Literatura


Ahern, J. Green infrastructure for cities: The spatial dimension. In *Cities of the Future: Towards Integrated Sustainable Water and Landscape Management*; Novotny, V., Brown, P., Eds.; IWA Publishing: London, UK, **2007**; pp. 267–283.

Ajzen, I. The Theory of Planned Behavior. *Organ. Behav. Hum. Decis. Process.* **1991**, *50*, 179–211. https://doi.org/10.1016/0749-5978(91)90020-T

Akbari, H., Pomerantz, M., & Taha, H. (**2001**). Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Solar Energy, 70(3), 295–310. https://doi.org/10.1016/S0038-092X(00)00089-X

Aslam, B., Maqsoom, A., Khalid, N., Ullah, F., & Sepasgozar, S. (**2021**). Urban Overheating Assessment through Prediction of Surface Temperatures: A Case Study of Karachi, Pakistan. ISPRS International Journal of Geo-Information, 10(8), 539. https://doi.org/10.3390/IJGI10080539

Balram, S.; Dragićević, S. Attitudes toward urban green spaces: Integrating questionnaire survey and collaborative GIS techniques to improve attitude measurements. *Landsc. Urban Plan.* **2005**, *71*, 147–162. https://doi.org/10.1016/S0169-2046(04)00052-0

Bass, B. (**2001**). *Addressing Urban Environmental Problems with Green Roof. Encyclopedia of Global Environmental Change* (Vol. 3). John Wiley & Sons.

Baur, J.W.R.; Tynon, J.F.; Ries, P.; Rosenberger, R.S. Public attitudes about urban forest ecosystem services management: A case study in Oregon cities. *Urban For. Urban Green.* **2016**, *17*, 42–53. https://doi.org/10.1016/j.ufug.2016.03.012

Beckett, K. P., Freer-Smith, P. H., & Taylor, G. (**1998**). Urban woodlands: their role in reducing the effects of particulate pollution. *Environmental Pollution*, *99*(3), 347–360. https://doi.org/10.1016/S0269-7491(98)00016-5

Benedict, M.A.; McMahon, E.T. Green Infrastructure. Linking Landscapes and Communities; Island Press: Washington, DC, USA, **2012**.

Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., Deangelo, B. J., Flanner, M. G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., … Zender, C. S. (**2013**). Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres*, *118*(11), 5380–5552. https://doi.org/10.1002/JGRD.50171

Branea, A.-M., Gaman, M. S., Badescu, S., Ana-Maria, B., Mihai-Ionut, D., Stelian, G. M., & Ștefana, B. (**2016**). Challanges regarding the study of urban heat islands. Ruleset for researchers. In *In Proceedings of the Risk Reduction for Resilient Cities*. https://www.researchgate.net/publication/309740257

Brantley, H. L., Hagler, G. S. W., J. Deshmukh, P., & Baldauf, R. W. (**2014**). Field assessment of the effects of roadside vegetation on near-road black carbon and particulate matter. Science of The Total Environment, 468–469, 120–129. https://doi.org/10.1016/J.SCITOTENV.2013.08.001

Brauer, M., Hoek, G., Smit, H. A., de Jongste, J. C., Gerritsen, J., Postma, D. S., Kerkhof, M., & Brunekreef, B. (**2007**). Air pollution and development of asthma, allergy and infections in a birth cohort. *European Respiratory Journal*, *29*(5), 879–888. https://doi.org/10.1183/09031936.00083406

Bureau, P. R. (**2007**). *World Population Highlights: Key Findings from PRB's 2007 World Population Data Sheet*.

Burkhardt, J. (**2010**). Hygroscopic particles on leaves: nutrients or desiccants? *Ecological Monographs*, *80*(3), 369–399. https://doi.org/10.1890/09-1988.1

CAFE. (**2004**). *Second Position Paper on Particulate Matter CAFE Working Group on Particulate Matter Foreword*.

Cavanagh, J. (**2008**). *Influence of urban trees on air quality in Christchurch; preliminary estimates LC0708/097*.

Cen, S. (**2015**). Biological Monitoring of Air Pollutants and Its Influence on Human Beings. *The Open Biomedical Engineering Journal*, *9*(1), 219–223. https://doi.org/10.2174/1874120701509010219

Chen, L., Liu, C., Zhang, L., Zou, R., & Zhang, Z. (**2017**). Variation in Tree Species Ability to Capture and Retain Airborne Fine Particulate Matter (PM2.5). Scientific Reports 2017 7:1, 7(1), 1–11. https://doi.org/10.1038/s41598-017-03360-1

Coombes, E.; Jones, A.P.; Hillsdon, M. The relationship of physical activity and overweight to objectively measured green space accessibility and use. *Soc. Sci. Med.* **2010**, *70*, 816–822. https://doi.org/10.1016/j.socscimed.2009.11.020

Costanza, R.; D’Arge, R.; de Groot, R.; Farber, S.; Grasso, M.; Hannon, B.; Limburg, K.; Naeem, S.; O’Neill, R.V.; Paruelo, J.; et al. The value of the world’s ecosystem services and natural capital. *Nature* **1997**, *387*, 253–260.

Cunningham, B. ., Cunningham, M. A. ., & Saigo, B. W. (**2005**). *Environmental Science: A Global Concern* (8th ed.). McGraw Hill.

Daily, G. C. (**1997**). Introduction: what are ecosystem services. Nature’s services: Societal dependence on natural ecosystems, 1(1).

Daily, G.C. Nature’s Services: Societal Dependence on Natural Ecosystems; Island Press: Washington, DC, USA, **1997**; pp. 1–19.

Day, S.D.; Dove, J.E.; Bartens, J.; Harris, J.R. Stormwater Management that Combines Paved Surfaces and Urban Trees. *GeoCongress* **2008**, 1129–1136. https://doi.org/10.1061/40971(310)141

De Vries, S.; van Dillen, S.M.E.; Groenewegen, P.P.; Spreeuwenberg, P. Streetscape greenery and health: Stress, social cohesion and physical activity as mediators. *Soc. Sci. Med.* **2013**, *94*, 26–33. https://doi.org/10.1016/j.socscimed.2013.06.030

Dizengremel, P., Le Thiec, D., Hasenfratz-Sauder, M. P., Vaultier, M. N., Bagard, M., & Jolivet, Y. (**2009**). Metabolic-dependent changes in plant cell redox power after ozone exposure. *Plant Biology*, *11*(SUPPL.1), 35–42. https://doi.org/10.1111/J.1438-8677.2009.00261.X

Dominick, D., Juahir, H., Latif, M. T., Zain, S. M., & Aris, A. Z. (**2012**). Spatial assessment of air quality patterns in Malaysia using multivariate analysis. *Atmospheric Environment*, *60*, 172–181. https://doi.org/10.1016/J.ATMOSENV.2012.06.021

Donovan, G.H.; Butry, D.T. The value of shade: Estimating the effect of urban trees on summertime electricity use. *Energy Build.* **2009**, *41*, 662–668. https://doi.org/10.1016/j.enbuild.2009.01.002

Donovan, G.H.; Michael, Y.L.; Butry, D.T.; Sullivan, A.D.; Chase, J.M. Urban trees and the risk of poor birth outcomes. *Health Place* **2011**, *17*, 390–393. https://doi.org/10.1016/j.healthplace.2010.11.004

Donzelli, G.; Cioni, L.; Cancellieri, M.; Llopis-Morales, A.; Morales-Suárez-Varela, M. Air Quality during COVID-19 Lockdown. *Encyclopedia* **2021**, *1*, 519-526. https://doi.org/10.3390/encyclopedia1030043

Duan, J.; Chen, Y.; Fang, W.; Su, Z. Characteristics and Relationship of PM, PM10, PM2.5 Concentration in a Polluted City in Northern China. *Procedia Eng.* **2015**, *102*, 1150–1155. https://doi.org/10.1016/j.proeng.2015.01.239

EEA. *Climate Change, Impacts and Vulnerability in Europe* **2012***; An Indicator-Based Report*;

EEA: Copenhagen, Denmark, **2012**.

Escobedo, F. J., Kroeger, T., & Wagner, J. E. (**2011**). Urban forests and pollution mitigation: Analyzing ecosystem services and disservices. Environmental Pollution, 159(8–9), 2078–2087. https://doi.org/10.1016/J.ENVPOL.2011.01.010

Fantke, P.; Jolliet, O.; Evans, J.S.; Apte, J.S.; Cohen, A.J.; Hänninen, O.O.; Hurley, F.; Jantunen, M.J.; Jerrett, M.; Levy, J.I.; et al. Health effects of fine particulate matter in life cycle impact assessment: Findings from the Basel Guidance Workshop. *Int. J. Life Cycle Assess.* **2014**, *20*, 276–288. https://doi.org/10.1007/s11367-014-0822-2

FAO. (**2009**). *Global agriculture towards 2050*.

FAO. *Guidelines on Urban and Peri-Urban Forestry*; FAO Forestry Paper No. 178; FAO: Rome, Italy, **2016**

Feng, X.; Porporato, A.; Rodriguez-Iturbe, I. Changes in rainfall seasonality in the tropics. *Nat. Clim. Chang.* **2013**, *3,* 811–815. https://doi.org/10.1038/nclimate1907

Foszcz, D.; Niedoba, T.; Siewior, J. Models of Air Pollution Propagation in the Selected Region of Katowice. *Atmosphere* **2021**, *12*, 695. https://doi.org/10.3390/atmos12060695

Freer-Smith, P. H., Beckett, K. P., & Taylor, G. (**2005**). Deposition velocities to Sorbus aria, Acer campestre, Populus deltoides × trichocarpa 'Beaupré', Pinus nigra and × Cupressocyparis leylandii for coarse, fine and ultra-fine particles in the urban environment. Environmental Pollution, 133(1), 157–167. https://doi.org/10.1016/J.ENVPOL.2004.03.031

Gallagher, M. W., Beswick, K. M., Duyzer, J., Westrate, H., Choularton, T. W., & Hummelshøj, P. (**1997**). Measurements of aerosol fluxes to speulder forest using a micrometeorological technique. *Atmospheric Environment*, *31*(3), 359–373. https://doi.org/10.1016/S1352-2310(96)00057-X

Gómez-Baggethun, E.; Gren, Å.; Barton, D.N.; Langemeyer, J.; McPhearson, T.; O'Farrell, P.; Andersson, E.; Hamstead, Z.; Kremer, P. Urban Ecosystem Services. In Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities: A Globle Assessment; Springer: Dordrecht, The Netherlands, **2013**; pp. 175–251.

Greksa, A., Ljevnaić-Mašić, B., Grabić, J., Benka, P., Radonić, V., Blagojević, B., & Sekulić, M. (**2019**). Potential of urban trees for mitigating heavy metal pollution in the city of Novi Sad, Serbia. Environmental Monitoring and Assessment, 191(10), 1–13. https://doi.org/10.1007/S10661-019-7791-7

Grote, R., Samson, R., Alonso, R., Amorim, J. H., Cariñanos, P., Churkina, G., Fares, S., Thiec, D. Le, Niinemets, Ü., Mikkelsen, T. N., Paoletti, E., Tiwary, A., & Calfapietra, C. (**2016**). Functional traits of urban trees: air pollution mitigation potential. Frontiers in Ecology and the Environment, 14(10), 543–550. https://doi.org/10.1002/FEE.1426

Gulia, S., Shiva Nagendra, S. M., Khare, M., & Khanna, I. (**2015**). Urban air quality management-A review. Atmospheric Pollution Research, 6(2), 286–304. https://doi.org/10.5094/APR.2015.033

Guo, S., Hu, M., Zamora, M. L., Peng, J., Shang, D., Zheng, J., Du, Z., Wu, Z., Shao, M., Zeng, L., Molina, M. J., & Zhang, R. (**2014**). Elucidating severe urban haze formation in

China. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(49), 17373–17378.

Haase, D.; Larondelle, N.; Andersson, E.; Artmann, M.; Borgström, S.; Breuste, J.; Gomez-Baggethun, E.; Gren, Å.; Hamstead, Z.; Hansen, R.; et al. A Quantitative Review of Urban Ecosystem Service Assessments: Concepts, Models, and Implementation. *AMBIO* **2014**, *43*, 413–433. **https://doi.org/10.1007/s13280-014-0504-0**

Hagler, G. S. W., Lin, M. Y., Khlystov, A., Baldauf, R. W., Isakov, V., Faircloth, J., & Jackson, L. E. (**2012**). Field investigation of roadside vegetative and structural barrier impact on near-road ultrafine particle concentrations under a variety of wind conditions. Science of The Total Environment, 419, 7–15. https://doi.org/10.1016/J.SCITOTENV.2011.12.002

Hansmann, R.; Hug, S.M.; Seeland, K. Restoration and stress relief through physical activities in forests and parks. *Urban For. Urban Green.* **2007**, *6*, 213–225. https://doi.org/10.1016/j.ufug.2007.08.004

Heal, M. R., Kumar, P., & Harrison, R. M. (**2012**). Particles, air quality, policy and health. *Chemical Society Reviews*, *41*(19), 6606–6630. https://doi.org/10.1039/C2CS35076A

Heberlein, T.A. Navigating Environmental Attitudes. *Conserv. Biol.* **2012**, *26*, 583–585. https://doi.org/10.1111/j.1523-1739.2012.01892.x

Heynen, N. Green Urban Political Ecologies: Toward a Better Understanding of Inner-City Environmental Change. *Environ. Plan. A* **2016**, *38*, 499–516. https://doi.org/10.1068/a37365

Hirabayashi, S., Kroll, C. N., & Nowak, D. J. (**2012**). *i-Tree Eco Dry Deposition Model Descriptions*. Model Descriptions. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.365.190&rep=rep1&type=pdf

Ho, M. S., & Nielsen, C. P. (**2007**). Clearing the Air: The Health and Economic Damages of Air Pollution in China (M. S. . Ho & C. P. . Nielsen (Eds.)).

Holahan, C.J. Environmental Psychology. *Annu. Rev. Psychol.* **2003**, *37*, 381–407. https://doi.org/10.1146/annurev.ps.37.020186.002121

Homer, P.M.; Kahle, L.R. A Structural Equation Test of the Value-Attitude-Behavior Hierarchy. *J. Pers. Soc. Psychol.* **1988**, *54*, 638–646. https://doi.org/10.1037/0022-3514.54.4.638

Huang, K., Li, X., Liu, X., & Seto, K. C. (**2019**). Projecting global urban land expansion and heat island intensification through 2050. *Environmental Research Letters*, *14*(11), 114037. https://doi.org/10.1088/1748-9326/AB4B71

Hwang, H. J., Yook, S. J., & Ahn, K. H. (**2011**). Experimental investigation of submicron and ultrafine soot particle removal by tree leaves. *Atmospheric Environment*, *45*(38), 6987–6994. https://doi.org/10.1016/J.ATMOSENV.2011.09.019

Hystad, P.; Davies, H.W.; Frank, L.; Van Loon, J.; Gehring, U.; Tamburic, L.; Brauer, M. Residential Greenness and Birth Outcomes: Evaluating the Influence of Spatially

Correlated Built-Environment Factors. *Environ. Health Perspect.* **2014**, *122*, 1095–1102. https://doi.org/10.1289/ehp.1308049

Janhäll, S. (**2015**). Review on urban vegetation and particle air pollution – Deposition and dispersion. Atmospheric Environment, 105, 130–137. https://doi.org/10.1016/J.ATMOSENV.2015.01.052

Jasiński, R.; Galant-Gołębiewska, M.; Nowak, M.; Ginter, M.; Kurzawska, P.; Kurtyka, K.; Maciejewska, M. Case Study of Pollution with Particulate Matter in Selected Locations of Polish Cities. *Energies* **2021**, *14*, 2529. https://doi.org/10.3390/en14092529

Jennings, V.; Larson, L.; Yun, J. Advancing Sustainability through Urban Green Space: Cultural Ecosystem Services, Equity, and Social Determinants of Health. Int. J. Environ. Res. Public Health **2016**, 13, 196

Jeong, S. J. (**2013**). The Impact of Air Pollution on Human Health in Suwon City. *Asian Journal of Atmospheric Environment*, *7*(4), 227–233. https://doi.org/10.5572/AJAE.2013.7.4.227

Jim, C.Y.; Chen, W.Y. Ecosystem services and valuation of urban forests in China. Cities **2009**, 26, 187–194

Jim, C.Y.; Chen, W.Y. Ecosystem services and valuation of urban forests in China. *Cities* **2009**, *26*, 187–194. https://doi.org/10.1016/j.cities.2009.03.003

Jones, R. Business News Wales. Available online: https://businessnewswales.com/port-talbots-new-5-6m-integrated-transport-hub-opens/ (accessed on 1 August 2021).

Jones, R.E.; Davis, K.L.; Bradford, J. The Value of Trees: Factors Influencing Homeowner Support for Protecting Local Urban Trees. *Environ. Behav.* **2012**, *45*, 650–676. https://doi.org/10.1177/0013916512439409

Kaltenborn, B.P.; Bjerke, T. Associations between environmental value orientations and landscape preferences. *Landsc. Urban Plan.* **2002**, *59*, 1–11. https://doi.org/10.1016/S0169-2046(01)00243-2

Kardel, F., Wuyts, K., Maher, B. A., Hansard, R., & Samson, R. (**2011**). Leaf saturation isothermal remanent magnetization (SIRM) as a proxy for particulate matter monitoring: Inter-species differences and in-season variation. *Atmospheric Environment*, *45*(29), 5164–5171. https://doi.org/10.1016/J.ATMOSENV.2011.06.025

Khelfi, A. Sources of Air Pollution. In *Handbook of Research on Microbial Tools for Environmental Waste Management*; Pathak, V.M., Navneet, Eds.; IGI Global Publisher of Timely Knowledge: Hershey, PA, USA, **2008**. DOI: 10.4018/978-1-5225-3540-9.ch011

Kurpius, M. R., & Goldstein, A. H. (**2003**). Gas-phase chemistry dominates O3 loss to a forest, implying a source of aerosols and hydroxyl radicals to the atmosphere. *Geophysical Research Letters*, *30*(7). https://doi.org/10.1029/2002GL016785

Kurt, O.K.; Zhang, J.; Pinkerton, K.E. Pulmonary Health Effects of Air Pollution. *Curr. Opin. Pulm. Med.* **2016**, *22*, 138–143. https://doi.org/10.1097/MCP.0000000000000248

La Rosa, D.; Wiesmann, D. Land cover and impervious surface extraction using parametric and non-parametric algorithms from the open-source software R: An application to sustainable urban planning in Sicily. GIScience Remote Sens. **2013**, 50, 231–250.

Langemeyer, J.; Gómez-Baggethun, E.; Haase, D.; Scheuer, S.; Elmqvist, T. Bridging the gap between ecosystem service assessments and land-use planning through Multi-Criteria Decision Analysis (MCDA). *Environ. Sci. Policy* **2016**, *62*, 45–56. https://doi.org/10.1016/j.envsci.2016.02.013

Laurans, Y.; Mermet, L. Ecosystem services economic valuation, decision-support system or advocacy? *Ecosyst. Serv.* **2014**, *7*, 98–105. https://doi.org/10.1016/j.ecoser.2013.10.002

Laurent, O.; Wu, J.; Li, L.; Milesi, C. Green spaces and pregnancy outcomes in Southern California. *Health Place* **2013**, *24*, 190–195. https://doi.org/10.1016/j.healthplace.2013.09.016

Litschke, T., & Kuttler, W. (**2008**). On the reduction of urban particle concentration by vegetation-a review. *Meteorologische Zeitschrift* , *17*(3), 229–240.

López-Marrero, T.; Meyn, M.; Nieves-Crespo, H.I.; Morales-López, R.; Balloffet, N.M. *Public Knowledge and Perceptions about Urban Forests in a Watershed Context; ConoBosque Briefing*; Misión Industrial de Puerto Rico: San Juan, PR, USA, **2011**.

Matus, K., Nam, K. M., Selin, N. E., Lamsal, L. N., Reilly, J. M., & Paltsev, S. (**2012**). Health damages from air pollution in China. *Global Environmental Change*, *22*(1), 55–66. https://doi.org/10.1016/J.GLOENVCHA.2011.08.006

McDonald, A. G., Bealey, W. J., Fowler, D., Dragosits, U., Skiba, U., Smith, R. I., Donovan, R. G., Brett, H. E., Hewitt, C. N., & Nemitz, E. (**2007**). Quantifying the effect of urban tree planting on concentrations and depositions of PM10 in two UK conurbations. *Atmospheric Environment*, *41*(38), 8455–8467. https://doi.org/10.1016/J.ATMOSENV.2007.07.025

Mencwel, J. (**2020**). *Betonoza. Jak się niszczy polskie miasta*. Wydawnictwo Krytyki Politycznej.

Milfont, T.L.; Duckitt, J.; Wagner, C. A Cross-Cultural Test of the Value–Attitude–Behavior Hierarchy. *J. Appl. Soc. Psychol.* **2010**, *40*, 2791–2813. https://doi.org/10.1111/j.1559-1816.2010.00681.x

Nowak, David J., Greenfield, E. J., Hoehn, R. E., & Lapoint, E. (**2013**). Carbon storage and sequestration by trees in urban and community areas of the United States. Environmental Pollution, 178, 229–236. https://doi.org/10.1016/J.ENVPOL.2013.03.019

Nowak, David J., Hirabayashi, S., Bodine, A., & Hoehn, R. (**2013**). Modeled PM2.5 removal by trees in ten U.S. cities and associated health effects. *Environmental Pollution*, *178*, 395–402. https://doi.org/10.1016/J.ENVPOL.2013.03.050

Nowak, Dawid J., & Crane, D. E. (**2000**). The Urban Forest Effects (UFORE) model: quantifying urban forest structure and functions. In M. Hansen & T. Burk (Eds.), *Integrated tools for natural resources inventories in the 21st century. General Technical Report NC-*

*212. St. Paul*. U.S. Dept. of Agriculture, Forest Service, North Central Forest Experiment Station.

Pappa, A.; Kioutsioukis, I. Forecasting Particulate Pollution in an Urban Area: From Copernicus to Sub-Km Scale. *Atmosphere* **2021**, *12*, 881. https://doi.org/10.3390/atmos12070881

Peckham, S.C.; Duinker, P.N.; Ordóñez, C. Urban forest values in Canada: Views of citizens in Calgary and Halifax. *Urban For. Urban Green.* **2013**, *12*, 154–162. https://doi.org/10.1016/j.ufug.2013.01.001

Perpina Castillo, C., Kavalov, B., Jacobs-Crisioni, C., Baranzelli, C., Batista e Silva, F., Lavalle, C., Perpina Castillo, C., Kavalov, B., Jacobs-Crisioni, C., Baranzelli, C., Batista e Silva, F., & Lavalle, C. (**2019**). Main land-use patterns in the EU within 2015-2030. Joint Research Centre (Seville site). https://econpapers.repec.org/RePEc:ipt:iptwpa:jrc115895

Pishgar-Komleh, S. H., Zylowski, T., Rozakis, S., & Kozyra, J. (**2020**). Efficiency under different methods for incorporating undesirable outputs in an LCA+DEA framework: A case study of winter wheat production in Poland. *Journal of Environmental Management*, *260*, 110–138. https://doi.org/10.1016/j.jenvman.2020.110138

Prusty, B. A. K., Mishra, P. C., & Azeez, P. A. (**2005**). Dust accumulation and leaf pigment content in vegetation near the national highway at Sambalpur, Orissa, India. *Ecotoxicology and Environmental Safety*, *60*(2), 228–235. https://doi.org/10.1016/J.ECOENV.2003.12.013

Przybysz, A., Nersisyan, G., & Gawroński, S. W. (**2018**). Removal of particulate matter and trace elements from ambient air by urban greenery in the winter season. Environmental Science and Pollution Research, 26(1), 473–482. https://doi.org/10.1007/S11356-018-3628-0

Rai, A., Kulshreshtha, K., Srivastava, P. K., & Mohanty, C. S. (**2009**). Leaf surface structure alterations due to particulate pollution in some common plants. *The Environmentalist 2009 30:1*, *30*(1), 18–23. https://doi.org/10.1007/S10669-009-9238-0

Räsänen, J. V., Holopainen, T., Joutsensaari, J., Ndam, C., Pasanen, P., Rinnan, Å., & Kivimäenpää, M. (**2013**). Effects of species-specific leaf characteristics and reduced water availability on fine particle capture efficiency of trees. Environmental Pollution, 183, 64–70. https://doi.org/10.1016/J.ENVPOL.2013.05.015

Reid, W. Millennium Ecosystem Assessment. *Ann. N. Y. Acad. Sci.* **2008**, *1134*, 25–60.

Roe, J.; Aspinall, P. The restorative benefits of walking in urban and rural settings in adults with good and poor mental health. *Health Place* **2011**, *17*, 103–113. https://doi.org/10.1016/j.healthplace.2010.09.003

Roy, S.; Byrne, J.; Pickering, C. A systematic quantitative review of urban tree benefits, costs, and assessment methods across cities in different climatic zones. *Urban For. Urban Green.* **2012**, *11*, 351–363. https://doi.org/10.1016/j.ufug.2012.06.006

Roy, S.; Byrne, J.; Pickering, C. A systematic quantitative review of urban tree benefits, costs, and assessment methods across cities in different climatic zones. *Urban For. Urban Green.* **2012**, *11*, 351–363. https://doi.org/10.1016/j.ufug.2012.06.006

Russell, A. G., & Brunekreef, B. (**2009**). A focus on particulate matter and health. *Environmental Science and Technology*, *43*(13), 4620–4625. https://doi.org/10.1021/ES9005459/ASSET/IMAGES/MEDIUM/ES-2009-005459_0001.GIF

Sæbø, A., Popek, R., Nawrot, B., Hanslin, H. M., Gawronska, H., & Gawronski, S. W. (**2012**). Plant species differences in particulate matter accumulation on leaf surfaces. Science of The Total Environment, 427–428, 347–354. https://doi.org/10.1016/J.SCITOTENV.2012.03.084

Salmond, J.A.; Tadaki, M.; Vardoulakis, S.; Arbuthnott, K.; Coutts, A.; Demuzere, M.; Dirks, K.N.; Heaviside, C.; Lim, S.; Macintyre, H.; et al. Health and climate related ecosystem services provided by street trees in the urban environment. *Environ. Health* **2016**, *15*, 95–111. https://doi.org/10.1186/s12940-016-0103-6

Santiago, L.; Gladkikh, T.; Betancourt, L.; Vargas, Y. Green versus Gray: Attitudes toward Vegetation in a Tropical Metropolitan Square. *Environ. Nat. Resour. Res.* **2015**, *5*, 109–120. https://doi.org/10.5539/enrr.v5n2p109

Sawidis, T., Breuste, J., Mitrovic, M., Pavlovic, P., & Tsigaridas, K. (**2011**). Trees as bioindicator of heavy metal pollution in three European cities. *Environmental Pollution*, *159*(12), 3560–3570.

Schroeder, H.; Flannigan, J.; Coles, R. Residents' Attitudes Toward Street Trees in the UK and U.S. Communities. *Arboric. Urban For.* **2006**, *32*, 236–246.

Sgrigna, G., Sæbø, A., Gawronski, S., Popek, R., & Calfapietra, C. (**2015**). Particulate Matter deposition on Quercus ilex leaves in an industrial city of central Italy. Environmental Pollution, 197, 187–194. https://doi.org/10.1016/J.ENVPOL.2014.11.030

Słownik Języka Polskiego. https://sjp.pwn.pl/slowniki/aleja.html (dostęp 26.10.2025 r.)

Stern, P.C.; Dietz, T.; Abel, T.; Guagnano, G.; Kalof, L. A Value-Belief-Norm Theory of Support for Social Movements: The Case of Environmentalism. *Hum. Ecol. Rev.* **1999**, *6*, 81–97.

Stigsdotter, U.K.; Ekholm, O.; Schipperijn, J.; Toftager, M.; Kamper-Jørgensen, F.; Randrup, T.B. Health promoting outdoor environments—Associations between green space, and health, health-related quality of life and stress based on a Danish national representative survey. *Scand. J. Public Health* **2010**, *38*, 411–417. https://doi.org/10.1177/1403494810367468

Tallis, H.; Polasky, S. Mapping and Valuing Ecosystem Services as an Approach for Conservation and Natural-Resource Management. *Year Ecol. Conserv. Biol.* **2009**, *1162*, 265–283. https://doi.org/10.1111/j.1749-6632.2009.04152.x

Taylor, M.S.; Wheeler, B.W.; White, M.P.; Economou, T.; Osborne, N.J. Research note: Urban street tree density and antidepressant prescription rates—A cross-sectional study in

London, UK. *Landsc. Urban Plan.* **2015**, *136*, 174–179. https://doi.org/10.1016/j.landurbplan.2014.12.005

Tu, L., Qin, Z., Li, W., Geng, J., Yang, L., Zhao, S., Zhan, W., & Wang, F. (**2016**). Surface urban heat island effect and its relationship with urban expansion in Nanjing, China. Journal of Applied Remote Sensing, 10(2), 026037. https://doi.org/10.1117/1.JRS.10.026037

Ünal, Y. S., Sonuç, C. Y., Incecik, S., Topcu, H. S., Diren-Üstün, D. H., & Temizöz, H. P. (**2019**). Investigating urban heat island intensity in Istanbul. *Theoretical and Applied Climatology 2019 139:1*, *139*(1), 175–190. https://doi.org/10.1007/S00704-019-02953-2

Van den Berg, A.E.; Maas, J.; Verheij, R.A.; Groenewegen, P.P. Green space as a buffer between stressful life events and health. *Soc. Sci. Med.* **2010**, *70*, 1203–1210. https://doi.org/10.1016/j.socscimed.2010.01.002

Wang, L., Gong, H., Liao, W., & Wang, Z. (**2015**). Accumulation of particles on the surface of leaves during leaf expansion. *Science of The Total Environment*, *532*, 420–434. https://doi.org/10.1016/J.SCITOTENV.2015.06.014

Wang, Y. C. (**2011**). Carbon sequestration and foliar dust retention by woody plants in the greenbelts along two major Taiwan highways. *Annals of Applied Biology*, *159*(2), 244–251. https://doi.org/10.1111/J.1744-7348.2011.00494.X

Wesely, M. L., & Hicks, B. B. (**2000**). A review of the current status of knowledge on dry deposition. *Atmospheric Environment*, *34*(12–14), 2261–2282. https://doi.org/10.1016/S1352-2310(99)00467-7

Weyens, N., Thijs, S., Popek, R., Witters, N., Przybysz, A., Espenshade, J., Gawronska, H., Vangronsveld, J., & Gawronski, S. W. (**2015**). The Role of Plant–Microbe Interactions and Their Exploitation for Phytoremediation of Air Pollutants. International Journal of Molecular Sciences 2015, Vol. 16, Pages 25576-25604, 16(10), 25576–25604. https://doi.org/10.3390/IJMS161025576

WHO. (**2022**). Household air pollution and health. https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health

WUP. (**2018**). *World Urbanization Prospects: The 2018 Revision, Online Edition*.

Xiao, Q.; McPherson, E.G.; Simpson, J.R.; Ustin, S.L. Rainfall interception by Sacramento’s urban forest. *J. Arboric.* **1998**, *24*, 235–244.

Xu, X., Xia, J., Gao, Y., & Zheng, W. (**2020**). Additional focus on particulate matter wash-off events from leaves is required: A review of studies of urban plants used to reduce airborne particulate matter pollution. *Urban Forestry & Urban Greening*, *48*, 126559. https://doi.org/10.1016/J.UFUG.2019.126559

Yin, S., Shen, Z., Zhou, P., Zou, X., Che, S., & Wang, W. (**2011**). Quantifying air pollution attenuation within urban parks: An experimental approach in Shanghai, China. Environmental Pollution, 159(8–9), 2155–2163. https://doi.org/10.1016/J.ENVPOL.2011.03.009

Zanobetti, A., & Schwartz, J. (**2012**). Mortality Displacement in the Association of Ozone with Mortality. American Journal of Respiratory and Critical Care Medicine, 177(2), 184–189. https://doi.org/10.1164/RCCM.200706-823OC

Zhang, S., & Witlox, F. (**2020**). Analyzing the impact of different transport governance strategies on climate change. *Sustainability (Switzerland)*, *12*(1), 200. https://doi.org/10.3390/su12010200

## 9. Inne osiągnięcia

Wykaz artykułów naukowych, których byłam współautorką i które powstały w trakcie trwania studiów doktoranckich:

- Suchocka, M., Heciak, J., Błaszczyk, M., Adamczyk, J., Gaworski, M., Gawłowska, A., Mojski, J., Kalaji, Hazem, M., **Kais, K.**, Kosno-Jończy, J., Wojnowska-Heciak, M., Comparison of Ecosystem Services and Replacement Value calculations performed for urban trees, *Ecosystem Services*, Volume 63, 2023, https://doi.org/10.1016/j.ecoser.2023.101553;
- Sulewski, P.; **Kais, K.**; Gołaś, M.; Rawa, G.; Urbańska, K.; Wąs, A. Home Bio-Waste Composting for the Circular Economy. *Energies* 2021, 14, 6164. https://doi.org/10.3390/en14196164
- Sikorski, P., Sudnik-Wójcikowska, B., **Kais, K.** 2020, Roślinność parku Pole Mokotowskie w Warszawie, *Prace i Studia Geograficzne*, 65.1, Wydział Geografii i Studiów Regionalnych Uniwersytetu Warszawskiego, Warszawa, 43–52.

Konferencje/seminaria naukowe:

- Mielczarek D., Sikorski P., Archiciński P., Kais K., Truszkowska-Zaniewska E., Chormański J., Referat pt.: "Wykorzystanie skanera Riegl VQ-1560i-DW do szybkiej identyfikacji inwazyjnych gatunków w lasach nadrzecznych na przykładzie klonu jesionolistnego", konferencja**:** Polscan, I Krajowe Forum Użytkowników LiDAR, Sękocin Stary, 22-23.10.2019 r.;
- Kais Karolina, Referat pt.: **"**Smart plants in the workspace and their impact on work efficiency and stress reduction", konferencja: Smart plants in the workplace and their impact on work efficiency and stress reduction, SGGW w Warszawie, 06.05.2020 r.**;**

- Suchocka M., Adamczyk J., Błaszczyk M., Szkop Z., Gawłowska A., Wojnowska-Heciak M., Kais K., Kosno-Jończy J., Orzińska J., Referat pt. “How much does a tree earn? Assessment and valuation of ecosystem services in the selected area of Warsaw”, konferencja: 2nd International seminar and workshop on geoinformatics, remote sensing and engineering in spatial planning and environmental science. Warszawa, 27-28.09.2021;
- Suchocka M., Kais K., Referat pt: “Zazielenianie obszarów miejskich. Koszty i zyski”, konferencja: Konferencja Innowacyjna Gmina, Warszawa, 05.10.2023 r.;
- Suchocka M., Kais K., Referat pt.: “Proekologiczne projektowanie współczesnych miast - drzewa i wartość usług ekosystemowych”, konferencja: Usługi ekosystemowe w dobie zmian klimatu, Liga Ochrony Przyrody, Warszawa, 30.10.2024r.
- Kais K., Kosno-Jończy J., Rybicki K., Mazurek K., Suchocka M., Błaszczyk M., Referat pt: “Urban heat stress mitigation - cooling with trees and vegetation”, konferencja: ECOSERV 2025, Poznań, 18-19.09.2025r.
- Suchocka M., Kosno-Jończy J., Kais K., Referat pt: “Zielona infrastruktura na terenach objętych ochroną konserwatorską - wyzwania współczesności”, konferencja: I Ogólnopolska Konferencja Zieleń Zabytkowa, Architektura, Krajobraz, Konserwacja, Szczecin, 9-10.10.2025 r.

  Szkolenia:
- Kais K., Suchocka M., Referat pt: “Zielona infrastruktura i metody zwiększania małej retencji. Rola roślinności w zwiększeniu małej retencji i rezyliencji wobec zmian klimatu”, szkolenie pt: “Projektowanie w otoczeniu drzew - Inżynieryjne metody poprawy warunków siedliskowych drzew miejskich”, Instytut Rozwoju Miast i Regionów, 04.11.2024 r., 31.03.2025 r.

Udział w projektach badawczych:

- Ocena i wycena usług ekosystemowych na wybranym obszarze Miasta Stołecznego Warszawy, Biuro Ochrony Powietrza i Polityki Klimatycznej Urzędu m.st. Warszawy, 2021, Rola Autorki: wykonawca
- Badanie efektywności zastosowania nowych, eksperymentalnych doborów opartych o rośliny synantropijne wzdłuż wybranych ulic Warszawy, Zarząd Zieleni m. st. Warszawy, 2019, Rola Autorki: wykonawca

- Wykorzystanie skanera Riegl VQ-1560i-DW do szybkiej identyfikacji inwazyjnych gatunków w lasach nadrzecznych na przykładzie klonu jesionolistnego, OPEGIEKA, 2019, Rola Autorki: wykonawca
- Inwentaryzacja fotograficzna oraz ocena krajobrazu, a także sporządzenie wizualizacji typu 1 i 4 na potrzeby oceny oddziaływania na krajobraz i estetykę przestrzeni wykorzystanej w procesie inwestycyjnym polskiej elektrowni jądrowej o mocy ok. 3.000 MW, WYG International, 2019, Rola Autorki: wykonawca
- Ocena i wycena usług ekosystemowych wybranych drzew na terenie Miasta Białystok, Miasto Białystok, Rola Autorki: wykonawca (zespół dr hab. inż. Marzena Suchocka, mgr inż. Karolina Kais)

Udział w projektach badawczo-edukacyjnych:

- GINA - Green Infrastructure in Urban Areas - Innovative Educational Course. Blended-learning, climate adaptation, Nature-Based Solutions, Projekt realizowany jest przez konsorcjum międzynarodowe z udziałem: Politechniki Gdańskiej, Hanzehogeschool Groningen Stichting, Stichting Hogeschool Rotterdam, Universitaet Klagenfurt, Szkoły Głównej Gospodarstwa Wiejskiego, VIA University College, 2024-2027, Rola Autorki: członek zespołu projektowego realizującego projekt badawczo-edukacyjny w ramach programu Erasmus+

Ważniejsze zrealizowane projekty:

- Nadzór przyrodniczy nad inwestycjami:
    - Budowa nowego źródła wytwórczego energii zasilanego paliwem gazowym o mocy elektrycznej 450-600 MWe wraz z infrastrukturą towarzyszącą w Grudziądzu, EKOSYSTEM Sp. z o.o., 2023-2025;
    - Rozbudowa drogi krajowej nr 25 na odcinku Obodowo-Mąkowarsko, PROKOM Construction Sp. z o.o., 2025 -;
    - Projekt i Budowa obwodnicy Kamienia Krajeńskiego i Sępólna Krajeńskiego z podziałem na dwie części. Część 1 Projekt i budowa obwodnicy Kamienia Krajeńskiego w ciągu drogi krajowej nr 25 na odcinku od km 81+100 do km 84+405. Część 2 Projekt i budowa obwodnicy

Sępólna Krajeńskiego w ciągu drogi krajowej nr 25 na odcinku od km 90+540 do km 96+317, PROKOM Construction Sp. z o.o., 2025 -;

- Projekt i budowa drogi ekspresowej S19 Lublin-Lubartów od Węzła "Lubartów Północ" (wraz z węzłem) do Węzła "Lublin Rudnik" (bez węzła), EKOSYSTEM Sp. z o.o., 2024 - ;
- Budowa obwodnicy miejscowości Gąski w ciągu drogi krajowej nr 65 na odcinku od istniejącego 49+207 do istniejącego km 52+151, EKOSYSTEM Sp. z o.o., 2024 -;
- Budowa Parku przy Bażantarni w Warszawie, EKOSYSTEM Sp. z o.o., 2024

- Kierownik robót oraz koordynator projektu w trakcie projektowania i budowy terenów zieleni na 10 osiedlach mieszkaniowych (Wilgi Park, Wilgi Park 2, Osiedle Kolorowe 3, Novisa Modern, Novisa Park, Pod Topolami, Nova Magdalenka 2, Nova Magdalenka 3, Ogrody Przyjaciół 3, Ogrody Przyjaciół 5) w ramach współpracy z firmą Novisa Development;
- Ważniejsze prace projektowe w zakresie zieleni i inwentaryzacje dendrologiczne m.in.:
    - Budowa obwodnicy Więcborka - opracowanie dokumentacji projektowej, EKOSYSTEM Sp. z o.o.;
    - Opracowanie dokumentacji projektowej wraz z nadzorem autorskim w ramach budowy gazociągu Rembelszczyzna - Mory - Wola Karczewska - opracowanie inwentaryzacji dendrologicznej, LandArt Architektura Krajobrazu;
    - Rozbudowa i budowa infrastruktury kolejowej w Rejonie Przeładunkowym Małaszewicze korytarza 8 linii towarowych na granicy UE z Białorusią, LandArt Architektura Krajobrazu;
    - Projekty 3 skwerów w Gminie Rypin oraz 3 skwerów w Gminie Golub-Dobrzyń, LandArt Architektura Krajobrazu.

# 10. Publikacje naukowe

## 10.1. Artykuł 1

**Kais, K.**; Gołaś, M.; Suchocka, M. Awareness of Air Pollution and Ecosystem Services Provided by Trees: The Case Study of Warsaw City. Sustainability 2021, 13, 10611. https://doi.org/10.3390/su131910611

sustainability

MDPI

*Article*

# Awareness of Air Pollution and Ecosystem Services Provided by Trees: The Case Study of Warsaw City

**Karolina Kais [1], Marlena Gołaś [2,*] and Marzena Suchocka [1]**

[1] Institute of Environmental Engineering, Warsaw University of Life Sciences—SGGW, Nowoursynowska 166, 02-787 Warsaw, Poland; karolina_kais@sggw.edu.pl (K.K.); marzena_suchocka@sggw.edu.pl (M.S.)

[2] Institute of Economics and Finance, Warsaw University of Life Sciences—SGGW, Nowoursynowska 166, 02-787 Warsaw, Poland

* Correspondence: marlena_golas@sggw.edu.pl; Tel.: +48-607-061-776

**Abstract:** One of the consequences of the constant urban development in numerous countries is a growing concentration of air pollution, which adversely affects both the environment and people's health. One of the ways of changing this negative trend is to maintain green areas and trees within cities, as they serve many ecosystem functions, including biological absorption of particles and other types of air pollution. This article provides the findings of a study carried out among the residents of Warsaw, the capital of Poland, in order to assess social awareness of air pollution and the importance of trees. The study of the residents' awareness was supplemented with the assessment of the parameters of the trees' capacity for pollution absorption in selected locations performed with the help of the i-Tree Eco tool, which allowed the authors to compare the residents' impressions on the role of trees in the process of absorption of pollution with their actual potential. The analyses showed that the majority of city residents are concerned with the problem of air in the city, but at the same time failing to notice its negative impact on their health. The majority of respondents were not aware of the role the trees play in the process of pollution absorption, suggesting that there is a real need for raising social awareness of functions served by trees and green areas in urban spaces. The comparison of the city residents' opinions on the importance of trees in the process of pollution absorption with objective data obtained with the help of i-Tree Eco tool shows that the majority of people's impressions of pollution absorption by trees in urban areas is correct.

**Keywords:** ecosystem services; environmental awareness; PM2.5 removal



**Citation:** Kais, K.; Gołaś, M.; Suchocka, M. Awareness of Air Pollution and Ecosystem Services Provided by Trees: The Case Study of Warsaw City. *Sustainability* **2021**, *13*, 10611. https://doi.org/10.3390/su131910611

Academic Editor: Francesco Boscutti

Received: 26 August 2021
Accepted: 23 September 2021
Published: 24 September 2021



## 1. Introduction

One of the main environmental challenges, apart from GHG emissions (and their consequences), has been air pollution caused by mineral or anthropogenic particulates [1] which cause adverse effects on humans and the environment [2–5]. The types of air pollution with the most detrimental influence on people's health are: particulate matter (PM) [3,5–7], nitrogen dioxide ($NO_2$), ozone ($O_3$) and sulphur dioxide ($SO_2$) [8–11]. Air pollution causes respiratory and circulatory problems and contributes to premature death [12–14]. As listed in the available statistical data, outdoor air pollution has contributed to 0.5 million premature deaths in the EU and 4.2 million cases globally [15,16]. Suspended particulate matter (PM) is one of the main sources or air pollution in cities [17–19], which is why its direct impact on people's health has been observed in industrial and urban areas. It is estimated that due to growing migration from rural to urban areas the percentage of the population in the cities will reach 60% by 2030 [20], 70% on a global scale [21] and 82% in the EU [22] by 2050. Despite the fact that the process of urbanisation provides numerous social benefits, it can be seen as a significant factor behind environmental issues [23,24] such as the Urban Heat Island (UHI) [24–27], caused by changes in land use and construction developments [28,29]. Research conducted by the World Health Organisation in more than 3000 cities found that outdoor air pollution has grown 8% globally in the last five years [15].

One of the factors which reduce the negative consequences of air pollution in urbanised areas is the tree cover [30]. As air pollution grows in city agglomerations, the subject of trees in urban management grows in importance. Urban trees provide various ecosystem services to the residents [31]. Some of their functions include filtration of atmospheric air and accumulation (retention) of toxic substances [32,33]. Research shows that one of the most effective methods of elimination of suspended particulate matter in the environment is the presence of vegetation [34,35]. Data provided by the UN [22] shows that more than half of the world's population currently lives in urban areas. In Poland, the percentage of people living in cities is almost 60% [36]. It is vital to conduct research on the level of awareness of the residents of urban areas in the scope of air pollution and its impact on health, and, in related matters—their knowledge on the ecosystem functions of trees as biological absorbers of particles and other impurities [34]. Raising awareness in the scope discussed here is necessary in order to increase the surface of green areas in urban agglomerations. This awareness is probably lacking in numerous countries (e.g., Chile in North America) [37]—most definitely in Poland, where vegetation is frequently removed from public spaces and replaced with concrete (as shown on the examples of revitalisation of main squares in numerous Polish cities and towns, such as Włocławek, Kutno, Białystok, Kielce, Skierniewice, Wągrowiec, Warsaw) [38]. This phenomenon is confirmed by the continuous increase in the loss of trees in urban space in Poland, which in 2019 amounted to 125,706 pieces and accounted for 141% of the loss of trees in 2004 [39]. Social awareness surveys on air pollution have been conducted by many authors in various countries [40–43], however, not to a large extent in Poland [44,45]. Moreover, none of the works referenced here draw attention to the social awareness on ecosystem functions of trees and their role in reduction of pollution, hence why the aim of this study is to assess the social awareness of air pollution among city inhabitants and investigating the functions realized by trees in large cities taking into account the example of Warsaw. The survey consisted of two stages: The first one involved interviews on city residents which were used to assess the social awareness of air pollution and functions of trees. Stage two of the research focused on tree inventory in two specifically selected locations in the city which provided data necessary to establish the parameters of the trees' capacity to absorb impurities. This approach allowed the authors to confront the residents' opinions (and misconceptions) on the functions of trees in the city with an objective assessment of the potential capacity to absorb impurities.

## 2. Literature Review

### *2.1. Ecosystem Services and Benefits Generated by Trees*

Ecosystem services may be described as conditions and processes provided by natural ecosystems and their species by means of maintaining and enriching people's lives [46]. Ecosystem services may also be defined as benefits drawn directly and indirectly by the members of communities from ecosystem functions [47,48]. Due to steadily increasing urban populations [15,21,22] and limited green areas, the urban ecosystem functions, which create a link between the cities and the biosphere, improve public health of the residents, reduce noise levels, purify wastewater systems and reduce the urban ecological debt [49–51] have become endangered [52]. Green infrastructure provides the residents of urban agglomerations with social and environmental services in order to improve their quality of life serve as generators of urban ecosystem services [53–57]. In addition, as one of the major elements of the social and ecological urban systems, green infrastructure has become an increasingly crucial point of reference in discussions on sustainable development and urban planning [49,57–59]. Trees at the roadside, in parks, gardens, remaining woodlands and on buildings create the largest segment of the urban green areas [60,61]. Research shows that trees enrich the landscape and play a major role in the process of limiting adverse effects of residential estates on the environment [62]. These benefits are described as ecosystem services provided by trees and provide other advantages: economic, health, social and visual benefits, but also create the process of environment regulation [63]. In practice, trees and other elements of the green infrastructure in the cities are used to manage stormwater runoff [64,65], provide solutions to problems with impermeable surfaces [66] and capture rainwater before it reaches stormwater systems [66]. They are also useful in the process of lowering energy consumption levels; indeed, trees growing to the south and west of houses contribute to lower costs of cooling the buildings [67]. According to other authors, trees also positively influence public health by increasing the quality of air, thus encouraging physical activity of the residents, lowering stress levels and improving social relationships [68]. A study showed that residents of districts with better access to parks and green areas play more sports [69,70], while it has also been proved that a higher number of green areas positively influences the possibility of taking walks in the neighborhood [71], with trees, and access to them, contributing to lower levels of stress [72–75]. Independent studies showed that women who lived in close proximity of trees (within a 50-metre radius) were less likely to give birth to children with a low birth weight [76,77]. At the same time, it must be noted that the trees which provide ecosystem services may also damage the infrastructure elements and cause allergies [49]. Appropriate urban planning in line with sustainable development should take into account the correlations between the residents' attitude towards the green areas and their influence on the development and management of the green urban infrastructure [78–81].

### *2.2. Social Awareness in the Scope of Environmental Benefits Generated by Trees*

Trees in cities have various levels of importance for the society. Some city residents consider them as an opportunity to stay in touch with nature, while others see them as nuisance [63]. The relationships between the natural environment and people may be considered on the basis of numerous theories of environmental psychology [82]; Ajzen's theory of planned behavior, Stern's value-belief-norm theory [83,84] and Rokeach's theory of cognitive hierarchy are of importance here [85,86]. Homer and Kale, on the basis of the models listed here, created their value–attitude–behavior model, which can be applied in the environmental discourse [86,87]. Attitudes are defined within the model as positive and negative ones (differentiated as preference, affection or dislike) towards certain objects, including trees, among others [88–90]. The data shows that people have a very positive attitude towards trees in cities [52,91–97], which, in combination with the value–attitude–behavior hierarchy model, is applied in research on potential behaviors in the urban space, where specific attitudes of the residents also influence decisions on the green infrastructure [98]. The analysis of the opinions of city residents conducted in the San Juan Metropolitan Area in Puerto Rico shows that city residents are able to identify numerous ecosystem services provided by the green urban areas [99,100]. The findings show that the perception of ecosystem services may differ in small areas [99]. The most popular ecosystem service listed by the visitors of Plaza de Convalecencia was the landscape value [100]. A cross-sectional study with data gathered in London [52] shows that the number of antidepressant prescriptions was lower in areas with higher street tree density [93]. A study conducted in the Netherlands focused on green street areas showed their positive influence on the general health condition and mental health of the residents [94]. Research conducted by Peckham and others [95] shows that the residents of Halifax and Calgary present various attitudes and ways of perceiving of urban trees. During their commute, some residents used the green urban areas, and many of them named birds singing as a calming factor. Keeping the residents informed about the correlations between green area management and the ecosystem services may contribute to the application of holistic strategies in green management [101]. There are numerous studies on the ways that the amount and quality of information on ecosystem services influence the decision-making process of policymakers [102].

### *2.3. Political Efforts Made in Order to Decrease Air Pollution in Urban Areas*

The improvement of air quality is one of the main tasks of environmental protection institutions [103]. Air quality policies vary depending on the country and its regions, and rich countries tend to introduce more rigorous restrictions and advanced strategies in order to reduce air pollution. Developing countries make use of existing standards and practices used by the United States and the European Union, the leaders in the field [104].

In 1968, the World Meteorological Organisation developed an air pollution level monitoring program. It served as the basis for the first global network of Background Air Pollution Monitoring, which provides information on the impact of pollution on the climate [105]. In the 1970s, the air quality and its protection became a subject of international priority in the field of environment protection. The OSCE (Organisation for Security and Co-operation in Europe) Final Act included information on transboundary air pollution and the necessity of close cooperation among countries in order to maintain air quality. It was noticed that pollution emissions in one country had a negative impact on air in other countries. The Convention on Long-range Transboundary Air Pollution (LRTAP) was concluded in 1979, and its main objective was the protection of people and the environment against long-range air pollution by means of limiting emissions and reducing pollutant level [106].

Urban air quality policy often combines methods aimed at discouraging the use of private cars with activities meant to increase the use of less emission-heavy means of transport as more desirable ones [107]; such actions are implemented in the form of infrastructure investments in bicycle route networks and public transportation systems. While these systems generate high costs over a short period, they enable—and facilitate—a long-term change in behavior which, in turn, results in lowering the level of traffic-generated pollution [107].

It is worth mentioning that low emission zones (LEZ) are created within urban agglomerations. These are areas where limits on vehicle use were introduced in order to reduce exhaust emissions, and represent a very popular measure to improve air quality in the United Kingdom, Italy, Sweden and the Netherlands, among others [108]. Limitations usually apply to Diesel-powered utility vehicles and very old cars which produce a large amount of pollution [109]. Countries such as Singapore are planning to create integrated transport hubs, which will provide easier access to different means of transport, for example, switching from a bus to a tram [107]. In 2017 a transport hub which links a bus terminal, a train station and a bicycle station was opened in Port Talbot in Wales [110]. In San Francisco, employers are obligated to encourage workers to use bicycles, carpooling or public transport by offering transport cost tax deductions [111]. Speed limits may also serve as a method of air quality control near roads [112] and are included in air quality plans in several European countries [113].

Information and marketing are other crucial activities which resulted in improved social awareness and compliance with air quality regulations [114]. Actions in Singapore may be an example of raising social responsibility in the scope of air quality improvement: Community and youth for environment events are held yearly, while The Green Champions campaign was launched in the Royal Borough of Kensington and Chelsea in order to educate its residents on energy efficiency and pollution reduction issues [111], and a 100-metre-tall air purification tower has been built in Xi'an in China [115]. Reagents such as $NO_2$ and absorbent substances are also being tested in several countries, such as the Netherlands, Japan and Great Britain [116]. Attempts at the development and improvement of air quality monitoring networks are also being made in China and cities of UE. The Chinese government has built a nationwide network of monitors tracking levels of PM2.5 where the data are made publicly available and can be checked by any smartphone user [117]. Cities in Poland also implement actions aimed at the improvement of air quality—e.g., in Poznań, where the municipal police are involved in a fight against the use of inappropriate fuel [118]; elsewhere, the Low Emission Reduction Program for the city of Kraków and Warsaw was introduced with the goal of replacing the most harmful furnaces [119,120]. Another program was also prepared for the residents who bear the highest costs involved in the modernisation of the heating system. Further, anti-smog towers which remove PM and purify air are also being tested in the city of Kraków [121].

Apart from this, some cities in Poland have implemented tree-planting initiatives, such as the Platanus program in Szczecin [122], aimed at planting air purifying trees or the "Million Trees" app used in Warsaw, which allows the city residents to report spots where trees are lacking [123]. Similar programs, such as re-forestation initiatives and urban forest protection campaigns, have also been implemented in other cities worldwide [124–126]. The aim is to increase the tree canopy cover percentage, as applied in the "Million Trees" campaign in New York City [127] or a Melbourne initiative to reach the level of 40% tree canopy cover. In Balder et al.'s study [128], 100 trees per kilometer of road was considered the optimal tree density; indeed, planting trees in cities is promoted as an urban solution [129] which reduces environmental degradation caused by urban development. The aim of these actions is to increase sustainable development of urban areas, to alleviate and adapt to the climate changes and to improve people's health and wellbeing [63,130].

## 3. Case Study Area Description

Warsaw—the capital of Poland, the largest city in the country, located in its centre as well as in the central part of Europe, was selected for the research area (Figure 1). Similar to numerous Polish cities, Warsaw is listed among the places with the worst air quality on a world scale. In February 2021, Warsaw placed 2nd among the cities with the lowest air quality according to the World Air Quality Ranking [131], where PM10 concentration level was exceeded by 232% and the PM2.5 level by a staggering 364%. This January, Warsaw was the 6th most polluted city in the world according to the Air Quality Index Ranking [132]. One of the most serious smog episodes in the city happened in January 2017, while very high levels exceeding air pollution standards were recorded in the majority of Poland. In Warsaw, the permissible average PM10 concentration level was exceeded on 19–22 days in January 2017 (60–70% of time over the course of the month), while the average PM2.5 concentration level was too high on 25–28 days of the month (80–90% of the time) [133].


**Figure 1.** Location of the case study area—Warsaw city.

The city, with an area of 517.2 km$^2$, is currently inhabited by 1,794,166 people [134] with 56.9% of residents being working age, 18.6% of pre-working age and 24.5% of retirement age [134].

The tree inventory was carried out on two 300-metre-long street sections in Warsaw. The roads were selected as the inventory sites, due to their varied tree cover and their crucial communication function in the city, with heavy traffic on both of them. The streets in question have the same layout (without curves or bends) which does not influence the variability of air pollution measurements. In both cases, the trees are in public spaces and they are easily accessible.

One of the segments (Figure 2)—Marszałkowska Street—is located in the centre of Warsaw, in the neighborhood of the Palace of Culture and Science and the Warsaw Central Railway Station, and there are a small number of green areas and trees around. Concrete squares, wide concrete pavements and commercial buildings are predominant there, and the road fits three traffic lanes in each direction. The tree alley along the street consists mostly of small-leaved linden trees (*Tilia cordata* Mill) planted between the pavement and the road. There are concrete walkways on both sides of the road and the spaces in front of buildings do not feature any shrubbery.


**Figure 2.** Location of the tree inventory at Marszałkowska Street.

The second segment (Figure 3)—Żwirki i Wigury Street—is the main communication artery, as it connects the southern part of Warsaw with Chopin airport and the city centre. A closed military area, multi-family residential buildings and allotment gardens are located along the street. Due to the closeness of allotment gardens along Żwirki i Wigury, there are more trees and other plants in the neighborhood of the street. There are two traffic lanes in each direction separated by small-leaved linden trees (*Tilia cordata*).

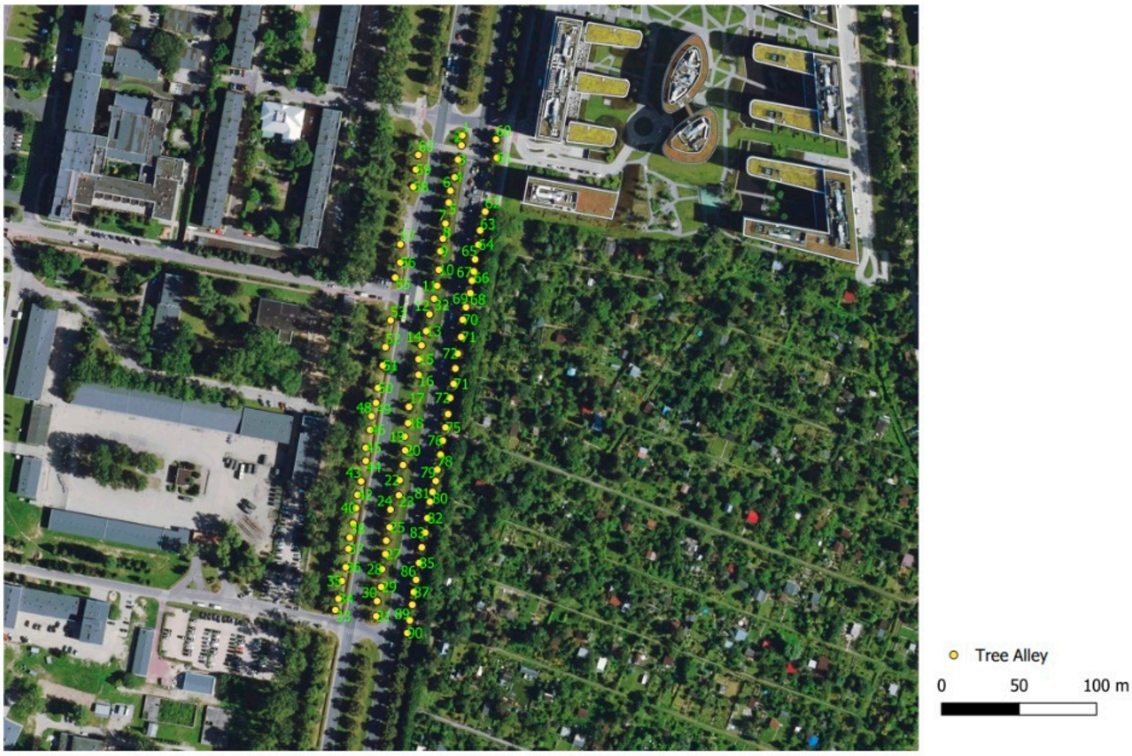



**Figure 3.** Location of the tree inventory at Żwirki i Wigury Street.

## 4. Materials and Methods

Two principal sources of data were used in the research, namely the i-Tree Eco tool (pollution model) and data collected in field interviews conducted with the use of the CAPI method (Computer-Assisted Personal Interview). In the survey, the interviewer's contact with the respondent was direct, while the information obtained was stored directly on a mobile device. During the research, the interviewers chose people willing to fill in the questionnaire. Therefore, it can be concluded that the sampling in this case was convenient. Conducting a survey using this method has several advantages, such as their comparatively low cost and quick turnaround time, but it can also undermine the representativeness of the sample obtained [135–137]. Given the disadvantages associated with non-probabilistic surveys with respect to sample representativeness, a minimum sample size was calculated. A group of 271 inhabitants of the capital city took part in the questionnaire conducted in the first half of August 2021.

The research allowed us to assess the level of social awareness of air pollution and the importance of trees in big cities. The assessment covered air quality, the impact of polluted air on health, and the ecosystem functions of trees. The assessment of the awareness of the inhabitants of Warsaw was measured on the Likert scale, and summary statistics were applied to further analyse the findings.

Data collected during the inventory with the use of i-Tree Eco tool were used in order to create the pollution model for two representative streets in Warsaw. I-Tree Eco uses the Urban Forest Effects (UFORE) model established by Nowak and Crane [138]. I-Tree Eco is a widely available programming tool developed by the United States Forest Service (USFS); it analyses the structure of urban trees with regard to the composition of species, leaf surface and health condition of trees in order to estimate the value of ecosystem services provided by the trees [138]. I-Tree Eco utilizes the dry deposition component included in the UFORE model to calculate pollution removed by the plants [139].

The guidelines about the research site listed in the i-Tree Eco user manual [140] were used during the field work and comprehensive inventory was carried out on the designated area. The tool requires a detailed tree inventory—species and location of trees were specified and dendrometric measurements were taken: trunk diameter (DBH—diameter at breast height), total tree height (TTH), live tree height (LTH), crown base (CB), crown width N–S (North–South), crown width E–W (East–West), crown percentage miss (CROWN%MISS), crown health (CH) and crown light exposure (CLE). DBH was measured with a caliper at 130 cm above the ground. Crown width N–S and E–W, total tree height, live tree height and crown base were measured with a Bosch GLM120c laser measure with up to 0.5 m accuracy.

Weather details and air quality data recorded in the i-Tree database tool were also included in the model. The meteorological data covered wind speed and height. Based on the metadata of the model, data on PM2.5 concentrations, recorded by monitors installed closest to the locations selected by the researcher, were used. In the case of our study, this was a monitor installed on Aleja Niepodległości Street in Warsaw. The i-Tree database also provides access to meteorological data and air quality details. The model was launched after all the necessary data was entered in the i-Tree Eco, and it provided estimates on the amount of pollutants removed by trees at Marszałkowska Street and Żwirki i Wigury Street.

## 5. Results

### *5.1. Characteristics of the Research Sample*

The field survey was conducted on 271 respondents—inhabitants of 18 districts in Warsaw. 137 men and 134 women aged 18 to 75 comprised the sample group (Figure 4). A total 7% of the respondents either worked or held degrees in the environmental protection.

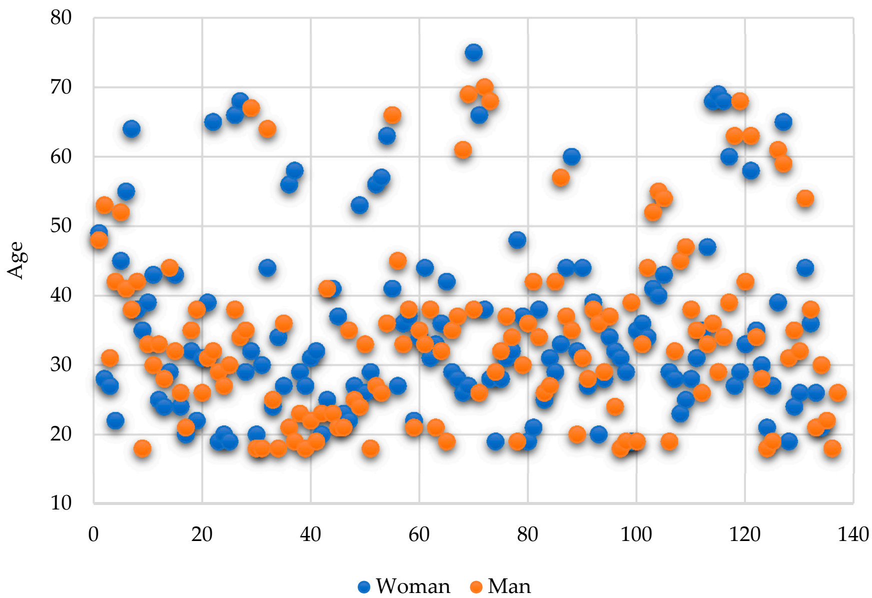



**Figure 4.** Respondent age distribution in the sample group. Source: own study base on the survey.

At later stages of the analysis, the sample group was divided with the used of the quartile method where the age of the respondents served as the decisive criterion. Due to the odd number of observations, the median indicated the middle value. The calculations provided the following age brackets for the respondent group (Table 1).

**Table 1.** Age brackets in the research sample.

| | Values in the Group below the 1st Quartile | Values in the Group between the 1st and 2nd Quartile | Values in the Group between the 2nd and 3rd Quartile | Values in the Group below the 4th Quartile |
|---|---|---|---|---|
| Age bracket | <18;25> | <26;31> | <32;40> | <41;75> |
| Percentage of respondents in each group | 25 | 25 | 25 | 25 |
| Average age in the group | 21 | 29 | 36 | 54 |

Source: own study base on the survey.

### 5.2. The Assessment of the Social Awareness of Air Pollution and Ecosystem Functions of Trees

The level of Warsaw inhabitants' consciousness on the issue of air pollution was studied by the authors. The respondents rated the issue on the scale from 0 to 5, where 0 meant a lack of concern and 5 indicated a high level of concern in the issue. The overview provided below (Table 2) shows that almost 75% of respondents are concerned about air pollution in Warsaw, although on average they do not perceive it as highly concerning. Among people who indicated a lack of concern (0 points on the scale) or a low level of concern (1 point) the most numerous (above 81%) was the 18 to 25-years-old age group.

**Table 2.** Percentage of the respondents' assessment of air quality and their concern for air pollution in Warsaw.

| | | Assessment | | | | | |
|---|---|---|---|---|---|---|---|
| | | **0** | **1** | **2** | **3** | **4** | **5** |
| Concern for the issue of air pollution | General assessment | 5.5 | 8.1 | 11.4 | 45.0 | 22.9 | 7.0 |
| | Assessment in specified age brackets | | | | | | |
| | <18;25> | 19.4 | 29.0 | 17.7 | 19.4 | 9.7 | 4.8 |
| | <26;31> | 1.6 | 1.6 | 11.1 | 61.9 | 15.9 | 7.9 |
| | <32;40> | 1.3 | 2.6 | 9.0 | 62.8 | 17.9 | 6.4 |
| | <41;75> | 1.5 | 1.5 | 8.8 | 32.4 | 47.1 | 8.8 |
| | | % of respondents | | | | | |
| Air quality | General assessment | 1.8 | 22.9 | 38.0 | 21.8 | 14.0 | 1.5 |
| | Assessment in specified age brackets | | | | | | |
| | <18;25> | 3.2 | 12.9 | 24.2 | 21.0 | 35.5 | 3.2 |
| | <26;31> | 0.0 | 17.2 | 56.3 | 20.3 | 3.1 | 3.1 |
| | <32;40> | 1.3 | 17.9 | 47.2 | 25.6 | 6.4 | 1.3 |
| | <41;75> | 2.9 | 42.6 | 22.1 | 19.1 | 13.2 | 0.0 |
| | | % of respondents | | | | | |

where: 0—absolutely unconcerned, 5—absolutely disturbing (Concern for the issue of air pollution). 0—very bad quality, 5—very good quality (Air quality). Source: own study base on the survey.

The residents also assessed air quality on the scale from 0 to 5, where 0 indicated very bad quality and 5 meant very good quality. The overview provided below (Table 2) shows that the majority of respondents (62.7%) indicated bad quality of air in the city, although on average they did not describe the air quality in the capital city as very bad. Bad and very bad air quality was reported most often by respondents aged 41 to 75, while good and very good assessment was given by people aged 18 to 25.

The authors also analysed the residents' perception of the impact on air pollution in Warsaw of such activities as using lignite, plastic, particle board and other unsuitable materials for fuel in central heating; burning waste (rubbish) in home furnaces; operation of CHP plants; exhaust emissions from traffic (e.g., passenger cars, lorries) and exhaust emissions generated by production plants (stacks). The respondents rated the impact of the indicated activities on air pollution in the city on the scale from 0 to 5, where 0 meant the activity of lowest negative impact and 5 indicated the most harmful issue. The overview provided below (Table 3) shows that, depending on the activity, from over 30% to almost 90% of respondents notice their harmful character. The most frequently noted harmful activities were: exhaust emissions from traffic (32.10% of respondents indicated them as harmful and 20.66% as the most harmful) operation of CHP plants (19.93% of level 4 and 5 notes) and the least frequently listed by the residents was using unsuitable materials for fuel in furnaces (5.54% indications of their harmful character and 7.38% of the highest level of harm), which is justified by the location of industrial plants on the outskirts of the city and in localities adjacent to the capital.

**Table 3.** Percentage of the respondents' assessment of the impact of activities on air pollution in Warsaw.

| | **Assessment** | | | | | |
|---|---|---|---|---|---|---|
| | **0** | **1** | **2** | **3** | **4** | **5** |
| Using lignite, plastic, particle board and other unsuitable materials for fuel in central heating | 7.4 | 32.8 | 26.6 | 20.3 | 5.5 | 7.4 |
| Burning waste (rubbish) in home furnaces | 5.5 | 11.4 | 29.3 | 30.6 | 14.0 | 8.5 |
| Exhaust emissions from traffic (e.g., passenger cars, lorries) | 1.1 | 4.4 | 12.2 | 29.5 | 32.1 | 20.7 |
| CHP plants | 2.2 | 8.1 | 27.3 | 36.2 | 19.9 | 6.3 |
| exhaust emissions generated by production plants (stacks) | 6.3 | 26.2 | 26.9 | 27.7 | 7.8 | 5.2 |
| | % of respondents | | | | | |

where: 0—not harmless at all, 5—very harmful. Source: own study base on the survey.

The researchers also attempted to establish the assessment of activities which contribute to reduction of air pollution in Warsaw (Table 4), including chimney stack filters (in industrial plants), renewable energy sources (such as solar photovoltaic panels in lanterns and at bus stops), green belts which separate industrial grounds, the presence of urban parks and forests, green areas and street greenery (such as squares, lawns, meadows), popularisation of using collective transport (urban public transport) and eco-friendly means of transport (such as bicycles). Similar to the previous stages of the research, the respondents assessed the activities on the scale of 0 (does not contribute) to 5 (heavily contributes). In the respondents' opinion, the action which contributes to the reduction of air pollution in Warsaw to the largest extent is the popularisation of individual eco-friendly means of transport (55.7% of level 5 grades) and the presence of urban parks and forests (49.8% of level 5 grades). The popularisation of collective transport (urban public transport—railway, buses and tramways) was graded slightly lower. The respondents considered the activities which involve installation of chimney stack filters (e.g., in industrial plants) to have a visibly smaller significance. Marginal assessment of this activity may suggest (as in the case of the impact of industrial plants on air pollution) that these plants are located on the outskirts of Warsaw or outside the city limits, which is why the respondents did not notice any necessity for action in this scope.

**Table 4.** Percentage of the respondents' assessment of activities which contribute to the reduction of air pollution in Warsaw.

| | **Assessment** | | | | | |
|---|---|---|---|---|---|---|
| **Activity** | **0** | **1** | **2** | **3** | **4** | **5** |
| Chimney stack filters (e.g., in industrial plants) | 6.6 | 29.5 | 29.9 | 25.1 | 6.3 | 2.6 |
| Renewable energy sources (photovoltaic panels in lanterns and at bus stops) | 0.7 | 2.6 | 17.3 | 39.5 | 29.2 | 10.7 |
| Green belts which separate industrial grounds | 5.2 | 16.6 | 29.2 | 31.0 | 12.2 | 5.9 |
| Presence of urban parks and forests | 1.8 | 4.4 | 17.0 | 26.9 | 33.9 | 15.9 |
| Green areas and street greenery (such as squares, lawns, meadows) | 4.1 | 11.8 | 25.1 | 32.8 | 15.1 | 11.1 |
| Popularisation of collective transport (urban public transport—railway, buses and tramways) | 0.7 | 3.0 | 12.9 | 36.2 | 31.0 | 16.2 |
| Popularisation of individual eco-friendly means of transport (e.g., bicycles) | 1.1 | 4.4 | 9.6 | 29.2 | 31.4 | 24.4 |
| | % of respondents | | | | | |

where: 0—it does not contribute at all, 5—contributes a lot. Source: own study base on the survey.

The awareness of the impact of air pollution on health was also subject to analysis (Table 5). Generally speaking, it can be stated that the respondents do not see any correlation between the presence of air pollution and health (75.28% of the responses ranked it at level 2 or lower). Among those who indicated lack of significance between air pollution and health, the largest age group consisted of people aged 18 to 25. Similar results were obtained in the assessment of the awareness of consequences of polluted air on health. The overview shows that all the listed health consequences of air pollution were assessed by the respondents as having low or no impact. The least frequently listed consequences of air pollution were headaches and respiratory problems, while the highest significance was usually given to cancer (with a higher frequency of level 4 and 5 grades).

**Table 5.** Percentage of the respondents' assessment of the impact of polluted air on health.

| | | **Assessment** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **0** | **1** | **2** | **3** | **4** | **5** |
| Impact of polluted air on health | General assessment | 12.9 | 43.2 | 19.2 | 14.0 | 6.3 | 4.4 |
| | Assessment in specified age brackets | | | | | | |
| | <18;25> | 35.5 | 29.0 | 9.7 | 12.9 | 9.7 | 3.2 |
| | <26;31> | 7.9 | 58.7 | 15.9 | 9.5 | 1.6 | 6.3 |
| | <32;40> | 5.1 | 57.7 | 24.4 | 6.4 | 2.6 | 3.8 |
| | <41;75> | 5.9 | 25.0 | 25.0 | 27.9 | 11.8 | 4.4 |
| | | % of respondents | | | | | |

**Table 5.** *Cont.*

| | Assessment | | | | | |
|---|---|---|---|---|---|---|
| | **0** | **1** | **2** | **3** | **4** | **5** |
| Consequences of polluted air on health | | | | | | |
| Chronic bronchitis | 15.5 | 45.0 | 19.6 | 12.5 | 5.2 | 2.2 |
| Runny nose, frequent colds | 20.7 | 42.4 | 18.1 | 8.5 | 6.6 | 3.7 |
| Accelerated process of aging | 43.5 | 26.2 | 10.0 | 8.5 | 8.9 | 3.0 |
| Increased cancer incidence | 45.4 | 25.1 | 8.9 | 7.4 | 8.5 | 4.8 |
| Reduced birth weight in newborns | 66.4 | 13.7 | 7.0 | 7.4 | 4.1 | 1.5 |
| Increased number of high-risk pregnancies and complications | 63.1 | 14.8 | 7.4 | 6.3 | 5.9 | 2.6 |
| Rash | 49.8 | 25.5 | 10.3 | 6.3 | 4.1 | 4.1 |
| Headache | 15.1 | 39.9 | 21.0 | 11.8 | 6.6 | 5.5 |
| Increased number of heart attacks and strokes | 32.1 | 35.4 | 11.8 | 12.9 | 4.8 | 3.0 |
| | % of respondents | | | | | |

where: 0—no impact, 5—influences very strongly (Impact of polluted air on health). 0—without consequences, 5—very high consequences (Consequences of polluted air on health). Source: own study base on the survey.

Another aspect analysed in the course of the research was the residents' perception of the importance of trees in their functions such as the decorative aspect, increased biological diversity of trees and animal species, cooling the air, slowing down precipitation, retention of rainwater, noise protection, reduction of stress and aggression levels and the development of local communities. The overview provided below (Table 6) shows that, in the respondents' opinion, the most significant ecosystem function of trees is the improvement of air quality. Among the ecosystem functions listed here, almost a half of the respondents assessed the impact of trees on the improvement of air quality as highly significant (48.71% of level 5 grades). A similarly large percentage of the interviewees assessed noise protection at a high level (43.54% of level 5 grades). An especially insignificant value was noted by the respondents with regard to the process of development of local communities (almost 50% of them rated it at 0). The function of increased biological diversity of trees and animal species and reduction of stress and aggression was also of low significance to the respondents.

**Table 6.** Percentage of the respondents' assessment of the importance of ecosystem functions of trees.

| | Assessment | | | | | |
|---|---|---|---|---|---|---|
| **Activity** | **0** | **1** | **2** | **3** | **4** | **5** |
| Decorative aspect | 0.7 | 1.8 | 11.1 | 26.2 | 28.8 | 31.4 |
| Increased biological diversity of tree species | 4.4 | 27.7 | 24.4 | 21.8 | 16.2 | 5.5 |
| Increased biological diversity of species (e.g., birds) | 1.1 | 24.0 | 26.9 | 23.2 | 15.5 | 9.2 |
| Cooling the air | 1.1 | 5.2 | 16.2 | 28.8 | 25.5 | 23.2 |
| Slowing down precipitation | 7.0 | 12.9 | 16.6 | 13.7 | 29.9 | 19.9 |
| Air quality improvement | 1.5 | 4.1 | 12.9 | 17.0 | 15.9 | 48.7 |
| Retention of rainwater | 9.2 | 17.3 | 11.1 | 14.8 | 28.4 | 19.2 |
| Noise protection | 0.4 | 7.4 | 15.1 | 18.1 | 15.5 | 43.5 |
| Reduction of stress and aggression levels | 12.5 | 21.4 | 24.7 | 11.8 | 17.3 | 12.2 |
| Development of local communities | 49.4 | 23.2 | 12.5 | 5.5 | 3.0 | 6.3 |
| | % of respondents | | | | | |

where: 0—not relevant at all, 5—even more important. Source: own study base on the survey.

In addition to the ecosystem functions presented here, the awareness of the residents as to the capacity of air pollution (PM2.5 and PM10) absorption by trees was also subject to analysis. Although many respondents are aware of the ecosystem functions of trees, as shown in the analyses above, a relatively low number of them had the awareness of the trees' capacity to absorb particle matter (Table 7). More than a half of the interviewees (57.2%) assessed the trees' capacity to absorb pollution as very low or non-existing. Among the respondents who indicated the lack of said capacity, the largest group (70%) consisted of 18 to 25-year-olds.

**Table 7.** Percentage of the respondents' assessment of the trees' capacity to absorb air pollution (PM2.5 and PM10).

| | | Assessment | | | | | |
|---|---|---|---|---|---|---|---|
| | | **0** | **1** | **2** | **3** | **4** | **5** |
| Absorption of air pollution (PM2.5 and PM10) by trees | General assessment | 12.2 | 45.0 | 21.4 | 11.4 | 5.5 | 4.4 |
| | Assessment in specified age brackets | | | | | | |
| | <18;25> | 37.1 | 27.4 | 9.7 | 17.7 | 4.8 | 3.2 |
| | <26;31> | 4.8 | 61.9 | 15.9 | 7.9 | 6.3 | 3.2 |
| | <32;40> | 3.8 | 67.9 | 16.7 | 3.8 | 5.1 | 2.6 |
| | <41;75> | 5.9 | 19.1 | 42.6 | 17.6 | 5.9 | 8.8 |
| | | % of respondents | | | | | |

where: 0—no possibility, 5—very high possibility. Source: own study base on the survey.

The perception of residents of such elements as the existing biodiversity, the trees' pollution reduction capacity and air-cooling potential, noise protection, retention of rainwater and the decorative aspect were also analysed. The assessment of these elements included both Marszałkowska Street and Żwirki i Wigury Street, where the tree inventory was completed (Table 8). All ecosystem functions of trees at Marszałkowska Street were assessed at very low levels. The only element which has received higher notes than the rest was the decorative aspect, as it may be associated with attractive urban developments in the area. The assessment of the respondents with regard to each of the ecosystem functions of trees at Żwirki i Wigury Street was decidedly higher. The ecosystem functions which received the highest grades were the decorative aspects and the noise protection feature. Despite the fact that the respondents assessed the trees' capacity to absorb air pollution (PM2.5 and PM10) as low, taking into consideration both locations, their assessment was higher in the area with a larger tree cover (Żwirki i Wigury Street).

**Table 8.** Percentage of the respondents' assessment of the significance of highlighted elements of Marszałkowska Street and Żwirki i Wigury Street.

| | **Marszałkowska Street** | | | | | |
|---|---|---|---|---|---|---|
| | **Assessment** | | | | | |
| **Element** | **0** | **1** | **2** | **3** | **4** | **5** |
| Biodiversity | 85.2 | 3.7 | 3.0 | 3.3 | 3.7 | 1.1 |
| Dust reduction provided by trees | 86.0 | 4.8 | 3.0 | 1.8 | 2.6 | 1.8 |
| Cooling down the air | 87.5 | 3.3 | 1.8 | 1.5 | 3.7 | 2.2 |
| Noise protection | 88.6 | 2.6 | 1.5 | 3.7 | 2.6 | 1.1 |
| Retention of rainwater | 88.9 | 3.3 | 1.1 | 2.6 | 2.2 | 1.8 |
| Decorative aspect | 41.0 | 39.5 | 11.1 | 4.4 | 1.8 | 2.2 |
| | % of respondents | | | | | |

**Table 8.** *Cont.*

| | Żwirki i Wigury Street | | | | | |
|---|---|---|---|---|---|---|
| | Assessment | | | | | |
| **Element** | **0** | **1** | **2** | **3** | **4** | **5** |
| Biodiversity | 0.7 | 18.5 | 29.5 | 25.5 | 19.2 | 6.6 |
| Dust reduction provided by trees | 12.9 | 39.9 | 21.8 | 13.7 | 8.5 | 3.3 |
| Cooling down the air | 0.7 | 9.2 | 18.1 | 26.6 | 23.6 | 21.8 |
| Noise protection | 0.4 | 11.1 | 14.4 | 18.8 | 10.7 | 44.6 |
| Retention of rainwater | 10.7 | 17.0 | 12.5 | 13.3 | 31.4 | 15.1 |
| Decorative aspect | 1.5 | 5.5 | 13.3 | 14.4 | 18.1 | 47.2 |
| | % of respondents | | | | | |

where: 0—not relevant at all, 5—even more important. Source: own study base on the survey.

### *5.3. The Assessment of the Capacity of Trees to Absorb Air Pollution*

The second part of the research involved a tree inventory conducted in two locations in Warsaw. As a result of the tree measurement at Marszałkowska Street and Żwirki i Wigury Street taken on 300-metre-long sections of both streets with the i-Tree Eco model the levels of absorption of $O_3$, $NO_2$, CO, $SO_2$ and PM2.5 were calculated. Air pollutants and their production affect human health—at various scales, both local and regional, as well as global [141]. Tropospheric ozone $O_3$ and fine particulate matter (PM2.5) are very dangerous pollutants due to the fact that they contribute to cardiovascular and lung diseases [141–143]. $CO_2$ (carbon dioxide) is considered a major contributor to global temperature increases, with negative impacts on human health manifested as the potential to cause 21,600 additional deaths worldwide [142]. NO is a short-lived intercellular messenger that is important and has many biological functions, e.g., immune function, inflammation—processes that are relevant to the lungs and cardiovascular system. They cause pathophysiology of the cardiovascular system [144]. The findings on PM2.5 pollution point out to changeability in dust absorption over the course of the year and given months in both locations (Figure 5). It can be seen that during winter months, the trees do not absorb PM2.5 impurities due to the lack of leaves. The highest value of PM2.5 absorption was noted in April—one tree at Marszałkowska Street removed 0.083 g of dust on average, while one tree at Żwirki i Wigury Street absorbed 0.52 g. The overview includes also negative readings, caused by the phenomemon of dust retention in the trees observed in May, July and September.

The analyses show changeability in the absorption of impurities (CO, $NO_2$, $O_3$, $SO_2$) by trees (Table 9). It was established in the course of the study that one tree at Marszałkowska Street absorbs an average 89.38 g of pollution per year, while a tree growing at Żwirki i Wigury included in the test absorbs 390.39 g of pollution per year. This phenomenon is caused by the poor quality of trees at Marszałkowska Street; there, they grow in unfavourable conditions, often in spaces covered with paving stones with the exception of tree trunk openings, which in turn results in limited access to water and stilted root growth, trees growing at Żwirki i Wigury Street grow in more natural conditions of open space. The highest capacity of absorption of pollution was recorded in April, May and July for both streets and referred to the absorption of ozone, where the result for individual trees was 4.5 times higher on average at Żwirki i Wigury Street.

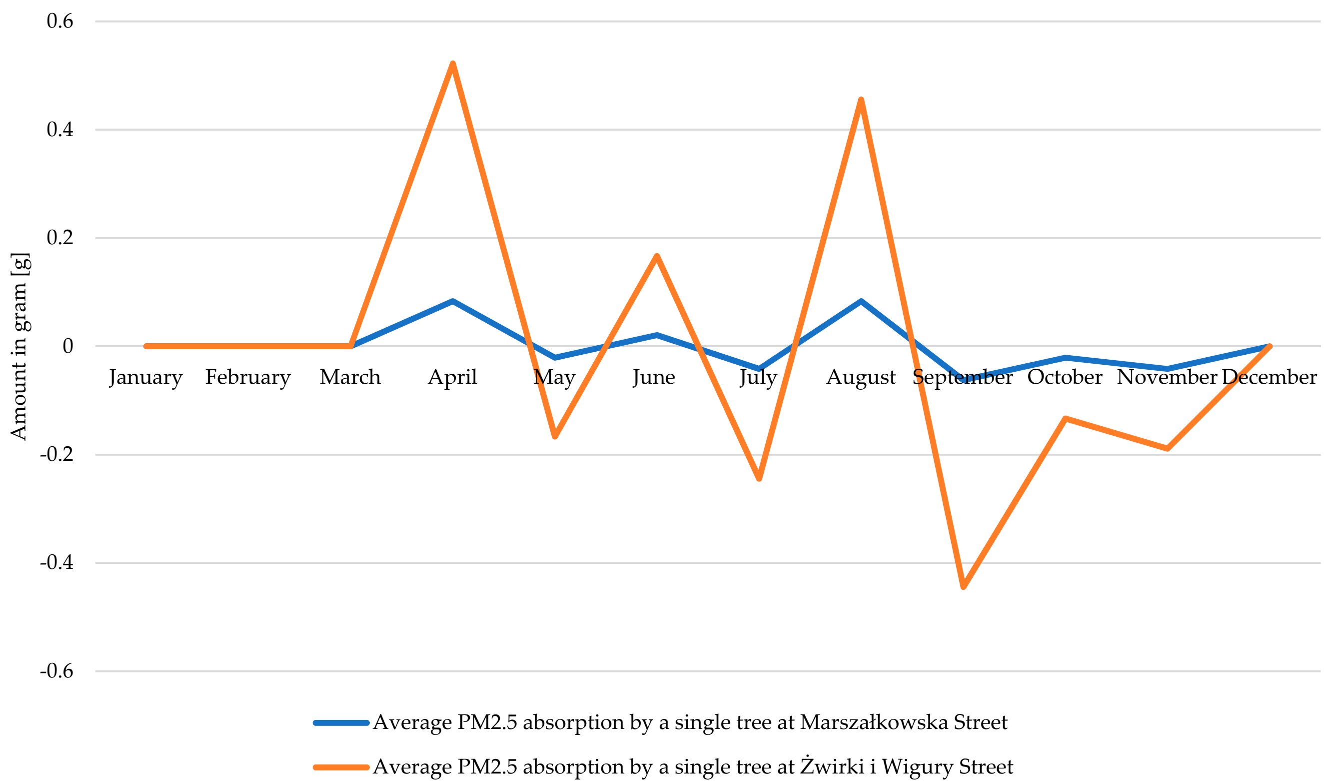



**Figure 5.** Average PM2.5 absorption by a single tree. Source: own study base on the survey.

**Table 9.** Average absorption of impurities: CO, $NO_2$, $O_3$, $SO_2$ by a single tree.

| Average Absorption of Impurities by a Single Tree [g] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Marszałkowska Street | | | | Żwirki i Wigury Street | | | |
| Month | CO | $NO_2$ | $O_3$ | $SO_2$ | CO | $NO_2$ | $O_3$ | $SO_2$ |
| January | 0.04 | 0.77 | 0.50 | 0.10 | 0.09 | 2.99 | 1.98 | 0.41 |
| February | 0.04 | 0.94 | 0.40 | 0.13 | 0.11 | 4.01 | 2.03 | 0.44 |
| March | 0.04 | 1.13 | 0.67 | 0.13 | 0.09 | 4.43 | 2.70 | 0.44 |
| April | 0.31 | 3.69 | 4.85 | 0.29 | 1.24 | 17.99 | 24.99 | 1.33 |
| May | 0.44 | 5.60 | 7.19 | 0.44 | 1.71 | 27.31 | 32.91 | 1.92 |
| June | 0.40 | 5.46 | 8.13 | 0.44 | 1.52 | 26.37 | 36.87 | 1.93 |
| July | 0.38 | 5.08 | 9.23 | 0.44 | 1.49 | 1.49 | 42.07 | 2.01 |
| August | 0.38 | 4.29 | 8.56 | 0.35 | 1.43 | 20.72 | 39.19 | 1.69 |
| September | 0.40 | 4.23 | 4.92 | 0.35 | 1.52 | 20.44 | 22.29 | 1.69 |
| October | 0.31 | 2.60 | 2.40 | 0.31 | 1.27 | 12.57 | 11.14 | 1.43 |
| November | 0.04 | 0.88 | 0.40 | 0.08 | 0.09 | 3.48 | 1.53 | 0.37 |
| December | 0.02 | 0.81 | 0.81 | 0.00 | 0.08 | 3.13 | 3.13 | 0.33 |
| Total | 2.79 | 35.48 | 48.04 | 3.06 | 10.64 | 144.93 | 220.83 | 14.01 |
| Average | 0.23 | 2.96 | 4.00 | 0.26 | 0.89 | 12.08 | 18.40 | 1.17 |

Source: own study base on the survey.

## 6. Discussion

Over the last few decades, the notion of air pollution has become a significant subject of the public debate [145,146]. It comes as a result of growing environmental issues caused by extensive economic development. One of the aspects which contributes to economic development is the constant process of urbanisation. Green areas are commonly transformed into concrete squares, shopping galleries or residential estates, which in turn causes further decline in the amount of greenery in the cities or making them worse [147]. The result is the intensification of smog and an increase in air pollution in urban agglomerations. Recently, both mass media and local communities have started to popularise activities which contribute to mitigation of urban air pollution, which is also confirmed by the results obtained. Planting trees is one of those activities, and, as research shows, they are the most effective biological absorbers of particle matter and other sources of pollution [34]. However, according to our study, trees with smaller crowns (of poorer condition) have lower ecosystem service effectiveness. Similar results were also obtained by other authors, who indicate that the location of trees affects their ecological functions and is important in the removal potential of air pollutants [148,149].

It is reasonable to assume that this relationship also applies to new plantings, the presence of which, according to research conducted in megacities, would increase the value of ecosystem services by 85% [150]. It is therefore justified to promote activities which lead to an increase in the tree cover. It is therefore reasonable to promote activities aimed at increasing the area of wooded land, but especially protection of existing trees and concern for their site conditions [151]. That is why raising the social awareness of ecosystem functions of trees, effectiveness and the issue of air pollution in the cities has become such a crucial topic. Previous studies conducted both in Poland and abroad show that social awareness of air pollution is quite varied, although a rather low level of awareness is often indicated [41,44,45,152]. In addition, a UK study found not only low awareness of tree ecosystem services among residents, but also noted the willingness of residents to remove trees due to problems with blocking sunlight or leaf fall [153]. It generates the need for educational activities which involve learning about the features of residents with different levels of awareness of air pollution and, especially, its impact on their health.

The analyses show that the majority of respondents in Warsaw is concerned with the problem of air pollution in the city, although on average it was not deemed a truly alarming issue. Wang et al. [154] obtained similar results, where 92.28% of the residents of Zibo showed concern or a high level of concern about air pollution in the city. As in our study, residents usually noticed the impact of detrimental activities on the quality of air in the capital. They quoted exhaust emissions from traffic and the operation of CHP plants as two factors which most heavily contribute to the problem. This is in line with the findings of the research Chin et al. [41] conducted—according to them, the majority of respondents were aware of the fact that engine cars create the major source of pollution in the city. The respondents also assessed the activities which are meant to alleviate air pollution in the capital. The highest rated solution was the popularisation of individual eco-friendly means of transport and the presence of parks and forests in the city. These findings differ from the ones collected by Wang et al. [154] where over 75% of the respondents pointed out that using public transport is the main activity which contributes to the reduction of air pollution. This is the first time that a study of the importance of green space and awareness of its ecosystem services has been conducted in a small number of cities in Poland. In the case of one of these cities, residents indicated that green space was valued for its recreational value [155]. In another, residents indicated that they valued the decorative, environmental and recreational aspects [156]. In the case of the Warsaw study, the most important ecosystem function provided by trees was improving air quality. Similar results were obtained in a Hong Kong survey, in which respondents pointed to the microclimatic benefits of green spaces rather than their social or recreational functions [157]. There is also consensus in support for two other microclimatic functions, namely cooling of air temperature and protection from noise. The moderate support given to air-cooling is consistent with studies conducted in Helsinki and New Zealand [158,159]; however, it contrasts with the results of similar studies where this function is rated as very important [157,160,161]. Warsaw residents also rated the noise protection function highly, which contrasts with the results of similar studies where the rating of this element was low [157,160,162,163].

One of the most interesting findings of this study is that residents rated the function of lowering stress and aggression low. However, this factor is highly valued in many studies [158,164–166]. Additionally, despite the function of improving air quality being identified as the most important, residents' awareness of the ability of trees to absorb pollutants was low, which is consistent with a study conducted in Rotterdam that indicated residents' unawareness of the ability of green infrastructure to adapt to climate change [167]. Moreover, the low assessment of the impact of air pollution on health by residents in Warsaw is worrying, which contrasts with results conducted in Helsinki, Hong Kong or Kalton, where this aspect was treated as a key attribute [157,165,168]. It is worth noting that the demonstration of the relationship between air pollution and health in the literature has been widely reported for both children and adults [169–175].

## 7. Conclusions

The city residents also identified the ecosystem functions of trees; for them, the most crucial aspect of that was the improvement of air quality. However, when comparing the two locations, the awareness and the effectiveness of the tree work was higher, especially with a planting density considered to be optimal. However, despite the fact that the above notion was ranked as the most important one, the awareness of the interviewees on the ability of the trees to absorb particle matter was rather low. While comparing both locations, it was established that the awareness was higher in the area with a higher tree cover. The assessment of the potential to absorb pollutants indicated by trees growing at two different streets was in line with the results obtained in the pollution model prepared with the help of the i-Tree Eco tool.

The analysis of the model data has shown that, on average, a single tree surrounded by concrete areas has the capacity to absorb pollution at a level four times lower than that of a tree located at the side of the street surrounded with greenery with optimal habitat conditions and saturation. This phenomenon may be caused by adverse conditions of tree growth at Marszałkowska Street. The results of the analysis indicate that it is necessary to conduct information campaigns on the ecosystem services of trees and their proper care in the urban space among local communities, media, as well as local authorities and NGOs. These campaigns should be conducted for different age groups, so that the message can be adjusted to the age of the recipients.

It is worth noting that, in most of the analysed cases of social awareness of air pollution and related issues, the lowest awareness and knowledge was shown by respondents aged 18–25. Assessment of awareness of people of this age was not positioned in other air pollution awareness studies. The results of the study may cause concern, as it was found that Warsaw residents do not recognise the impact of air pollution on their health (as indicated by as many as 75% of respondents).

However, a number of limitations of the survey conducted among Warsaw residents should be noted. First, the residents' opinion was obtained using convenience sampling techniques and there are no representative samples of the surveyed population; thus, it becomes necessary to repeat the survey in a representative sample in order to be able to generalize the results to the entire city population. In addition, the selection of ecosystem services, air pollution mitigation activities could be expanded or replaced by other elements. In addition, the study could be extended the use of interviews to be able to explore more deeply the awareness of residents. Third, while the survey results suggest consensus for some ecosystem services or air pollution awareness, they also indicate that there are differences in relation to tree benefits.

The present study is a step towards a better understanding of how urban residents evaluate the benefits associated with trees. From both a theoretical and policy perspective, this topic is of great importance when it comes to urban development and proper care of urban spaces. The results of the study support the thesis of the desirability of spreading public awareness in this area as well, although firm conclusions require further comprehensive research.

**Author Contributions:** Conceptualization, K.K. and M.G.; methodology, K.K. and M.G.; software, K.K.; validation, M.G.; formal analysis, K.K. and M.G.; resources, K.K. and M.G.; writing—original draft preparation, K.K., M.G. and M.S.; writing—review and editing, M.G. and M.S.; visualization, M.G.; supervision, M.G.; project administration, K.K. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Khelfi, A. Sources of Air Pollution. In *Handbook of Research on Microbial Tools for Environmental Waste Management*; Pathak, V.M., Navneet, Eds.; IGI Global Publisher of Timely Knowledge: Hershey, PA, USA, 2008.
2. EEA. *Climate Change, Impacts and Vulnerability in Europe 2012; An Indicator-Based Report*; EEA: Copenhagen, Denmark, 2012.
3. Jasiński, R.; Galant-Gołębiewska, M.; Nowak, M.; Ginter, M.; Kurzawska, P.; Kurtyka, K.; Maciejewska, M. Case Study of Pollution with Particulate Matter in Selected Locations of Polish Cities. *Energies* **2021**, *14*, 2529. [CrossRef]
4. Pappa, A.; Kioutsioukis, I. Forecasting Particulate Pollution in an Urban Area: From Copernicus to Sub-Km Scale. *Atmosphere* **2021**, *12*, 881. [CrossRef]
5. Juneng, L.; Latif, M.T.; Tangang, F. Factors influencing the variations of PM10 aerosol dust in Klang Valley, Malaysia during the summer. *Atmos. Environ.* **2011**, *45*, 4370–4378. [CrossRef]
6. Chen, S.C.; Liao, C.M. Health risk assessment on human exposed to environmental polycyclic aromatic hydrocarbons pollution sources. *Sci. Total Environ.* **2006**, *366*, 112–123. [CrossRef] [PubMed]
7. Duan, J.; Chen, Y.; Fang, W.; Su, Z. Characteristics and Relationship of PM, PM10, PM2.5 Concentration in a Polluted City in Northern China. *Procedia Eng.* **2015**, *102*, 1150–1155. [CrossRef]
8. Donzelli, G.; Cioni, L.; Cancellieri, M.; Llopis-Morales, A.; Morales-Suárez-Varela, M. Air Quality during COVID-19 Lockdown. *Encyclopedia* **2021**, *1*, 519-526. [CrossRef]
9. Foszcz, D.; Niedoba, T.; Siewior, J. Models of Air Pollution Propagation in the Selected Region of Katowice. *Atmosphere* **2021**, *12*, 695. [CrossRef]
10. Kurt, O.K.; Zhang, J.; Pinkerton, K.E. Pulmonary Health Effects of Air Pollution. *Curr. Opin. Pulm. Med.* **2016**, *22*, 138–143. [CrossRef]
11. Fantke, P.; Jolliet, O.; Evans, J.S.; Apte, J.S.; Cohen, A.J.; Hänninen, O.O.; Hurley, F.; Jantunen, M.J.; Jerrett, M.; Levy, J.I.; et al. Health effects of fine particulate matter in life cycle impact assessment: Findings from the Basel Guidance Workshop. *Int. J. Life Cycle Assess.* **2014**, *20*, 276–288. [CrossRef]
12. Dockery, D.W.; Pope, C.A.; Xu, X.; Spengler, J.D.; Ware, J.H.; Fay, M.E.; Ferris, B.G.J.; Speizer, F.E. An Association between Air Pollution and Mortality in Six U.S. Cities. *N. Engl. J. Med.* **1993**, *329*, 1753–1759. [CrossRef]
13. Wan Mahiyuddin, W.R.; Sahani, M.; Aripin, R.; Latif, M.T.; Thach, T.Q.; Wong, C.M. Short-term effects of daily air pollution on mortality. *Atmos. Environ.* **2013**, *65*, 69–79. [CrossRef]
14. ChooChuay, C.; Pongpiachan, S.; Tipmanee, D.; Suttinun, O.; Deelaman, W.; Wang, Q.; Xing, L.; Li, G.; Han, Y.; Palakun, J.; et al. Impacts of PM2.5 sources on variations in particulate chemical compounds in ambient air of Bangkok, Thailand. *Atmos. Pollut. Res.* **2020**, *11*, 1657–1667. [CrossRef]
15. WHO World Health Organization. Available online: https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health (accessed on 14 August 2021).
16. Sicard, P.; Agathokleous, E.; De Marco, A.; Paoletti, E.; Calatayud, V. Urban population exposure to air pollution in Europe over the last decades. *Environ. Sci. Eur.* **2021**, *33*, 28. [CrossRef]
17. Gulia, S.; Shiva Nagendra, S.M.; Khare, M.; Khanna, I. Urban air quality management—A review. *Atmos. Pollut. Res.* **2015**, *6*, 286–304. [CrossRef]
18. Zhang, C.; Wohlhueter, R.; Zhang, H. Genetically modified foods: A critical review of their promise and problems. *Food Sci. Hum. Wellness* **2016**, *5*, 116–123. [CrossRef]
19. Dominick, D.; Juahir, H.; Latif, M.T.; Zain, S.M.; Aris, A.Z. Spatial assessment of air quality patterns in Malaysia using multivariate analysis. *Atmos. Environ.* **2012**, *60*, 172–181. [CrossRef]
20. Population Reference Bureau. *World Population Highlights: Key Findings from PRB's 2007 World Population Data Sheet*; Population Reference Bureau: Washington, DC, USA, 2007.
21. FAO. *Guidelines on Urban and Peri-Urban Forestry*; FAO Forestry Paper No. 178; FAO: Rome, Italy, 2016.
22. *World Urbanization Prospects Highlights (ST/ESA/SER.A/421)*; United Nations: New York, NY, USA, 2019.

23. Ünal, Y.S.; Sonuç, C.Y.; Incecik, S.; Topcu, H.S.; Diren-Üstün, D.H.; Temizöz, H.P. Investigating urban heat island intensity in Istanbul. *Theor. Appl. Climatol.* **2019**, *139*, 175–190. [CrossRef]
24. Pishgar-Komleh, S.H.; Zylowski, T.; Rozakis, S.; Kozyra, J. Efficiency under different methods for incorporating undesirable outputs in an LCA+DEA framework: A case study of winter wheat production in Poland. *J. Environ. Manag.* **2020**, *260*, 110–138. [CrossRef] [PubMed]
25. Huang, K.; Li, X.; Liu, X.; Seto, K.C. Projecting global urban land expansion and heat island intensification through 2050. *Environ. Res. Lett.* **2019**, *14*, 114037. [CrossRef]
26. Aslam, B.; Maqsoom, A.; Khalid, N.; Ullah, F.; Sepasgozar, S. Urban Overheating Assessment through Prediction of Surface Temperatures: A Case Study of Karachi, Pakistan. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 539. [CrossRef]
27. Branea, A.-M.; Gaman, M.S.; Badescu, S.; Ana-Maria, B.; Mihai-Ionut, D.; Stelian, G.M.; Ștefana, B. Challanges Regarding the Study of Urban Heat Islands. Ruleset for Researchers. In Proceedings of the International Conference: The Risk Reduction for Resilient Cities, Bucharest, Romania, 3–4 November 2016.
28. Perpina Castillo, C.; Kavalov, B.; Jacobs-Crisioni, C.; Baranzelli, C.; Batista e Silva, F.; Lavalle, C.; Perpina Castillo, C.; Kavalov, B.; Jacobs-Crisioni, C.; Baranzelli, C.; et al. *Main land-use patterns in the EU within 2015-2030*; Joint Research Centre (Seville Site): Brussels, Belgium, 2019.
29. Tu, L.; Qin, Z.; Li, W.; Geng, J.; Yang, L.; Zhao, S.; Zhan, W.; Wang, F. Surface urban heat island effect and its relationship with urban expansion in Nanjing, China. *J. Appl. Remote Sens.* **2016**, *10*, 026037. [CrossRef]
30. Akbari, H.; Pomerantz, M.; Taha, H. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Sol. Energy* **2001**, *70*, 295–310. [CrossRef]
31. Escobedo, F.J.; Kroeger, T.; Wagner, J.E. Urban forests and pollution mitigation: Analyzing ecosystem services and disservices. *Environ. Pollut.* **2011**, *159*, 2078–2087. [CrossRef] [PubMed]
32. Sawidis, T.; Breuste, J.; Mitrovic, M.; Pavlovic, P.; Tsigaridas, K. Trees as bioindicator of heavy metal pollution in three European cities. *Environ. Pollut.* **2011**, *159*, 3560–3570. [CrossRef] [PubMed]
33. Greksa, A.; Ljevnaić-Mašić, B.; Grabić, J.; Benka, P.; Radonić, V.; Blagojević, B.; Sekulić, M. Potential of urban trees for mitigating heavy metal pollution in the city of Novi Sad, Serbia. *Environ. Monit. Assess.* **2019**, *191*, 636. [CrossRef]
34. Przybysz, A.; Nersisyan, G.; Gawroński, S.W. Removal of particulate matter and trace elements from ambient air by urban greenery in the winter season. *Environ. Sci. Pollut. Res.* **2018**, *26*, 473–482. [CrossRef]
35. Xu, X.; Xia, J.; Gao, Y.; Zheng, W. Additional focus on particulate matter wash-off events from leaves is required: A review of studies of urban plants used to reduce airborne particulate matter pollution. *Urban For. Urban Green.* **2020**, *48*, 126559. [CrossRef]
36. Central Statistical Office. *Population in Cities in% of the Total Population in Poland*; Central Statistical Office: Warsaw, Poland, 2020.
37. Pauchard, A.; Aguayo, M.; Peña, E.; Urrutia, R. Multiple effects of urbanization on the biodiversity of developing countries: The case of a fast-growing metropolitan area (Concepción, Chile). *Biol. Conserv.* **2006**, *127*, 272–281. [CrossRef]
38. Mencwel, J. *Betonoza. Jak Się Niszczy Polskie Miasta*; Wydawnictwo Krytyki Politycznej: Warszawa, Poland, 2020; ISBN 978-83-66586-25-3.
39. Central Statistical Office. *Nasadzenia i Ubytki wg Lokalizacji w Powiatach—Plantings and Cavities by Location in Counties*; Central Statistical Office: Warsaw, Poland, 2019.
40. Munro, N. Profiling the Victims: Public awareness of pollution-related harm in China. *J. Contemp. China* **2014**, *23*, 314–329. [CrossRef]
41. Chin, Y.S.J.; De Pretto, L.; Thuppil, V.; Ashfold, M.J. Public awareness and support for environmental protection—A focus on air pollution in peninsular Malaysia. *PLoS ONE* **2019**, *14*, e0212206. [CrossRef]
42. Ramírez, A.S.; Ramondt, S.; Van Bogart, K.; Perez-Zuniga, R. Public Awareness of Air Pollution and Health Threats: Challenges and Opportunities for Communication Strategies To Improve Environmental Health Literacy. *J. Health Commun.* **2019**, *24*, 75–83. [CrossRef]
43. Saksena, S. *Public Perceptions of Urban Air Pollution with a Focus on Developing Countries*; East-West Center: Honolulu, HI, USA, 2007.
44. Piekut, A.; Dziubanek, G. Awareness of environmental health risks in selected social groups in Silesian voivodeship. *Ann. Acad. Med. Silesiensis* **2012**, *66*, 34–44.
45. Adamkiewicz, Ł. Polish people awareness on the impact of air pollution on health. *Sci. J. Mil. Inst. Health. Serv.* **2016**, *94*, 28–31.
46. Daily, G.C. *Nature's Services: Societal Dependence on Natural Ecosystems*; Island Press: Washington, DC, USA, 1997; pp. 1–19.
47. Reid, W. Millennium Ecosystem Assessment. *Ann. N. Y. Acad. Sci.* **2008**, *1134*, 25–60.
48. Costanza, R.; D'Arge, R.; de Groot, R.; Farber, S.; Grasso, M.; Hannon, B.; Limburg, K.; Naeem, S.; O'Neill, R.V.; Paruelo, J.; et al. The value of the world's ecosystem services and natural capital. *Nature* **1997**, *387*, 253–260. [CrossRef]
49. Gómez-Baggethun, E.; Gren, Å.; Barton, D.N.; Langemeyer, J.; McPhearson, T.; O'Farrell, P.; Andersson, E.; Hamstead, Z.; Kremer, P. Urban Ecosystem Services. In *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities: A Globle Assessment*; Springer: Dordrecht, The Netherlands, 2013; pp. 175–251. [CrossRef]
50. Langemeyer, J.; Gómez-Baggethun, E.; Haase, D.; Scheuer, S.; Elmqvist, T. Bridging the gap between ecosystem service assessments and land-use planning through Multi-Criteria Decision Analysis (MCDA). *Environ. Sci. Policy* **2016**, *62*, 45–56. [CrossRef]

51. Haase, D.; Larondelle, N.; Andersson, E.; Artmann, M.; Borgström, S.; Breuste, J.; Gomez-Baggethun, E.; Gren, Å.; Hamstead, Z.; Hansen, R.; et al. A Quantitative Review of Urban Ecosystem Service Assessments: Concepts, Models, and Implementation. *AMBIO* **2014**, *43*, 413–433. [CrossRef] [PubMed]
52. Salmond, J.A.; Tadaki, M.; Vardoulakis, S.; Arbuthnott, K.; Coutts, A.; Demuzere, M.; Dirks, K.N.; Heaviside, C.; Lim, S.; Macintyre, H.; et al. Health and climate related ecosystem services provided by street trees in the urban environment. *Environ. Health* **2016**, *15*, 95–111. [CrossRef] [PubMed]
53. La Rosa, D.; Wiesmann, D. Land cover and impervious surface extraction using parametric and non-parametric algorithms from the open-source software R: An application to sustainable urban planning in Sicily. *GIScience Remote Sens.* **2013**, *50*, 231–250. [CrossRef]
54. Jennings, V.; Larson, L.; Yun, J. Advancing Sustainability through Urban Green Space: Cultural Ecosystem Services, Equity, and Social Determinants of Health. *Int. J. Environ. Res. Public Health* **2016**, *13*, 196. [CrossRef]
55. Jim, C.Y.; Chen, W.Y. Ecosystem services and valuation of urban forests in China. *Cities* **2009**, *26*, 187–194. [CrossRef]
56. Benedict, M.A.; McMahon, E.T. *Green Infrastructure. Linking Landscapes and Communities*; Island Press: Washington, DC, USA, 2012.
57. Ahern, J. Green infrastructure for cities: The spatial dimension. In *Cities of the Future: Towards Integrated Sustainable Water and Landscape Management*; Novotny, V., Brown, P., Eds.; IWA Publishing: London, UK, 2007; pp. 267–283.
58. Wu, J. Urban ecology and sustainability: The state of the science and future directions. *Landsc. Urban Plan.* **2014**, *125*, 209–221. [CrossRef]
59. Lovell, S.T.; Taylor, J.R. Supplying urban ecosystem services through multifunctional green infrastructure in the United States. *Landsc. Ecol.* **2013**, *28*, 1447–1463. [CrossRef]
60. Feng, X.; Porporato, A.; Rodriguez-Iturbe, I. Changes in rainfall seasonality in the tropics. *Nat. Clim. Chang.* **2013**, *3*, 811–815. [CrossRef]
61. Jim, C.Y. Highrise Greenery: Ancient Invention with New Lease of Life. In *Advances in 21st Century Human Settlements*; Dahiya, B., D'Silva, L., Eds.; Springer: Singapore, 2017; pp. 227–249.
62. Silvera Seamans, G. Mainstreaming the environmental benefits of street trees. *Urban For. Urban Green.* **2013**, *12*, 2–11. [CrossRef]
63. Roy, S.; Byrne, J.; Pickering, C. A systematic quantitative review of urban tree benefits, costs, and assessment methods across cities in different climatic zones. *Urban For. Urban Green.* **2012**, *11*, 351–363. [CrossRef]
64. Day, S.D.; Dove, J.E.; Bartens, J.; Harris, J.R. Stormwater Management that Combines Paved Surfaces and Urban Trees. *GeoCongress* **2008**, 1129–1136. [CrossRef]
65. Xiao, Q.; McPherson, E.G.; Simpson, J.R.; Ustin, S.L. Rainfall interception by Sacramento's urban forest. *J. Arboric.* **1998**, *24*, 235–244.
66. Villarreal, E.L.; Semadeni-Davies, A.; Bengtsson, L. Inner city stormwater control using a combination of best management practices. *Ecol. Eng.* **2004**, *22*, 279–298. [CrossRef]
67. Donovan, G.H.; Butry, D.T. The value of shade: Estimating the effect of urban trees on summertime electricity use. *Energy Build.* **2009**, *41*, 662–668. [CrossRef]
68. Hystad, P.; Davies, H.W.; Frank, L.; Van Loon, J.; Gehring, U.; Tamburic, L.; Brauer, M. Residential Greenness and Birth Outcomes: Evaluating the Influence of Spatially Correlated Built-Environment Factors. *Environ. Health Perspect.* **2014**, *122*, 1095–1102. [CrossRef]
69. Coombes, E.; Jones, A.P.; Hillsdon, M. The relationship of physical activity and overweight to objectively measured green space accessibility and use. *Soc. Sci. Med.* **2010**, *70*, 816–822. [CrossRef]
70. Hansmann, R.; Hug, S.M.; Seeland, K. Restoration and stress relief through physical activities in forests and parks. *Urban For. Urban Green.* **2007**, *6*, 213–225. [CrossRef]
71. Frank, L.D.; Schmid, T.L.; Sallis, J.F.; Chapman, J.; Saelens, B.E. Linking objectively measured physical activity with objectively measured urban form: Findings from SMARTRAQ. *Am. J. Prev. Med.* **2005**, *28*, 117–125. [CrossRef]
72. Hartig, T.; Staats, H. The need for psychological restoration as a determinant of environmental preferences. *J. Environ. Psychol.* **2006**, *26*, 215–226. [CrossRef]
73. Roe, J.; Aspinall, P. The restorative benefits of walking in urban and rural settings in adults with good and poor mental health. *Health Place* **2011**, *17*, 103–113. [CrossRef] [PubMed]
74. Stigsdotter, U.K.; Ekholm, O.; Schipperijn, J.; Toftager, M.; Kamper-Jørgensen, F.; Randrup, T.B. Health promoting outdoor environments—Associations between green space, and health, health-related quality of life and stress based on a Danish national representative survey. *Scand. J. Public Health* **2010**, *38*, 411–417. [CrossRef] [PubMed]
75. Van den Berg, A.E.; Maas, J.; Verheij, R.A.; Groenewegen, P.P. Green space as a buffer between stressful life events and health. *Soc. Sci. Med.* **2010**, *70*, 1203–1210. [CrossRef]
76. Donovan, G.H.; Michael, Y.L.; Butry, D.T.; Sullivan, A.D.; Chase, J.M. Urban trees and the risk of poor birth outcomes. *Health Place* **2011**, *17*, 390–393. [CrossRef]
77. Laurent, O.; Wu, J.; Li, L.; Milesi, C. Green spaces and pregnancy outcomes in Southern California. *Health Place* **2013**, *24*, 190–195. [CrossRef]
78. Freeman, C.; Dickinson, K.J.M.; Porter, S.; van Heezik, Y. "My garden is an expression of me": Exploring householders' relationships with their gardens. *J. Environ. Psychol.* **2012**, *32*, 135–143. [CrossRef]

79. Cook, E.M.; Hall, S.J.; Larson, K.L. Residential landscapes as social-ecological systems: A synthesis of multi-scalar interactions between people and their home environment. *Urban Ecosyst.* **2011**, *15*, 19–52. [CrossRef]
80. Casado-Arzuaga, I.; Madariaga, I.; Onaindia, M. Perception, demand and user contribution to ecosystem services in the Bilbao Metropolitan Greenbelt. *J. Environ. Manag.* **2013**, *129*, 33–43. [CrossRef] [PubMed]
81. Urgenson, L.S.; Prozesky, H.E.; Esler, K.J. Stakeholder Perceptions of an Ecosystem Services Approach to Clearing Invasive Alien Plants on Private Land. *Ecol. Soc.* **2013**, *18*, 26. [CrossRef]
82. Holahan, C.J. Environmental Psychology. *Annu. Rev. Psychol.* **2003**, *37*, 381–407. [CrossRef]
83. Ajzen, I. The Theory of Planned Behavior. *Organ. Behav. Hum. Decis. Process.* **1991**, *50*, 179–211. [CrossRef]
84. Stern, P.C.; Dietz, T.; Abel, T.; Guagnano, G.; Kalof, L. A Value-Belief-Norm Theory of Support for Social Movements: The Case of Environmentalism. *Hum. Ecol. Rev.* **1999**, *6*, 81–97.
85. Baur, J.W.R.; Tynon, J.F.; Ries, P.; Rosenberger, R.S. Public attitudes about urban forest ecosystem services management: A case study in Oregon cities. *Urban For. Urban Green.* **2016**, *17*, 42–53. [CrossRef]
86. Milfont, T.L.; Duckitt, J.; Wagner, C. A Cross-Cultural Test of the Value–Attitude–Behavior Hierarchy. *J. Appl. Soc. Psychol.* **2010**, *40*, 2791–2813. [CrossRef]
87. Homer, P.M.; Kahle, L.R. A Structural Equation Test of the Value-Attitude-Behavior Hierarchy. *J. Pers. Soc. Psychol.* **1988**, *54*, 638–646. [CrossRef]
88. Jones, R.E.; Davis, K.L.; Bradford, J. The Value of Trees: Factors Influencing Homeowner Support for Protecting Local Urban Trees. *Environ. Behav.* **2012**, *45*, 650–676. [CrossRef]
89. Balram, S.; Dragićević, S. Attitudes toward urban green spaces: Integrating questionnaire survey and collaborative GIS techniques to improve attitude measurements. *Landsc. Urban Plan.* **2005**, *71*, 147–162. [CrossRef]
90. Kaltenborn, B.P.; Bjerke, T. Associations between environmental value orientations and landscape preferences. *Landsc. Urban Plan.* **2002**, *59*, 1–11. [CrossRef]
91. Tzoulas, K.; Korpela, K.; Venn, S.; Yli-Pelkonen, V.; Kaźmierczak, A.; Niemela, J.; James, P. Promoting ecosystem and human health in urban areas using Green Infrastructure: A literature review. *Landsc. Urban Plan.* **2007**, *81*, 167–178. [CrossRef]
92. Schroeder, H.; Flannigan, J.; Coles, R. Residents' Attitudes Toward Street Trees in the UK and U.S. Communities. *Arboric. Urban For.* **2006**, *32*, 236–246.
93. Taylor, M.S.; Wheeler, B.W.; White, M.P.; Economou, T.; Osborne, N.J. Research note: Urban street tree density and antidepressant prescription rates—A cross-sectional study in London, UK. *Landsc. Urban Plan.* **2015**, *136*, 174–179. [CrossRef]
94. De Vries, S.; van Dillen, S.M.E.; Groenewegen, P.P.; Spreeuwenberg, P. Streetscape greenery and health: Stress, social cohesion and physical activity as mediators. *Soc. Sci. Med.* **2013**, *94*, 26–33. [CrossRef]
95. Peckham, S.C.; Duinker, P.N.; Ordóñez, C. Urban forest values in Canada: Views of citizens in Calgary and Halifax. *Urban For. Urban Green.* **2013**, *12*, 154–162. [CrossRef]
96. Heynen, N. Green Urban Political Ecologies: Toward a Better Understanding of Inner-City Environmental Change. *Environ. Plan. A* **2016**, *38*, 499–516. [CrossRef]
97. Tallis, H.; Polasky, S. Mapping and Valuing Ecosystem Services as an Approach for Conservation and Natural-Resource Management. *Year Ecol. Conserv. Biol.* **2009**, *1162*, 265–283. [CrossRef] [PubMed]
98. Heberlein, T.A. Navigating Environmental Attitudes. *Conserv. Biol.* **2012**, *26*, 583–585. [CrossRef]
99. López-Marrero, T.; Meyn, M.; Nieves-Crespo, H.I.; Morales-López, R.; Balloffet, N.M. *Public Knowledge and Perceptions about Urban Forests in a Watershed Context; ConoBosque Briefing*; Misión Industrial de Puerto Rico: San Juan, PR, USA, 2011.
100. Santiago, L.; Gladkikh, T.; Betancourt, L.; Vargas, Y. Green versus Gray: Attitudes toward Vegetation in a Tropical Metropolitan Square. *Environ. Nat. Resour. Res.* **2015**, *5*, 109–120. [CrossRef]
101. Fish, R.D. Environmental decision making and an ecosystems approach: Some challenges from the perspective of social science. *Prog. Phys. Geogr. Earth Environ.* **2011**, *35*, 671–680. [CrossRef]
102. Laurans, Y.; Mermet, L. Ecosystem services economic valuation, decision-support system or advocacy? *Ecosyst. Serv.* **2014**, *7*, 98–105. [CrossRef]
103. Zhang, K.; Wen, Z. Review and challenges of policies of environmental protection and sustainable development in China. *J. Environ. Manag.* **2008**, *88*, 1249–1261. [CrossRef] [PubMed]
104. Kuklinska, K.; Wolska, L.; Namiesnik, J. Air quality policy in the U.S. and the EU—A review. *Atmos. Pollut. Res.* **2015**, *6*, 129–137. [CrossRef]
105. Köhler, A. Wmo's activities on background atmospheric pollution and integrated monitoring and research. *Environ. Monit. Assess.* **1988**, *11*, 253–268. [CrossRef]
106. Wettestad, J. The Convention on Long-Range Transboundary Air Pollution (CLRTAP). In *Environmental Regime Effectiveness: Confronting Theory with Evidence*; Miles, E.L., Underdal, A., Andresen, S., Wettestad, J., Skjaerseth, J.B., Carlin, E.M., Eds.; The MIT Press: London, UK, 2001.
107. UNEP. *Actions on Air Quality: Policies and Programmes for Improving Air Quality around the World*; UNEP: Nairobi, Kenya, 2016.
108. Holman, C.; Harrison, R.; Querol, X. Review of the efficacy of low emission zones to improve urban air quality in European cities. *Atmos. Environ.* **2015**, *111*, 161–169. [CrossRef]
109. Government Digital Service Transport for London. Available online: https://tfl.gov.uk/modes/driving/low-emission-zone (accessed on 3 August 2021).

110. Jones, R. Business News Wales. Available online: https://businessnewswales.com/port-talbots-new-5-6m-integrated-transport-hub-opens/ (accessed on 1 August 2021).
111. Hesketh, R.E.; Hinrichs-Krapels, S.; Jones, L.E.B. King's College London. Available online: https://www.kcl.ac.uk/sspp/policy-institute/publications/Air-quality-improvement-initiatives-in-other-cities.pdf (accessed on 5 August 2021).
112. Porter, C.; Kall, D.; Selin, T.; Baker, R.; Kishan, S.; Preusse, D.; Stanard, A. *Evaluate the Interactions between Transportation-Related Particulate Matter, Ozone, Air Toxics, Climate Change, and Other Air-Pollutant Control Strategies*; Cambridge Systematics, Inc.: Cambridge, MA, USA, 2010.
113. GOV Welsh Government Services and Information. Available online: https://gov.wales/ps20m-air-quality-fund-among-new-measures-improve-air-quality-wales (accessed on 6 August 2021).
114. York Bigazzi, A.; Rouleau, M. Can traffic management strategies improve urban air quality? A review of the evidence. *J. Transp. Health* **2017**, *7*, 111–124. [CrossRef]
115. Lewis, A. The Conversation. Available online: https://theconversation.com/beware-chinas-anti-smog-tower-and-other-plans-to-pull-pollution-from-the-air-90596 (accessed on 9 August 2021).
116. Lorch, M. The Conversation. Available online: https://theconversation.com/a-layerof-sunscreen-on-the-street-might-fight-smog-16545 (accessed on 1 August 2021).
117. Gardiner, B. National Geographic. Available online: https://www.nationalgeographic.com/science/article/china-air-pollution-solutions-environment-tangshan (accessed on 9 August 2021).
118. Poznań City Hall—Department of Environmental Protection Program KAWKA—Szansą na Ograniczanie Niskiej Emisji w Poznaniu (The KAWKA Program—An Opportunity to Reduce Low Emissions in Poznań). Available online: https://www.poznan.pl/mim/public/main/attachments.att?co=show&instance=1017&parent=69945&lang=pl&id=179846 (accessed on 19 September 2021).
119. Marshal's Office of the Mazowieckie Voivodeship in Warsaw Air Protection Programs. Available online: http://www.powietrze.mazovia.pl/pop-i-pdk/program-ograniczania-niskiej-emisji-pone-1 (accessed on 19 September 2021).
120. Krakow City Hall Environmental Protection. Available online: https://www.bip.krakow.pl/?dok_id=105326 (accessed on 19 September 2019).
121. Kowalska, F. Air pollution is a significant threat to the health of the inhabitants of Polish cities. *Refleksje Pismo Nauk. Stud. Dr. WNPiD UAM* **2020**. [CrossRef]
122. Association of the Szczecin Metropolitan Area. News Szczecin. Available online: http://som.szczecin.pl/2019/04/29/szczecin-program-platan/ (accessed on 19 September 2019).
123. Capital City of Warsaw Municipal Greenery. Available online: https://warszawa19115.pl/-/milion-drzew-dla-warszawy (accessed on 19 September 2019).
124. Green Forest Fund Forest Donation. Available online: https://www.greenforestfund.de/en/ (accessed on 19 September 2019).
125. Lawton, G.; Markuly, I. Greening the Desert Project. Available online: https://www.greeningthedesertproject.org/ (accessed on 19 September 2021).
126. Ripple Africa Inspiring Communities to Achieve a Sustainable Future. Available online: https://rippleafrica.org/ (accessed on 19 September 2021).
127. Rae, R.A.; Simon, G.; Braden, J. Public Reactions to New Street Tree Planting. *Cities Environ.* **2010**, *3*, 1–21. [CrossRef]
128. Balder, H.; Ehlebracht, K.; Mahler, E. *Stressen Baume Planen, Pflanzen, Pfelgen am Beispiel Berlin*; Patzer Verlag: Berlin, Germany; Hanover, Germany, 1997.
129. Han, Q.; Keeffe, G.; Caplat, P.; Simson, A. Cities as hot stepping stones for tree migration. *Urban Sustain.* **2021**, *1*, 1–5. [CrossRef]
130. Andersson-Sköld, Y.; Thorsson, S.; Rayner, D.; Lindberg, F.; Janhäll, S.; Jonsson, A.; Moback, U.; Bergman, R.; Granberg, M. An integrated method for assessing climate-related risks and adaptation alternatives in urban areas. *Clim. Risk Manag.* **2015**, *7*, 31–50. [CrossRef]
131. Kołodziej, E. NOIZZ Ekologia. Available online: https://noizz.pl/ekologia/warszawa-gorsza-niz-kalkuta-jest-na-2-miejscu-miast-z-najgorszym-powietrzem/c3jn196 (accessed on 2 August 2021).
132. Krzysztoszek, A.; Jakubowska, J. Euractiv.pl. Available online: https://www.euractiv.pl/section/energia-i-srodowisko/news/mroz-smog-piec-warszawa-wroclaw-zanieczyszczenie-powietrze-miasta/ (accessed on 2 August 2021).
133. Karaczun, Z.; Michalak, W. *Impact of the Hange and Air Pollution for the Health of Warsaw Inhabitants*; Polish Ecological Club, Mazowiecki District: Warszawa, Poland, 2019.
134. Poland in Numbers. The City of Warsaw in Numbers. Available online: https://www.polskawliczbach.pl/Warszawa (accessed on 2 August 2021).
135. Glen, S. Convenience Sampling (Accidental Sampling): Definition, Examples. Available online: https://www.statisticshowto.com/convenience-sampling/ (accessed on 20 September 2021).
136. Salkind, N. *Encyclopedia of Research Design*; SAGE Publications, Inc.: New York, NY, USA, 2012. [CrossRef]
137. Nielsen, J.S. Use of the Internet for willingness-to-pay surveys: A comparison of face-to-face and web-based interviews. *Resour. Energy Econ.* **2011**, *33*, 119–129. [CrossRef]
138. Nowak, D.J.; Crane, D.E. The Urban Forest Effects (UFORE) model: Quantifying urban forest structure and functions. In *Integrated Tools for Natural Resources Inventories in the 21st Century; General Technical Report, NC-212*; Hansen, M., Burk, T., Eds.; U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: St. Paul, MN, USA, 2000.

139. Hirabayashi, S.; Kroll, C.N.; Nowak, D.J. i-Tree Eco Dry Deposition Model Descriptions. Available online: https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.365.190&rep=rep1&type=pdf (accessed on 26 August 2021).
140. i-Tree Eco User's Manual. Available online: https://www.itreetools.org/documents/275/EcoV6_UsersManual.2021.04.19.pdf (accessed on 1 August 2021).
141. Laden, F.; Schwartz, J.; Speizer, F.E.; Dockery, D.W. Reduction in Fine Particulate Air Pollution and Mortality. *Am. J. Respir. Crit. Care Med.* **2012**, *173*, 667–672. [CrossRef] [PubMed]
142. Jacobson, M.Z. On the causal link between carbon dioxide and air pollution mortality. *Geophys. Res. Lett.* **2008**, *35*, L03809. [CrossRef]
143. Jerrett, M.; Burnett, R.T.; Pope, C.A.I.; Ito, K.; Thurston, G.; Krewski, D.; Shi, Y.; Calle, E.; Thun, M. Long-Term Ozone Exposure and Mortality. *N. Engl. J. Med.* **2009**, *360*, 1085–1095. [CrossRef]
144. Adamkiewicz, G.; Ebelt, S.; Syring, M.; Slater, J.; Speizer, F.E.; Schwartz, J.; Suh, H. Association between air pollution exposure and exhaled nitric oxide in an elderly population. *Thorax* **2004**, *59*, 204–209. [CrossRef]
145. Siddi, M. *The European Green Deal: Assessing Its Current State and Future Implementation*; FIIA: Helsinki, Finland, 2020.
146. Wolf, S.; Teitge, J.; Mielke, J.; Schütze, F.; Jaeger, C. The European Green Deal—More Than Climate Neutrality. *Intereconomics* **2021**, *56*, 99–107. [CrossRef]
147. Suchocka, M.; Swoczyna, T.; Kosno-Jończy, J.; Kalaji, H.M. Impact of heavy pruning on development and photosynthesis of Tilia cordata Mill. trees. *PLoS ONE* **2021**, *16*, e0256465. [CrossRef]
148. Cimburova, Z.; Barton, D.N. The potential of geospatial analysis and Bayesian networks to enable i-Tree Eco assessment of existing tree inventories. *Urban For. Urban Green.* **2020**, *55*, 126801. [CrossRef]
149. Davies, H.; Doick, K.; Handley, P.; O'Brien, L.; Wilson, J. *Delivery of Ecosystem Services by Urban Forests*; Research Report; Forestry Commission: Bristol, UK, 2017.
150. Endreny, T.; Santagata, R.; Perna, A.; De Stefano, C.; Rallo, R.F.; Ulgiati, S. Implementing and managing urban forests: A much needed conservation strategy to increase ecosystem services and urban wellbeing. *Ecol. Modell.* **2017**, *360*, 328–335. [CrossRef]
151. Suchocka, M.; Jankowski, P.; Błaszczyk, M. Tree protection on construction sites—Knowledge and perception of Polish professionals. *Urban For. Urban Green.* **2019**, *46*, 126436. [CrossRef]
152. Suchocka, M.; Jankowski, P.; Błaszczyk, M. Perception of Urban Trees by Polish Tree Professionals vs. Nonprofessionals. *Sustainability* **2019**, *11*, 211. [CrossRef]
153. Davies, H.J.; Doick, K.J.; Hudson, M.D.; Schreckenberg, K. Challenges for tree officers to enhance the provision of regulating ecosystem services from urban forests. *Environ. Res.* **2017**, *156*, 97–107. [CrossRef] [PubMed]
154. Wang, Y.; Sun, M.; Yang, X.; Yuan, X. Public awareness and willingness to pay for tackling smog pollution in China: A case study. *J. Clean. Prod.* **2016**, *112*, 1627–1634. [CrossRef]
155. Pisarek, M. Znaczenie terenów zieleni w świadomości mieszkańców Tarnowa (The importance of green areas in the minds of the inhabitants of Tarnów). *Topiarius Stud. Kraj.* **2017**, *2*, 131–144.
156. Rykała, P. Miejskie przestrzenie publiczne—Przykład orientacyjnej wyceny terenu zieleni w Częstochowie (Urban public spaces—An example of an approximate evaluation of a green area in Częstochowa). *Rozw. Reg. Polityka Reg.* **2019**, *45*, 103–122. [CrossRef]
157. Lo, A.Y.H.; Jim, C.Y. Citizen attitude and expectation towards greenspace provision in compact urban milieu. *Land Use Policy* **2012**, *29*, 577–586. [CrossRef]
158. Tyrväinen, L.; Mäkinen, K.; Schipperijn, J. Tools for mapping social values of urban woodlands and other green areas. *Landsc. Urban Plan.* **2007**, *79*, 5–19. [CrossRef]
159. Vesely, É.T. Green for green: The perceived value of a quantitative change in the urban tree estate of New Zealand. *Ecol. Econ.* **2007**, *63*, 605–615. [CrossRef]
160. Lohr, V.I.; Pearson-Mims, C.H.; Tarnai, J.; Dillman, D.A. How urban residents rate and rank the benefits and problems associated with trees in cities. *J. Arboric.* **2004**, *30*, 28–35.
161. Sanesi, G.; Chiarello, F. Residents and urban green spaces: The case of Bari. *Urban For. Urban Green.* **2006**, *4*, 125–134. [CrossRef]
162. Turvey, C.G.; Kong, R. Weather risk and the viability of weather insurance in China's Gansu, Shaanxi, and Henan provinces. *China Agric. Econ. Rev.* **2010**, *2*, 5–24. [CrossRef]
163. Madureira, H.; Nunes, F.; Oliveira, J.V.; Cormier, L.; Madureira, T. Urban residents' beliefs concerning green space benefits in four cities in France and Portugal. *Urban For. Urban Green.* **2015**, *14*, 56–64. [CrossRef]
164. Ward Thompson, C.; Roe, J.; Aspinall, P.; Mitchell, R.; Clow, A.; Miller, D. More green space is linked to less stress in deprived communities: Evidence from salivary cortisol patterns. *Landsc. Urban Plan.* **2012**, *105*, 221–229. [CrossRef]
165. Jim, C.Y.; Shan, X. Socioeconomic effect on perception of urban green spaces in Guangzhou, China. *Cities* **2013**, *31*, 123–131. [CrossRef]
166. Arnberger, A.; Eder, R. Are urban visitors' general preferences for green-spaces similar to their preferences when seeking stress relief? *Urban For. Urban Green.* **2015**, *14*, 872–882. [CrossRef]
167. Derkzen, M.L.; van Teeffelen, A.J.A.; Verburg, P.H. Green infrastructure for urban climate adaptation: How do residents' views on climate impacts and green infrastructure shape adaptation preferences? *Landsc. Urban Plan.* **2017**, *157*, 106–130. [CrossRef]

168. Tyrväinen, L.; Pauleit, S.; Seeland, K.; de Vries, S. Benefits and Uses of Urban Forests and Trees. In *Urban Forests and Trees: A Reference Book*; Konijnendijk, C., Nilsson, K., Randrup, T., Schipperijn, J., Eds.; Springer: Berlin/Heidelberg, Germany, 2005; pp. 81–114.
169. Sram, R.J.; Binkova, B.; Dostal, M.; Merkerova-Dostalova, M.; Libalova, H.; Milcova, A.; Rossner, P.; Rossnerova, A.; Schmuczerova, J.; Svecova, V.; et al. Health impact of air pollution to children. *Int. J. Hyg. Environ. Health* **2013**, *216*, 533–540. [CrossRef]
170. Vichit-Vadakan, N.; Vajanapoom, N. Health impact from air pollution in thailand: Current and future challenges. *Environ. Health Perspect.* **2011**, *119*, 196–198. [CrossRef]
171. Rabl, A.; Spadaro, J.V. Public Health impact of air pollution and implicayions for the energy system. *Annu. Rev. Energy Environ.* **2003**, *25*, 601–627. [CrossRef]
172. Künzli, N.; Kaiser, R.; Medina, S.; Studnicka, M.; Chanel, O.; Filliger, P.; Herry, M.; Horak, F.; Puybonnieux-Texier, V.; Quénel, P.; et al. Public-health impact of outdoor and traffic-related air pollution: A European assessment. *Lancet* **2000**, *356*, 795–801. [CrossRef]
173. Jeong, S.J. The Impact of Air Pollution on Human Health in Suwon City. *Asian J. Atmos. Environ.* **2013**, *7*, 227–233. [CrossRef]
174. Bayat, R.; Ashrafi, K.; Shafiepour Motlagh, M.; Hassanvand, M.S.; Daroudi, R.; Fink, G.; Künzli, N. Health impact and related cost of ambient air pollution in Tehran. *Environ. Res.* **2019**, *176*, 108547. [CrossRef] [PubMed]
175. Naddafi, K.; Hassanvand, M.S.; Yunesian, M.; Momeniha, F.; Nabizadeh, R.; Faridi, S.; Gholampour, A. Health impact assessment of air pollution in megacity of Tehran, Iran. *Iran. J. Environ. Health Sci. Eng.* **2012**, *9*, 28. [CrossRef] [PubMed]

## 10.2. Artykuł 2

**Kais, K.**; Gołaś, M.; Suchocka, M.; Ziemiański, M.; Kalaji, H. M. The Role of Urban Trees in PM2.5 Mitigation: Air Quality Assessment and Absorption Capacity Comparison in Warsaw Alleys. JSPAE 2025, 4, 75–94 (SCOPUS: 2024 SJR = 0,525) https://doi.org/10.56946/jspae.v4i2.730

https://doi.org/10.56946/jspae.v4i2.730
ISSN: 2957-9082
*Journal of Soil, Plant and Environment*

ORIGINAL RESEARCH

# The Role of Urban Trees in $PM_{2.5}$ Mitigation: Air Quality Assessment and Absorption Capacity Comparison in Warsaw Alleys

Karolina Kais[1*], Marlena Gołaś[2], Marzena Suchocka[3], Maciej Ziemiański[4], Hazem M. Kalaji[5]

[1]Institute of Environmental Engineering, Warsaw University of Life Sciences – SGGW, Nowoursynowska St. 159, 02-776 Warsaw, Poland.
[2]Institute of Economics and Finance, Warsaw University of Life Sciences – SGGW, Nowoursynowska St. 159, 02-776 Warsaw, Poland.
[3]Landscape Architecture Department Warsaw University of Life Science, SGGW, Nowoursynowska St. 159, 02-776 Warsaw, Poland.
[4]Faculty of Biology, University of Warsaw, Miecznikowa Str. 1, 02-096 Warsaw, Poland.
[5]Department of Plant Physiology, Institute of Biology, Warsaw University of Life Sciences - SGGW, Nowoursynowska St. 159, 02-776 Warsaw, Poland.

*Corresponding author: karolina_kais@sggw.edu.pl

Received: 07 July 2024
Revised: 19 August 2025
Accepted: 29 August 2025

**ABSTRACT:** Rapid urbanization is intensifying air pollution across cities worldwide, with fine particulate matter ($PM_{2.5}$) emerging as one of the most hazardous pollutants to public health. While urban trees are widely recognized for their role in air purification, particularly through pollutant absorption and filtration, most existing studies rely on predictive models such as i-Tree Eco and rarely incorporate direct field-based validation of $PM_{2.5}$ exposure levels for urban residents. A critical gap remains in understanding the actual distribution of health-threatening $PM_{2.5}$ concentrations and the localized effectiveness of urban vegetation in mitigating these pollutants. This study addresses this gap by assessing $PM_{2.5}$ pollution levels and evaluating the particulate matter absorption capacity of urban trees in two street alleys with contrasting tree canopy cover (TCC) in Warsaw, Poland. The research was conducted in two phases: first, $PM_{2.5}$ concentrations were monitored using dust sensors during peak and post-peak traffic periods; second, the i-Tree Eco model was employed to quantify pollutant uptake by trees at each site. The findings indicate that exceedances of the WHO $PM_{2.5}$ air quality standard (15 µg/m³) occurred 1.5 times more frequently on streets with only 6% tree canopy cover (TCC), compared to streets with more than 30% TCC. Moreover, the site with optimal TCC, trees demonstrated over 14-fold greater effectiveness in $PM_{2.5}$ removal. Furthermore, the model has been shown to be statistically significant, meaning that one of the predictors, TCC or DBH, has a significant impact on $PM_{2.5}$ removal levels. These findings highlight the critical role of tree canopy density in enhancing urban air quality and suggest that sole reliance on modeled estimations without ground-level data may significantly underestimate residents' exposure to $PM_{2.5}$. By integrating in-situ pollution monitoring with ecosystem service modeling, this study provides a more accurate assessment of urban trees' capacity to mitigate air pollution. The findings underscore the need for data-driven urban greening policies and offer actionable insights for improving air quality in cities like Warsaw.

**KEYWORDS:** Air pollution, $PM_{2.5}$ mitigation, tree canopy cover, urban forestry, vegetation absorption



## 1. Introduction

Air pollution has become one of the most serious environmental and public health challenges of the 21st century, particularly in densely populated urban areas. The rise in global urbanization, industrial activities, traffic congestion, and diminishing green spaces has led to the widespread degradation of air quality. According to the World Health Organization, more than 90% of the world's population resides in areas where air quality exceeds recommended limits, with urban populations being most vulnerable to its effects (Akbari et al., 2001).

Particulate matter (PM), especially $PM_{10}$ and $PM_{2.5}$, is considered among the most harmful air pollutants due to its small size and ability to penetrate deep into the human respiratory system. These particles primarily originate from vehicle emissions, industrial activities, open burning, and fossil fuel combustion (Aslam et al., 2021). Much of the research has focused on the impact of air pollution on health problems, where it has been shown that once inhaled, fine particles can reach the alveoli in the lungs and enter the bloodstream, contributing to a wide range of health problems including asthma, bronchitis, cardiovascular diseases, chronic obstructive pulmonary disease (COPD), and lung cancer (Bass, 2001; Bates, 2005). Studies have shown that even short-term exposure to elevated $PM_{2.5}$ levels can increase hospital admissions and premature mortality, especially among vulnerable groups such as children and the elderly (Beckett et al., 1998). For instance, research conducted in Beijing reported that a 10 $\mu g/m^3$ increase in $PM_{2.5}$ levels was associated with a statistically significant rise in lung cancer incidence among both men and women (Beckett et al., 2000).

In addition to its health effects, air pollution contributes to environmental degradation and economic loss. It leads to reduced agricultural productivity, damages buildings and cultural monuments, and increases healthcare costs (Bond, 2013). Despite global efforts to regulate emissions and promote cleaner technologies, urban air pollution continues to rise, especially in developing and transitional economies where enforcement of environmental regulations remains weak.

One promising strategy to combat air pollution involves the use of urban vegetation, particularly trees, which offer a cost-effective and sustainable means of improving air quality. Trees and other green infrastructure components provide a range of ecosystem services, including shading, temperature regulation, carbon sequestration, and—most importantly—pollution removal from the atmosphere (Bonire and Gbenga-Ilori, 2021; Branea et al., 2016). Through the processes of dry deposition and stomatal uptake, trees can trap and absorb particulate matter on leaf surfaces or within plant tissues, effectively reducing airborne concentrations of harmful pollutants (Brantley et al., 2014). Research from cities like Christchurch (New Zealand), London (UK), and New York (USA) has demonstrated that urban trees can remove hundreds of tons of air pollutants annually, thereby contributing significantly to public health and environmental quality (Brauer et al., 2007; Bureau. 2007).

However, the effectiveness of different tree species and vitality in removing PM varies considerably. Factors such as leaf surface micromorphology, canopy density, stomatal behavior, waxy cuticle thickness, and tree architecture influence the capacity of trees to capture or absorb airborne particles (Burkhardt, 2010; CAFE 2004; Song et al., 2025; Popek et al., 2024; Hoppa et al., 2025; Przybysz et al., 2024). Coniferous trees and rough-leaved deciduous species, for example, tend to accumulate more PM than smooth-leaved species due to their surface characteristics (Cavanagh, 2008). These differences highlight the need for localized, species-specific assessments to inform urban forestry practices aimed at pollution control.

To estimate the pollution mitigation potential of trees, several analytical models and tools have been developed. One of the most widely adopted is the i-Tree Eco model, created by the U.S. Forest Service. This model calculates a range of ecosystem services provided by urban forests, including air pollution removal, carbon storage, and avoided stormwater runoff, based on tree species, structure, and local meteorological data (Cavanagh et al., 2009). The i-Tree model has been successfully applied in multiple urban contexts—including New York City, Dublin, Krakow, and London—to quantify the environmental contributions of trees (Cen, 2015; Chenet al., 2017). Additionally, other studies have utilized GIS-based spatial modeling, leaf-level PM deposition assessments, or atmospheric dispersion models to evaluate vegetation-air quality interactions (Chen et al., 2017). Moreover, in Central and Eastern Europe—particularly in Warsaw, Poland—applications of the i-Tree model remain limited, and empirical evidence on the particulate matter absorption efficiency of local tree species is lacking. Thus, there is a need for localized assessments that integrate urban forestry with air quality management to better guide policy and planning.

Despite growing global interest in nature-based solutions for pollution control, empirical data on species-specific pollution mitigation potential in Warsaw's urban environment are scarce. Moreover, recent trends in urban development in Poland, including the replacement of green spaces with impervious infrastructure, threaten to reduce the natural capacity of cities to cope with pollution (Chen, 2006). Understanding the role of existing urban trees in PM reduction, and identifying urban forest characteristic with the highest mitigation potential, is crucial for promoting environmentally sustainable urban planning (Konijnendijk, 2023; Lopez et al., 2025; Iqbal et al., 2025). For example, the mentioned above and widely discussed 3-30-300 guideline aims to establish a standard for enhancing urban dwellers' well-being, strongly linked to ecosystem services, including urban flooding mitigation (Vesuviano et al., 2025), improvements in mental and physical health, and reduction of overweight prevalence (Helbich et al., 2025); Zheng et al., 2024], as well as lower mortality rates among city residents (Giannico et al., 2025). This study aims to assess the capacity of roadside urban trees in Warsaw to mitigate particulate matter ($PM_{10}$ and $PM_{2.5}$) pollution using the i-Tree Eco model. The research questions are: (1) Does tree canopy cover (TCC) influence pollution levels in relation to street trees? (2) Does optimal TCC significantly reduce the likelihood of substantial exceedances of air quality standards that pose a threat to human health?

These questions are addressed through an analysis of measured pollution levels and simulations of $PM_{2.5}$ removal efficiency using the i-Tree Eco model, in the context of a minimum 30% TCC, which recent studies identify as optimal (Konijnendijk, 2023). Based on the existing literature, we hypothesize that local urban forest characteristics influence the efficiency of particulate matter (PM) removal: 1) the pollution removal efficiency of urban forests significantly varies with TCC (e.g., Marszałkowska Street <30% and Żwirki i Wigury Street >30%); 2) locations with differing TCC values will differ in the prevalence of high pollution levels, categorized as below 15 µg/m³ and above 15 µg/m³; and 3) removal efficiency is associated with tree diameter at breast height (DBH). By addressing these objectives, the study seeks to contribute to evidence-based policymaking and support Warsaw's efforts toward building greener, healthier, and more resilient urban ecosystems.

## 2. Materials and methods

### 2.1 Description of the study site

Warsaw, the capital of Poland and the largest city in the country, situated at the heart of Europe, was chosen as the research area (Figure 1). With a surface area of 517.2 km² and a population of 1,792,718 (Poland in numbers, 2020), Warsaw, like many other Polish cities, grapples with severe air quality issues on a global scale. In January 2017, the city experienced one of its most severe smog episodes, with pollution levels exceeding air quality standards across much of Poland.


Figure 1. Tree inventory along Marszałkowska and Żwirki i Wigury streets in Warsaw, Mazowieckie, Poland, showing tree ID numbers and locations on aerial imagery.

During this period, the permissible average concentrations of $PM_{10}$ were surpassed on 19-22 days, accounting for 60-70% of the month, while $PM_{2.5}$ concentrations exceeded standards on 25-28 days, covering 80-90% of the month (Karaczun & Michalak, 2019). In January 2021, Warsaw ranked 6th among cities with the lowest air quality according to the Air Quality Index (Krzysztoszek & Jakubowska 2021). Additionally, the World Air Quality Ranking in February 2021 identified Warsaw as the city with the second-worst air quality globally, with $PM_{10}$ concentrations exceeding by 232% and $PM_{2.5}$ levels by a staggering 364% (Kołodziej, 2021). Subsequently, in March, Warsaw topped the IQAir ranking as the most polluted major city in the world (IQAir, 2022), underscoring its selection as the research focus. The average daily lowest temperature was recorded at 8.2°C, and the average daily highest temperature reached 15.9°. The average daily lowest humidity rate was 71.9%, the recorded highest daily humidity rate was 90.1%. Wind speed during the analyzed period ranged from 2 to 7 m/s with gusts of 4 to 16 m/s occurring. Precipitation occurred 3 times - 2.4 mm of rain fell on September 23, 0.4 mm of rain on September 24 and 4 mm of rain on September 30. In summer, Warsaw is most often affected by winds from the west (24.7%) and north-west (10.7%), while in winter south-westerly winds prevail, and in spring and autumn gusts from the east and south-east dominate.There were no sudden changes in atmospheric conditions during the analyzed period.

The tree inventory was conducted along two 500-meter sections in Warsaw, Poland, chosen for their varied tree canopy cover and essential role in city communication (Table 2), experiencing heavy traffic throughout the day, with an average of 1070 cars per hour on Marszałkowska Street and 1049 cars per hour on Żwirki i Wigury Street during rush hour (Municipal Road Administration 2021). Traffic measurement points coincided with the tree inventory locations at spot 2307 on Marszałkowska Street and spot 1306 on Żwirki i Wigury Street (Municipal Road Administration 2021). Both streets feature similar geometry, minimizing variability in pollution level measurements, as they lack bends or curves. Traffic characteristics (heavy traffic lane) at both studied locations and the characteristics of the tree system - a linear alley system, and the way the measurements has been carried out - measurements recorded along the alley, have registered the linear characteristics of air purification in the studied alley sections. Both of these streets, as shown by the orthophoto (Figure 1) are not canyons according to the accepted definition ( $H / W \geq 1$) (Wan Mahiyuddin et al., 2013). None of the industrial emitters of pollution were located near the surveyed street sections (Spatial Information System 2022). The trees along these streets grow in public areas and are easily accessible. Marszałkowska Street predominantly features concrete squares, wide pavements, and commercial buildings, with minimal surrounding shrubbery (Figure 2).

The street accommodates three traffic lanes in each direction, with a tree alley mostly comprising small-leaved linden trees (*Tilia cordata* Mill) planted in designated spaces between the pavement and the road. The surveyed section boasts a 6% tree canopy cover, with 59 trees averaging 18.05 cm in diameter and 5 meters in height. In contrast, Żwirki i Wigury Street (Figure 3), a primary thoroughfare bordered by four rows of trees, benefits from closer proximity to allotment gardens, resulting in a greater abundance of trees and other vegetation.

With two traffic lanes in each direction separated by small-leaved linden trees, the surveyed section hosts 142 trees averaging 11 meters in height and boasting a 31% tree canopy cover. Tree canopy cover was determined using QGIS.

### 2.2 Methodology

The principal sources of data utilized in the research included monitoring the $PM_{2.5}$ concentration levels in urban streets with differing tree canopy cover (TCC) densities (Karaczun & Michalak 2019) during peak traffic periods and post-peak traffic periods. Additionally, tree inventory was conducted in selected locations, and the i-Tree Eco tool was employed to calculate the pollution removal capacity. Through data collected from these sources, the authors aim to assess the impact of trees on air quality in two distinct locations, identify statistically significant differences, and analyze the measurement findings of actual pollution levels alongside estimates provided by the i-Tree Eco model.

### 2.3 Air quality monitoring

Air quality monitoring was conducted at two locations: Marszałkowska Street and Żwirki i Wigury Street. Air quality sensors were strategically placed in central areas of one alley covered by trees and another devoid of tree cover, positioned 3 meters away from the edge of the road. Temtop M2000 sensors (2nd Generation Multi Functional Air Quality Detector with TFT color screen—EN 60825–1W/A11 US 21 CFR 1040.10), versatile air quality meters capable of measuring $PM_{2.5}$, $PM_{10}$, $CO_2$, HCHO, temperature, and humidity, were utilized for this purpose. $PM_{2.5}$ concentrations were monitored at a height of 1 m above ground level, which is considered the breathing zone. Equipped with PM laser sensors and Non-Dispersive Infrared (NDIR) $CO_2$ sensor, the Temtop M2000 meter offers measurements with an accuracy of 0.1 µg/m$^3$ for $PM_{2.5}$ dust, within a measurement range of 0-999 µg/m$^3$ with a measurement range of 0.1–10,000 µg/m$^3$, a resolution and sensitivity of 1 µg/m$^3$, an airflow rate of 1 L/min, and calibrated with Arizona Road Dust as reference material (Temtop M2000 User Manual, 2022). After being switched on, the detector was calibrated for approximately 10 minutes and then placed outdoors for another 10 minutes to ventilate. Each individual measurement lasted one minute, during which the average $PM_{2.5}$ concentration was calculated and displayed. At each location, monitoring was conducted for at least 10 minutes, with data recorded every minutes, to ensure an accurate average value. If necessary, the monitoring duration was extended until the readings stabilized. To minimize the impact of changing environmental conditions, total monitoring time per location (street) was limited to 2 hours. Furthermore, the monitoring protocol required measurements to be taken in quick succession while in motion. Air pollution concentration levels were recorded every minute during the monitoring period, spanning from 24th September 2021 to 8th October 2021, across two distinct time intervals: during rush hour and post-rush hour. The study was carried out in September and October to coincide with the peak usage period of the road zone, which is primarily active during rush hours. This timing ensured that the assessment captured conditions most relevant to users, as well as the ecological and health impacts of these urban green spaces during their most active phase. Measurements were conducted in September–October, when trees typically retain full foliage, enabling reliable assessment of $PM_{2.5}$ removal efficiency. This timing also facilitates detecting vitality differences between zones with contrasting TCC, as high canopy cover helps sustain physiological activity, whereas low-TCC areas may show early stress symptoms reducing purification performance.

Each sensor was stationed at the testing sites for 60 minutes during each period. Rush hour was defined as the timeframe between 4:00 p.m. and 6:00 p.m. on Mondays through Fridays, while non-rush hour periods encompassed the remaining time, excluding the hours between 8:00 a.m. and 10:00 a.m. . The average daily temperature during the mentioned period ranged from 7.5 to 14.2°C, and maximum temperatures ranged from 13.3 to 20.3°C.

## 2.4 The i-Tree Eco model

The i-Tree Eco version 6.0 model guided the collection of field data following its prescribed protocols, as outlined in the i-Tree Eco User Manual (i-Tree Eco User's Manual, 2019). Following the software's recommendations, one of the two tree sample selection options was employed, entailing a comprehensive survey of trees within the designated area. A thorough examination of trees in the research area was conducted, with data collection performed as per established procedures (Kais et al., 2021). This encompassed documenting tree species and locations, alongside dendrometric measurements including trunk diameter (DBH), total tree height, live tree height, crown base, North-South crown width, East-West crown width, crown loss percentage, crown health, and crown light exposure. DBH measurements were obtained using a caliper at 130 cm above ground level, while measurements for other parameters were acquired utilizing a Bosch GLM120c laser measure with up to 0.5 m accuracy. Additionally, weather details and air quality data sourced from the i-Tree database, including $PM_{2.5}$ concentration levels measured by PM level monitors positioned in Warsaw, were incorporated into the model. The i-Tree database facilitated access to meteorological data and air quality information. Subsequently, upon inputting all requisite data, the model was activated to generate estimates regarding the pollution removal efficacy of trees along Marszałkowska Street and Żwirki i Wigury Street. Furthermore, to ascertain the statistical significance of air quality measurement disparities between tree-covered and low tree cover segments, an analysis of $PM_{2.5}$ concentration level differences was conducted utilizing R software. Canopy cover measurements were taken using GIS software and correlated with field measurements. Dendrometric measurements and tree species identification were performed by a qualified landscape architect. The average parameters are shown in Table 1.

Table 1. Average tree growth parameters

| Measured parameter | Street name | Value (with Standard Error) |
|---|---|---|
| DBH [cm] | Marszałkowska | 18,05±11,43 |
| | Żwirki i Wigury | 38,82±9.72 |
| Total Tree Height [m] | Marszałkowska | 5,18±2,40 |
| | Żwirki i Wigury | 11,17±2,34 |
| Crown Width NS [m] | Marszałkowska | 3,42±2,05 |
| | Żwirki i Wigury | 7,71±2,10 |
| Crown Width EW [m] | Marszałkowska | 3,18±2,16 |
| | Żwirki i Wigury | 7,78±2,21 |
| Crown Miss [%] | Marszałkowska | 18,22±22,75 |
| | Żwirki i Wigury | 12,89±15,97 |

Tree health assessment was performed by determining the percentage of crown loss, in accordance with the i-Tree Eco methodology (i-Tree Eco User's Manual). Crown loss was expressed as an estimate of the percentage of dead branches in the crown of each of the trees studied during field inspections.

**2.5 Statistics**

To illustrate the $PM_{2.5}$ air pollution levels on Żwirki i Wigury Street and Marszałkowska Street, a comparison of average air pollution and the duration of recorded pollution levels (in minutes) in two categories: below 15 µg/m$^3$ and above 15 µg/m$^3$ was conducted. Both sets of data were presented by date and measurement time (high traffic or after the peak traffic). The results were analyzed using the pivot table tool in Microsoft Excel spreadsheet software. Additionally, line graphs were generated to depict the pollution levels on both streets throughout the entire study period.

**3. Results**

**3.1. Air quality measurement**

The research yielded data on pollution concentration levels in two locations: Marszałkowska Street and Żwirki i Wigury Street (Tables 2 and 3). Pollution level measurements were conducted over 9 consecutive days, totaling 1074 minutes at a road segment with low tree density (Marszałkowska Street) and 1189 minutes in a tree-lined alley at Żwirki i Wigury Street. An overview of concentration levels in both locations is provided in histograms (Figures 2 and 3), while the average pollution levels at each street are shown in the tables.

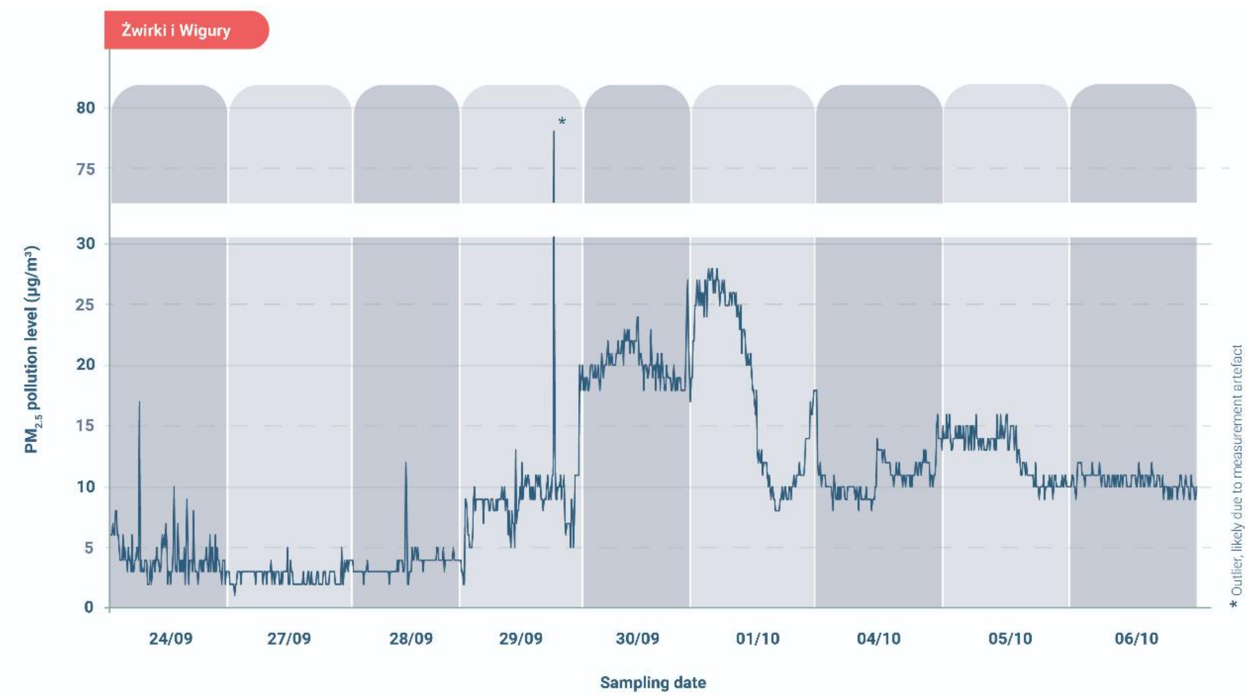



Figure 2. Żwirki i Wigury Street – $PM_{2.5}$ pollution level.


Figure 3. Marszałkowska Street – $PM_{2.5}$ pollution level .

Monitoring was simultaneous in both locations, and any discrepancies may result from occasional failure to register current pollution concentration readings. Tables 2 and 3 depict exceedances of $PM_{2.5}$ levels by peak hour, post-peak time, and total exceedance time by street. $PM_{2.5}$ limits exceeded by values higher than 15 µg/m$^3$ were recorded 1.5 times more frequently on the street with low tree cover. Furthermore,

$PM_{2.5}$ limits exceeded by values higher than 15 µg/m$^3$ occurred 3.5 times more frequently in the same area, and limits exceeded by values higher than 25 µg/m$^3$ happened 14 times more frequently. Dust concentrations are also illustrated in the graphs (Figs. 2 and 3). Considering a similar level of traffic congestion and the same tree species in both locations, it can be inferred that the main reason for the difference in pollution concentration levels is the poorer condition of trees at Marszałkowska Street. The trees there grow in designated spaces cut out in the pavement (1,9x1,9m), resulting in inadequate access to water and insufficient space for root system growth. As a consequence of these harsh site conditions (high concentration of paved areas), tree canopy cover is only 6% in that area.

Statistical analysis was conducted based on the collected data on PM concentration levels. A Shapiro-Wilk distribution test, covering $PM_{2.5}$ concentration levels at roads with low and high tree canopy cover, revealed significantly different distribution patterns from the norm ($p < 0.05$). Additionally, a parametric Mann-Whitney test was performed to assess the sum of ranks. The resulting sum provided the rank difference, aiding in categorizing groups into two separate populations. This test showed a significant difference ($W = 341450$, $p < 0.05$) between concentration levels in a street covered with trees and a street with low tree cover. The median for $PM_{2.5}$ concentration levels was 14 µg/m$^3$ in the segment of the street with low tree canopy cover and 10 µg/m$^3$ in the tree-covered alley. Additionally, an ANOVA table test was performed. The ANOVA table tests the overall significance of the model. The F-statistic of 120.103 with a p-value less than 0.001 indicates that the model is statistically significant, meaning at least one of the predictors has a significant impact on $PM_{2.5}$ removal value levels (Table 4). The multiple linear regression model demonstrates a strong relationship between the predictors (Crown % Miss, Total Tree Height, and Diameter) and the dependent variable ($PM_{2.5}$ removal value. The R-value of 0.837 suggests a high correlation between the predictors and the dependent variable. The model explains 70.1% of the variance in $PM_{2.5}$ removal value, as indicated by the $R^2$ value of 0.701. The adjusted $R^2$ is 0.695, meaning that the model maintains its explanatory power even when adjusting for the number of predictors. The table of coefficients provides insights into the individual contributions of each predictor: Diameter: The coefficient is 0.244 ($p < 0.001$), indicating a positive relationship between tree diameter and $PM_{2.5}$ removal value. A one-unit increase in Diameter is associated with a 0.244 increase in $PM_{2.5}$ removal value, holding other variables constant. Total Tree Height: The coefficient is 1.142 ($p < 0.001$), showing a strong positive impact on $PM_{2.5}$ removal value. An increase in tree height by one unit results in a 1.142 increase in $PM_{2.5}$ removal value. Crown % Miss: The coefficient is -0.148 ($p < 0.001$), meaning that a higher percentage of missing crown coverage reduces $PM_{2.5}$ removal value. For every 1% increase in Crown % Miss, $PM_{2.5}$ removal value decreases by 0.148. All predictors are statistically significant at the 0.001 level, confirming their strong contribution to the model.

### 3.1 The i-Tree Eco model

To prepare the model using the i-Tree Eco tool, a tree inventory was conducted at Marszałkowska Street (a segment with low TCC) and at Żwirki i Wigury Street (a segment with high TCC). The analysis of the tree inventory revealed that there were 59 trees along Marszałkowska Street, with the dominant species being *Tilia cordata* Mill. The diameter of the trees at Marszałkowska Street ranged mainly between 7.6 cm and 15.2 cm. Along the tree alley at Żwirki i Wigury Street, there were 142 trees, also predominantly *Tilia cordata* Mill., with diameters mainly between 30.5 cm and 45.7 cm (Table 1).

According to the i-Tree Eco report, the research was conducted on 500-meter-long street segments. After inputting the data, a model was launched using current data in the i-Tree Eco database on air pollution and meteorological conditions. The i-Tree Eco model assessed that the tree stand at Marszałkowska was capable of removing approximately 105.7 g of $PM_{2.5}$ over the course of a year, while the tree stands at Żwirki i Wigury had the capacity to remove 1.52 kg of $PM_{2.5}$ in a year. The highest value of $PM_{2.5}$ absorption for a single tree at Żwirki i Wigury was 24 g over the whole year, while the result for Marszałkowska was 19.9 g. Tables 2 and 3 show average values of $PM_{2.5}$ absorption for a single tree over the course of a year, indicating the variability of dust absorption throughout the year and in specific months in both locations.

Table 2. Measurement of pollution levels at Marszałkowska Street.

| | Time of recorded pollution levels lower than 15 μg/m$^3$ [in minutes] | | | Time of recorded pollution levels higher than 15 μg/m$^3$ [in minutes] | | |
|---|---|---|---|---|---|---|
| Date | After the peak traffic | High traffic | Total | After the peak traffic | High traffic | Total |
| 24.09.2021 | 14 | 22 | 36 | 40 | 32 | 72 |
| 27.09.2021 | 35 | 83 | 118 | 17 | 2 | 19 |
| 28.09.2021 | 0 | 52 | 52 | 60 | 5 | 65 |
| 29.09.2021 | 0 | 49 | 49 | 60 | 10 | 70 |
| 30.09.2021 | 48 | 5 | 53 | 8 | 50 | 58 |
| 01.10.2021 | 16 | 32 | 48 | 34 | 20 | 54 |
| 04.10.2021 | 63 | 33 | 96 | 9 | 20 | 29 |
| 05.10.2021 | 3 | 56 | 59 | 43 | 2 | 45 |
| 06.10.2021 | 3 | 52 | 55 | 44 | 12 | 66 |
| Average (with Standard Deviation) | 20,22±23,15 | 42,67±22,56 | 62,89±26,37 | 35,00±19,84 | 17,00±15,81 | 53,11±18,66 |

Table 3. Measurement of pollution levels at ul. Żwirki i Wigury.

| Date | Time of recorded pollution levels lower than 15 µg/m$^3$ [in minutes] | | | Time of recorded pollution levels higher than 15 µg/m$^3$ [in minutes] | | |
|---|---|---|---|---|---|---|
| | After the peak traffic | High traffic | Total | After the peak traffic | High traffic | Total |
| 24.09.2021 | 66 | 64 | 126 | 2 | 0 | 2 |
| 27.09.2021 | 63 | 61 | 124 | 0 | 0 | 0 |
| 28.09.2021 | 66 | 65 | 131 | 0 | 0 | 0 |
| 29.09.2021 | 62 | 62 | 124 | 0 | 1 | 1 |
| 30.09.2021 | 0 | 0 | 0 | 65 | 63 | 128 |
| 01.10.2021 | 0 | 58 | 58 | 66 | 8 | 74 |
| 04.10.2021 | 65 | 65 | 130 | 0 | 0 | 0 |
| 05.10.2021 | 60 | 66 | 126 | 8 | 0 | 8 |
| 06.10.2021 | 66 | 65 | 131 | 0 | 0 | 0 |
| Average (with Standard Deviation) | 49,78±28,30 | 56,22±21,24 | 105,56±45,84 | 15,67±28,37 | 8,00±20,79 | 23,67±45,95 |

Table 4. ANOVA test results for the regression model predicting $PM_{2.5}$ concentrations using Crown % Miss, Total Tree Height, and Diameter as predictors.

| Model | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| 1 | Regression | 3956,983 | 3 | 1318,994 | 120,103 | <,001b |
| | Residual | 1691,262 | 154 | 10,982 | | |
| | Total | 5648,244 | 157 | | | |

a. Dependent Variable: $PM_{2.5}$

b. Predictors: (Constant), Crown %Miss, Total Tree Hight, Diameter

The average value of $PM_{2.5}$ absorption for a single tree at Marszałkowska was 0.009 g, while the result for Żwirki i Wigury was 0.12 g. The highest capabilities of $PM_{2.5}$ pollution absorption at Żwirki i Wigury were recorded in September and October, while records for Marszałkowska indicate the highest results in May, September, and October. The observed differences in the test results for average pollutant uptake by a single tree may be attributed to the smaller canopy cover of the trees at Marszałkowska and their limited growing conditions, as they were planted in small pits with restricted access to soil, which affected their health

## 4. Discussion

As awareness of the impact of pollution on human health and the environment grows, measures to reduce urban air pollution are gaining prominence. Among these measures, planting trees has been identified as one of the most effective ways to mitigate dust and other pollutants (Przybysz et al., 2018). Encouraging activities aimed at expanding wooded areas is therefore reasonable. Previous research conducted in Warsaw demonstrated that trees have the capacity to absorb significant amounts of air pollutants annually (Kais et al., 2021). The study found that one tree on Marszakowska Street absorbs an average of 89.38 grams of pollution per year, while a tree located on Zwirki i Wigury Street absorbs 390.39 grams of pollution per year. The result for individual trees was on average 4.5 times higher at Żwirki i Wigury Street. Our research confirms the finding that tree planting is an effective means of absorbing particulate matter. According to i-Tree Eco model estimates, an avenue with large, mature trees absorbs 1.52 kg of $PM_{2.5}$ per year, while an avenue with small trees planted in tree pits set in the sidewalk absorbs only 105.7 g of $PM_{2.5}$ per year.

Annual PM exposure map prepared by Fisher et. al.,(2005) shoved that around 10 % of the central city were those with pollutants concentration above the 20 μg/m$^3$ i.e. exceeding national annual guidelines. In our study, we found that even areas placed close to each other but differing by TCC could have different pollutant absorption-$PM_{2.5}$ limits exceeded by values higher than 15 μg/m$^3$ were recorded 1.5 times more frequently on the street with low tree cover. Furthermore, $PM_{2.5}$ limits exceeded by values higher than 15 μg/m$^3$ occurred 3.5 times more frequently in the same area, and limits exceeded by values higher than 25 μg/m$^3$ happened 14 times more frequently, which indicates the importance of detailed empirical analyses to complement the results obtained with the i-Tree model, essential in the decison-making process concerning urban forest planting and maintaining polices. In New Zealand, over a year trees have been removed approx. 300 tons of air pollutants in the area of Christchurch (Cavanagh , 2008) but according to our results the same size of the studied area could have significantly different air pollution removal potential. It was found in the UK that planting trees on a quarter of the available urban area may lead to a decrease in $PM_{10}$ concentration by 2 to 10% (McDonald et al., 2007) in our study potential of mature and in good vitality trees was more than 14 times higher in comparison to trees growing in poor site condition in the empirical study. Considering similar levels of traffic volume and the same tree species in both locations, the median for $PM_{2.5}$ concentration levels was 14 μg/m$^3$ in the segment of the street with low tree canopy cover and 10 μg/m$^3$ in the tree-covered alley. Our results highlight the potential of high-quality green infrastructure to improve the well-being of urban residents, particularly those exposed to elevated concentrations of $PM_{2.5}$. The accepted daily standard for PM2.5 is 25 μg/m$^3$. In this study, we monitored actual PM2.5 concentrations, and the findings revealed notable spatial differences. Marszałkowska Street recorded 28 exceedances above the permissible threshold during peak hours, whereas Żwirki i Wigury Street recorded only 2 exceedance. As research specifies, particulate matter (PM) has the most detrimental effect on public health and the environment (Fisher et al., 2005; Russell & Brunekreef, 2009). It is due to the size of the particles - hence anthropogenic dust is considered the highest risk to human health (CAFE, 2004). Inhaling PM causes the particles to accumulate in lung tissue and enter the bloodstream, which in turn leads to a higher risk of circulatory and pulmonary illnesses (Cen, 2015), obstructive pulmonary disease, and lung cancer (Jeong, 2013). Research shows that lung cancer incidence in Beijing was 1.055 for men and 1.149 for women and the increase in incidence was caused by the increase of $PM_{2.5}$ levels by 10 mg -3 (Guo et al., 2014). Inhaling dust also causes deterioration of health in respiratory illnesses such as asthma (Bond et al., 2013; Brauer et al., 2007) and leads to respiratory infections in children (Bond et al., 2013). The i-Tree data shows that the absorption of pollutants in the low-density tree canopy cower area is 14 times lower but does not show how often pollution exceeds levels dangerous to the health of city dwellers, so the novelty of our study is to provide new information illustrating the risks to human health and life and to determine periods of time when the health risk is significant. This knowledge allows countermeasures to be taken, ranging from alerting residents to taking action to improve the quality of green infrastructure, for example through efforts to increase tree canopy cover and as a result risk mitigating. Studies using models like the i-Tree Eco model in Barcelona and the UFORE model in Perth have quantified the removal of air pollutants by urban forests. The survey was conducted for the entire city area, where tree canopy coverage is 22%. In the case of the study from Australia, the amount of $PM_{10}$ removed was converted to m2 and was 16.0 g/year/$m^2$. However, there is a need for tools that are validated with actual pollution data, as many studies rely on models. The i-Tree Eco model, while widely available, lacks studies verifying its accuracy, especially regarding comparisons of dust concentrations in areas with varying vegetation cover. Our study aimed to address this gap by comparing actual pollution measurements with i-Tree Eco model estimates in areas with different tree canopy cover. Although the results of analyses using the model for cities have been conducted (Szkop, 2020) but there is a lack of verification using empirical methods that provide data on the specifics of pollution distribution. From the results of our study, it can be concluded that urban trees contribute to improving urban air quality and human health. However, there are uncertainties regarding the accuracy of tools like the i-Tree Eco model in estimating pollutant absorption. Further research is needed to validate and refine these models.

Studies conducted in various locations, including Warsaw, Shanghai, New Zealand, and China, have shown that trees are effective in reducing air pollution levels. However, the effectiveness of trees in absorbing pollutants may vary depending on habitat conditions and tree canopy cover. Our study highlights the importance of adequate tree canopy cover in urban areas for maximizing the benefits of air pollutant removal crucial for the prevention of human health toxicity from exceeding air pollution norms. The analysis of air quality standards in Warsaw indicates that exceedances of these standards are frequent, particularly during peak hours. This underscores the need for further research on urban trees and air pollution using dust sensors, as most studies to date have relied on models rather than experimental data (Szkop, 2020; Kais et al., 2021). Holnicki et. al. (2017) conducted a study that consisted of running a model in the CALMET/CALPUFF tool. Based on the model, they determined the most polluted places in Warsaw. Work with the execution of generalized regression models (GRM) was also carried out by Majewski et. al. (2014). The impact of air pollution on visibility in the Warsaw metropolitan area, which was determined based on the aforementioned model, was investigated.

Despite the conclusions of King et. al. (2014) that who suggested that tree canopy cover likely has at most a small impact on neighborhood air quality visible in $PM_{2.5}$ concentration and represents a lack of pollution sources rather than active pollution removal we have found that on the same type of urban site and location in the city center, but with low tree canopy cover – 6% TCC (Marszałkowska Street), $PM_{2.5}$ absorption was found to be almost 14.5 times lower than on area with tree canopy cover meeting the assumptions of optimal green infrastructure density – 31% (Żwirki and Wigury Street). We assumed rather than the habitat conditions of the trees at Żwirki i Wigury Street positively affect the possibility of greater absorption of pollutants through greater opportunities for tree growth. According to Urban (2008) and Trowbridge et. al. (2004), trees need a suitable rooting space to develop properly and at the same time maximize ecosystem services. In the case of studied trees (average DBH is 18,05 cm) recommended soil volume for rooting is 13 $m^3$ (Trowbridge et al., 2004) in reality, tree pits provide 3,6 $m^3$ for rooting. Difficult habitat conditions (isolated tree pits) on Marszałkowska Street resulting in poor tree health, limit the ability of trees to absorb air pollutants. Maximizing ecosystem services in this area requires modifying (improving) habitat conditions. A study by Warsaw scientists (Olchonwik et al., 2023) showed that trees with limited rooting areas have more difficult conditions to develop than trees growing in the reserve. The differences associated with the number of mycorrhizal tops and mycorrhizal species were related to organic matter levels and soil chemical parameters, which were less favorable for root development in the rooting space limited by paving. Moreover, 25 years long research was conducted on the average life span of trees in roadside greenery zones (Dmuchowski & Badurek 2001), which showed that the average life expectancy of trees growing in small tree pits along Marszałkowska Street was 10-12 years. This indicates that it is not possible for a tree to reach full maturity and therefore high ecosystem service provision in excessively limited rooting space, common in urban locations.

## 5. Conclusion

Different levels of dust concentration were recorded on both streets depending on tree canopy cover. On the street with 6% tree canopy cover and poor habitat conditions (tree pits), exceedances of the WHO air quality standards (15 $\mu g/m^3$) were recorded 1.5 times more frequently. The results indicate that the effectiveness of purification depends on tree canopy cover. The compared avenues differ in terms of the occurrence of

PM pollutants hazardous to health according to WHO standards (15 μg/m$^3$) – on Marszałkowska Street, this type of pollution was recorded 1.5 times more often than on Żwirki i Wigury Street. All trees on Marszałkowska Street grow in pots with a maximum size of 1.9 x 1.9 m. Tree canopy cover is 25 pp. greater on streets with good site conditions for trees (separate green belt). On this basis, it can be inferred that under favorable site conditions, an increase in TCC is positively correlated with enhanced $PM_{2.5}$ capture capacity. The use of the potential of urban areas, expressed in the availability of optimal site conditions for the healthy growth of trees resulted, in our study, in more than 14 times greater effectiveness of trees in cleaning the air from $PM_{2.5}$. Our study contributes to this effort by providing empirical data on the effectiveness of trees in mitigating air pollution, but more research in context of site condition and potentially correlated TCC is warranted to fully understand the complexities of this issue. In conclusion, while there is growing public awareness of the importance of addressing urban air pollution, further research is needed to inform evidence-based decision-making in this area.

The limitations of our work are the period during which the data was collected; the work does not cover the entire year. Furthermore, comparison with municipal data was impossible due to excessive variability on small sections of streets and the distance of municipal sensors from the selected research site. It would also be advisable to install dedicated sensors that would enable comparison with municipal data

**Author contributions**

Conceptualization: Karolina Kais, Marzena Suchocka; methodology: Karolina Kais, Marzena Suchocka, ; writing—original draft preparation: Karolina Kais, Marzena Suchocka, Marlena Gołaś, Maciej Ziemiański, Hazem M. Kalaji; writing—review and editing, Karolina Kais, Marzena Suchocka, Marlena Gołaś, Maciej Ziemiański, Hazem M. Kalaji. All authors have read and agreed to the published version of the manuscript.

**Ethical Approval**

Not applicable

**Acknowledgments**

Not applicable

**Conflicts of interest**

The authors declare no conflict of interest.

**Availability of data and materials**

Data will be available on a formal request from the corresponding authors.

**Funding**

Not applicable

## REFERENCES

Akbari, H., Pomerantz, M., & Taha, H. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Solar Energy. (2001). 70(3), 295–310. https://doi.org/10.1016/S0038-092X(00)00089-X

Aslam, B., Maqsoom, A., Khalid, N., Ullah, F., & Sepasgozar, S. Urban overheating assessment through prediction of surface temperatures: A case study of Karachi, Pakistan. ISPRS International Journal of Geo-Information, (2021). 10(8), 539. https://doi.org/10.3390/IJGI10080539

Bass, B. Addressing urban environmental problems with green roofs. Encyclopedia of

Global Environmental Change (Vol. 3). John Wiley & Sons, (2001).

Bates, D. V. Ambient ozone and mortality. Epidemiology, (2005). 16(4), 427–429. https://doi.org/10.1097/01.EDE.0000165793.71278.EC

Beckett, K. P., Freer-Smith, P. H., & Taylor, G. Particulate pollution capture by urban trees: Effect of species and windspeed. Global Change Biology, (2000). 6(8), 995–1003. https://doi.org/10.1046/J.1365-2486.2000.00376.X

Beckett, K. P., Freer-Smith, P. H., & Taylor, G. Urban woodlands: their role in reducing the effects of particulate pollution. Environmental Pollution, (1998). 99(3), 347–360. https://doi.org/10.1016/S0269-7491(98)00016-5

Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., Deangelo, B. J., Zender, C. S. Bounding the role of black carbon in the climate system: A scientific assessment. Journal of Geophysical Research: Atmospheres, (2013). 118(11), 5380–5552. https://doi.org/10.1002/JGRD.50171

Bonire, G., & Gbenga-Ilori, A. Towards artificial intelligence-based reduction of greenhouse gas emissions in the telecommunications industry. Scientific African, (2021). 12, e00823. https://doi.org/10.1016/J.SCIAF.2021.E00823

Branea, A.-M., Gaman, M. S., Badescu, S., Mihai-Ionut, D., Stelian, G. M., & Ștefana, B. Challenges regarding the study of urban heat islands: Ruleset for researchers. In Proceedings of the Risk Reduction for Resilient Cities, (2016). https://www.researchgate.net/publication/309740257

Brantley, H. L., Hagler, G. S. W., Deshmukh, P., & Baldauf, R. W. Field assessment of the effects of roadside vegetation on near-road black carbon and particulate matter. Science of The Total Environment, (2014). 468–469, 120–129. https://doi.org/10.1016/J.SCITOTENV.2013.08.001

Brauer, M., Hoek, G., Smit, H. A., de Jongste, J. C., Gerritsen, J., Postma, D. S., Kerkhof, M., & Brunekreef, B. Air pollution and development of asthma, allergy and infections in a birth cohort. European Respiratory Journal, (2007). 29(5), 879–888. https://doi.org/10.1183/09031936.00083406

Bureau, P. R. World Population Highlights: Key findings from PRB's 2007 World Population Data Sheet. (2007).

Burkhardt, J. Hygroscopic particles on leaves: Nutrients or desiccants? Ecological Monographs, (2010). 80(3), 369–399. https://doi.org/10.1890/09-1988.1

CAFE. Second position paper on particulate matter. CAFE Working Group on Particulate Matter, (2004).

Cavanagh, J. A. E., Zawar-Reza, P., & Wilson, J. G. Spatial attenuation of ambient particulate matter air pollution within an urbanised native forest patch. Urban Forestry & Urban Greening, (2009). 8(1), 21–30. https://doi.org/10.1016/J.UFUG.2008.10.002

Cavanagh, J. Influence of urban trees on air quality in Christchurch: Preliminary estimates. LC0708/097, (2008).

Cen, S. Biological monitoring of air pollutants and its influence on human beings. The Open Biomedical Engineering Journal, (2015). 9(1), 219–223. https://doi.org/10.2174/1874120701509010219

Chen, G., Zhang, W., Li, S., Williams, G., Liu, C., Morgan, G. G., Jaakkola, J. J. K., & Guo, Y. Is short-term exposure to ambient fine particles associated with measles incidence in China? A multi-city study. Environmental Research, (2017). 156, 306–311. https://doi.org/10.1016/J.ENVRES.2017.03.046

Chen, L., Liu, C., Zhang, L., Zou, R., & Zhang, Z. Variation in tree species' ability to capture and retain airborne fine particulate matter (PM2.5). Scientific Reports, (2017). 7(1), 1–11. https://doi.org/10.1038/s41598-017-03360-1

Chen, S. C., & Liao, C. M. Health risk assessment on humans exposed to environmental polycyclic aromatic hydrocarbons pollution sources. Science of The Total Environment, (2006). 366(1), 112–123. https://doi.org/10.1016/J.SCITOTENV.2005.08.047

Dmuchowski, W., & Badurek, M. Stan zieleni przyulicznej w Warszawie na podstawie wieloletnich obserwacji i doświadczeń Ogrodu Botanicznego–CZRB PAN. Zieleń Warszawy. Problemy i Nadzieje, (2001). 5, 19–32.

Fisher, G., Kjellstrom, T., Woodward, A., Hales, S., Town, I., Sturman, A., Donnelly, P. Health and air pollution in New Zealand: Christchurch pilot study. (2005). https://environment.govt.nz/assets/Publications/Files/Health-and-air-pollution-nz-2005-pilot-study.pdf

Giannico, O. V., Addabbo, F., Catino, F., Bisceglia, L., Minerba, S., Mincuzzi, A., & Sardone, R. The mortality impacts of implementing the 3–30–300 greenness rule in Taranto, Southern Italy. Ecological Indicators, (2025). 178, 113895. https://doi.org/10.1016/j.ecolind.2025.113895

Gong, C., Xian, C., & Ouyang, Z. Assessment of NO2 purification by urban forests based on the i-Tree Eco model: Case study in Beijing, China. Forests, (2022). 13(3), 369. https://doi.org/10.3390/f13030369

Guo, S., Hu, M., Zamora, M. L., Peng, J., Shang, D., Zheng, J., Zhang, R. Elucidating severe urban haze formation in China. Proceedings of the National Academy of Sciences of the USA, (2014). 111(49), 17373–17378. https://doi.org/10.1073/pnas.1419604111

Helbich, M., Browning, M. H. E. M., Voets, D., & Dadvand, P. Adherence to the 3–30–300 urban green space rule and mental health, physical activity, and overweight: A population-based study in the Netherlands. Environment International, (2025). 202, 109643. https://doi.org/10.1016/j.envint.2025.109643

Ho, L., Truong, V., Pham, C., La, V., Dang, H., Nguyen, T., Tran, H. A preliminary study on the benefits of urban parks in Ho Chi Minh City using i-Tree tools. IOP Conference Series: Earth and Environmental Science, (2025). 1465(1), 012007. https://doi.org/10.1088/1755-1315/1465/1/012007

Holnicki, P., Kałuszko, A., Nahorski, Z., & Stankiewicz, K. Air quality modeling for Warsaw agglomeration. Applied Environmental Studies, (2017). 42–64. https://doi.org/10.1515/aep-2017-0005

Hoppa, A., Sikorski, P., Przybysz, A., Łaszkiewicz, E., Nawrocki, A., Archiciński, P., Sikorska, D. Wpływ drzew na jakość powietrza pyłowego: Zniuansowana perspektywa dynamiki zanieczyszczeń w drodze do szkoły. SSRN, (2024). https://ssrn.com/abstract=5173819

IQAir. Air quality and pollution city ranking. World Air Quality, (2022). https://www.iqair.com/world-air-quality-ranking

Iqbal, L. M., Njaim, G. A., Vos, D., & Permana, C. T. H. Parks please! Implementing the 3–30–300 green space rule in developing countries: The case of Surakarta, Indonesia. Urban Forestry & Urban Greening, (2025). 107, 128797. https://doi.org/10.1016/j.ufug.2025.128797

i-Tree Eco User's Manual. (2019). https://www.itreetools.org/documents/275/EcoV6_UsersManual.2021.04.19.pdf

Jeong, S. J. The impact of air pollution on human health in Suwon City. Asian Journal of Atmospheric Environment, (2013). 7(4), 227–233. https://doi.org/10.5572/AJAE.2013.7.4.227

Kais, K., Gołaś, M., & Suchocka, M. Awareness of air pollution and ecosystem services provided by trees: The case study of Warsaw City. Sustainability, (2021). 13(19), 10611. https://doi.org/10.3390/SU131910611

Konijnendijk, C. C. Evidence-based guidelines for greener, healthier, more resilient neighbourhoods: Introducing the 3–30–300 rule. Journal of Forestry Research, (2023). 34(3), 821–830.

Kołodziej, E. Warsaw 2nd city of the world with the most polluted air. Noizz Ekologia, (2021). https://noizz.pl/ekologia/warszawa-gorsza-niz-kalkuta-jest-na-2-miejscu-miast-z-najgorszym-powietrzem/c3jn196

Krzysztoszek, A., & Jakubowska, J. Poland: After the bout of frost, Warsaw and Wrocław are among the most polluted cities in the world. Euractiv.pl, (2021). https://www.euractiv.pl/section/energia-i-srodowisko/news/mroz-smog-piec-warszawa-wroclaw-zanieczyszczenie-powietrze-miasta/

Lopez, M. A., De Marco, A., Anav, A., Sorrentino, B., Paoletti, E., Manzini, J., Sicard, P. The 3–30–300 rule compliance: A geospatial tool for urban planning. Landscape and Urban Planning, (2025). 261, 105396. https://doi.org/10.1016/j.landurbplan.2025.105396

Majewski, G., Czechowski, P., Badyda, A., & Brandyk, A. Effect of air pollution on visibility in urban conditions: Warsaw case study. Environment Protection Engineering, (2014). https://doi.org/10.5277/epe140204

McDonald, A. G., Bealey, W. J., Fowler, D., Dragosits, U., Skiba, U., Smith, R. I., Nemitz, E. Quantifying the effect of urban tree planting on concentrations and depositions of PM10 in two UK conurbations. Atmospheric Environment, (2007). 41(38), 8455–8467. https://doi.org/10.1016/J.ATMOSENV.2007.07.025

Municipal Road Administration. Analysis of traffic in Warsaw. Traffic Analysis, (2021). https://zdm.waw.pl/dzialania/badania-i-analizy/analiza-ruchu-na-drogach/

Olchonwik, J., Jankowski, P., Suchocka, M., Malewski, T., Wiesiołek, A., & Hilszczańska, D. The impact of anthropogenic transformation of urban soils on ectomycorrhizal fungal communities associated with silver birch (Betula pendula Roth.) growth in natural versus urban soils. Scientific Reports, (2023). 13, 21268.

https://doi.org/10.1038/s41598-023-48592-6

Poland in Numbers. The city of Warsaw in numbers: Demographic data. (2020). https://www.polskawliczbach.pl/Warszawa

Popek, R., Przybysz, A., Łukowski, A., Baranowska, M., Bułaj, B., Hauke–Kowalska, M., & Kowalkowski, W. Shields against pollution: Phytoremediation and impact of particulate matter on trees at Wigry National Park, Poland. International Journal of Phytoremediation, (2024). 27(4), 448–461. https://doi.org/10.1080/15226514.2024.2426771

Przybysz, A., Nawrocki, A., Mirzwa-Mróz, E., et al. Gatunkowo-specyficzny wpływ grzybni mączniaka prawdziwego na efektywność akumulacji pyłu zawieszonego przez zieleń miejską. Environmental Science and Pollution Research, (2024). 31, 36163–36173. https://doi.org/10.1007/s11356-023-28371-6

Rasoolzadeh, R., Dinan, N., Esmaeilzadeh, H., Rashidi, Y., & Sadeghi, S. Assessment of air pollution removal by urban trees based on the i-Tree Eco model: The case of Tehran, Iran. Integrated Environmental Assessment and Management, (2024). 20(6), 2142–2152. https://doi.org/10.1002/ieam.4990

Riondato, E., Pilla, F., Basu, A. S., & Basu, B. Investigating the effect of trees on urban air quality in Dublin by combining air monitoring with the i-Tree Eco model. Sustainable Cities and Society, (2020). 61, 102356. https://doi.org/10.1016/j.scs.2020.102356

Russell, A. G., & Brunekreef, B. A focus on particulate matter and health. Environmental Science and Technology, (2009). 43(13), 4620–4625. https://doi.org/10.1021/es9005459

Song, J., Przybysz, A., & Zhu, C. Revealing the contribution of urban green spaces to improving the thermal environment under realistic stressors and their interactions. Sustainable Cities and Society, (2025). 126, 106426. https://doi.org/10.1016/j.scs.2025.106426

Szkop, Z. Evaluating the sensitivity of the i-Tree Eco pollution model to different pollution data inputs: A case study from Warsaw, Poland. Urban Forestry & Urban Greening, (2020). 55, 126859. https://doi.org/10.1016/j.ufug.2020.126859

Trowbridge, P., & Bassuk, N. Trees in the Urban Landscape: Site Assessment, Design and Installation. John Wiley & Sons, (2004).

Témtop. Temtop M2000 handheld air quality detector user manual. (2022). https://manuals.plus/temtop/m2000-handheld-air-quality-detector-manual#axzz7iclgeQSR

Vashist, M., Kumar, T. V., & Singh, S. K. Assessment of air quality benefits of vegetation in an urban-industrial region of India by integrating air monitoring with the i-Tree Eco model. CLEAN – Soil, Air, Water, (2024). 52(7). https://doi.org/10.1002/clen.202300198

Vesuviano, G., Fitch, A., Owen, D., Fletcher, D., & Jones, L. How well does the 3–30–300 rule mitigate urban flooding? Urban Forestry & Urban Greening, (2025). 104, 128661. https://doi.org/10.1016/j.ufug.2024.128661

Wan Mahiyuddin, W. R., Sahani, M., Aripin, R., Latif, M. T., Thach, T. Q., & Wong, C. M. Short-term effects of daily air pollution on mortality. Atmospheric Environment, (2013). 65, 69–79. https://doi.org/10.1016/J.ATMOSENV.2012.10.019

Akbari, H., Pomerantz, M., & Taha, H. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Solar Energy, (2001). 70(3), 295–310. https://doi.org/10.1016/S0038-092X(00)00089-X

Karaczun, Z., & Michalak, W. Impact of climate change and air pollution on the health of Warsaw inhabitants. (2019). https://meinwarschau.com/wp-content/uploads/2019/12/raport-klimatyczny-warszawa-koalicja-klimatyczna.pdf

**How to cite this article:** Kais, K., Gołaś, M., Suchocka, M., Ziemiański, M., & Kalaji, H. (2025). The Role of Urban Trees in PM2.5 Mitigation: Air Quality Assessment and Absorption Capacity Comparison in Warsaw Alleys. Journal of Soil, Plant and Environment, 4(2), 75–94.

## 10.3. Artykuł 3

**Kais, K.**; Suchocka, M.; Balcerzak, O.; Przybysz, A. Street Trees as Sustainable Urban Air Purifiers: A Methodological Approach to Assessing Particulate Matter Phytofiltration. Sustainability 2025, 17, 7451. (IF = 3.3) https://doi.org/10.3390/su17167451

*sustainability*

MDPI

*Article*

# Street Trees as Sustainable Urban Air Purifiers: A Methodological Approach to Assessing Particulate Matter Phytofiltration

**Karolina Kais [1,*], Marzena Suchocka [1], Olga Balcerzak [1] and Arkadiusz Przybysz [2,*]**

[1] Institute of Environmental Engineering, Warsaw University of Life Sciences—SGGW, Nowoursynowska St. 159, 02-787 Warsaw, Poland; marzena_suchocka@sggw.edu.pl (M.S.); olga_balcerzak@sggw.edu.pl (O.B.)
[2] Centre for Climate Research SGGW, Warsaw University of Life Sciences—SGGW, Nowoursynowska 166, 02-787 Warsaw, Poland
* Correspondence: karolina_kais@sggw.edu.pl (K.K.); arkadiusz_przybysz@sggw.edu.pl (A.P.)

**Abstract**

$PM_{2.5}$ is an air pollutant that has a direct link to increased cardiovascular and respiratory morbidity and mortality, which has been demonstrated in numerous studies. Existing research highlights species-specific variations in the capacity of trees to capture and retain particulate matter (PM). However, a critical gap remains regarding sensitivity analyses of i-Tree Eco model assumptions. Such analyses are crucial for validating the model's PM deposition estimates against empirically derived efficiencies, a deficiency that the present study addresses. The study consisted of two steps: a tree inventory was carried out at three selected sites, based on which, an ecosystem service analysis was performed using i-Tree Eco, and samples were taken from the leaves of trees at the analysed sites, which were the basis for comparing the data from the i-Tree Eco method and laboratory methods. The study focused on comparing $PM_{2.5}$ and $PM_{10}$ removal estimates derived from both the model and laboratory measurements. The results revealed significant discrepancies between the modelled and laboratory values. A comparison of the average annual $PM_{10}$ accumulation measured using laboratory methods for individual tree species showed that *Tilia* sp. achieved 24%, *Fraxinus* sp. 47.6%, *Aesculus* sp. 50.77%, and *Quercus robur* 23.4% of the $PM_{10}$ uptake efficiency estimated by the i-Tree Eco model. For $PM_{2.5}$ uptake, the values obtained through both methods were more consistent. Furthermore, trees growing under more challenging environmental conditions exhibited smaller diameter at breast height (DBH) and lower $PM_{10}$ and $PM_{2.5}$ removal efficiency according to both methods. While I-Tree Eco incorporates tree biophysical characteristics and health status, its methodology currently lacks the resolution to reflect site-specific environmental conditions and local pollutant concentrations at the individual tree level. Therefore, laboratory methods are indispensable for calibrating, validating, and supplementing i-Tree Eco estimates, especially when applied to diverse urban environments. Only the combined application of empirical and model-based methods provides a comprehensive understanding of the potential of urban greenery to improve air quality.

**Keywords:** air pollution; air phytofiltration; method comparison; urban trees; ecosystem services; sustainable cities

check for updates

Academic Editor: Hefa Cheng and Hui Zhi

Received: 12 July 2025
Revised: 3 August 2025
Accepted: 13 August 2025
Published: 19 August 2025

**Citation:** Kais, K.; Suchocka, M.; Balcerzak, O.; Przybysz, A. Street Trees as Sustainable Urban Air Purifiers: A Methodological Approach to Assessing Particulate Matter Phytofiltration. *Sustainability* **2025**, *17*, 7451. https://doi.org/10.3390/su17167451

## 1. Introduction

In recent years, $PM_{2.5}$ has been recognized as one of the most dominant types of air pollution. Numerous studies have demonstrated a clear link between exposure and increased rates of morbidity and mortality due to cardiovascular and respiratory conditions, including chronic obstructive pulmonary disease (COPD) and pneumonia, particularly in densely populated urban areas [1–6]. A study conducted in Shenyang, China [7] on the relationship between mortality and particle size found that PM with a diameter of less than 0.5 µm has the most adverse effect on health. Research for the Global Burden of Disease Study [8] estimates that air pollution (PM and $O_3$) may have caused 1.5 million deaths, accounting for 12.5% of all deaths in 2017. Furthermore, studies confirm the scale of PM's impact on human health, indicating that it is the second leading factor after high blood pressure, smoking, and poor diet [9].

At the same time, extensive research on the ability of plants to remove PM [10] has demonstrated their positive impact on air quality, resulting from their effectiveness in absorbing pollutants [11]. This has been confirmed by numerous laboratory and field studies analysing species relationships and the impact of tree density [12–15]. In Shanghai, it was shown that in urban forestry 50–100 m deep into the forest, PM concentrations were 9.1% lower than outside of them [16].

Urban conditions, resulting from significant human interference with the landscape, lead to the formation of anthropogenic soils, whose properties hinder the proper growth and development of vegetation [17]. These conditions are also believed to reduce the effectiveness of PM accumulation [18]. Moreover, factors such as tree canopy cover [19], plant condition [20], and terrain roughness [21] will significantly influence the level of urban pollution reduction—either positively or negatively depending on the factor.

In studies of pollutant accumulation, various methods are used to estimate PM absorption. These include models such as CNT's Green Values Calculator (greenvalues.cnt.org/national (accessed on 11 July 2024), the GreenSave Calculator (greenroofs.org (accessed on 11 July 2024)), the Street Tree Resource Analysis Tool for Urban Forest Managers (fs.fed.us/psw/programs/cufr/stratum.shtml (accessed on 11 July 2024)), The National Tree Benefit Calculator (www.treebenefits.com/calculator (accessed on 11 July 2024)) and the i-Tree Software Suite v6 (www.itreetools.org/index.php (accessed on 11 July 2024)), as well as laboratory methods such as static methods, dynamic methods, microscopic and spectroscopic methods, and methods based on weight and chemical analysis [22].

Key factors influencing the estimated pollutant absorption in these models include tree species, size (e.g., DBH, canopy spread), age, health condition, location (urban or suburban), and growth rate. Some models also incorporate site-specific data such as soil type, land use, and climatic conditions to verify estimations of ecosystem services provided by urban trees. However, these methods do not account for factors like the distance from pollution sources. Laboratory methods for estimating accumulated pollutants focus on the structure and morphology of leaf surfaces (e.g., trichomes, wax layer, stomatal density). These methods are applied to assess pollutant adsorption on a smaller time and spatial scale; gravimetric and chemical analyses quantify the mass and elemental content of deposited materials, while microscopic and spectroscopic techniques (e.g., scanning electron microscope Fourier transform infrared spectroscopy, and Energy Dispersive X-ray Spectroscopy) enable detailed visualization and identification of surface particulates and contaminant distribution.

To analyse the level of pollutants absorbed by trees, we chose the i-Tree Eco model [23], which is widely used in estimating PM absorption [24–26], as well as the laboratory method developed by Przybysz [27–29], which is well documented in the literature. However, there is a significant difference in the approach of both methods in solving the problem of estimating the amount of PM absorbed.

There is a lack of research results determining the effectiveness of air purification within certain species or in multi-species urban forests. Due to differences in leaf characteristics, tree species vary in their ability to capture and retain PM [30]. The properties that determine the ability of species to capture PM include epicuticular waxes [31], hair density [32], and surface roughness [33]. Empirical studies also show that conifers are generally more effective at capturing $PM_{2.5}$ than deciduous species [34]. Research is currently being conducted on the sensitivity of i-Tree Eco assumptions, with the aim of comparing the model's estimates with the deposition and resuspension mechanism in tree crowns [24].

It is the responsibility of landscape architects and urban forest managers to design street greenery in a way that ensures a diverse range of ecosystem services, including regulatory functions such as the absorption of air pollutants, including $PM_{10}$ and $PM_{2.5}$. While we assume that i-Tree Eco is available to urban forest managers and has the potential for widespread use, its suitability for local conditions remains uncertain. There is a possibility that the model's results may be either overestimated or underestimated.

A comparison between laboratory measurements and estimates from the i-Tree Eco model could offer a deeper understanding of how effectively urban forests retain air pollutants, helping to validate or refine the model for local applications. The use of both methods for obtaining data on pollutant adsorption is aimed at obtaining more detailed information on the adequacy of using the widely available i-Tree Eco model in the context of air purification efficiency through the use of a selected laboratory method, and, as a result, to assess the potential of the widely used i-Tree Eco model in shaping tree plantings in urban green spaces in terms of their effectiveness in the absorption of $PM_{10}$ and $PM_{2.5}$. We hypothesize that the results obtained from the i-Tree Eco model could differ in comparison with laboratory methods, with the latter overestimating the effectiveness of trees in capturing $PM_{10}$ and $PM_{2.5}$ in urban conditions compared to empirically measured values and having a limited capability to demonstrate differences in the effectiveness of air phytofiltration by different plant species, due to its failure to take into account local habitat conditions and pollutant concentrations.

## 2. Materials and Methods

The study consisted of two distinct stages: The first phase comprised a detailed tree inventory carried out in three urban sites, selected for their representative spatial and environmental characteristics. The collected dendrometric and site-specific data served as input for modelling ecosystem services using the i-Tree Eco tool. The second stage involved laboratory testing of the PM absorption capacity of tree leaves, by using the same samples which were collected from the previously analysed locations. The laboratory results were used to compare the data from the i-Tree Eco method and their similarity analysed.

This research was conducted in Warsaw, the capital of Poland, the largest city (Figure 1) in the country with an area of 517.2 $km^2$ and a population of 1,792,718 in 2022 [35]. The decision to choose this city was influenced by both its current, non-episodic poor air quality and its repeated frequent appearance in rankings of cities with the highest levels of particulate matter pollution. In January 2021, Warsaw ranked sixth in the global air pollution-ranking Air Quality Index [36], and then, in February of the same year, it was second in the World Air Quality Index [37]. As in many European cities, poor air quality in Warsaw poses a serious threat to public health and contributes to premature mortality [38].


**Figure 1.** Location of the analysed streets in Warsaw, Poland (Source: Own elaboration).

The inventory was carried out in three locations, on 700-metre sections of streets (Figure 2). Section 1 was located on Marszałkowska Street, in the immediate vicinity of the Palace of Culture and Science and the Centrum department store in the city centre. It consists of three lanes in each direction, with concrete squares and wide pavements on both sides, without any shrubbery. The area is enclosed on the eastern side by tall commercial and service buildings. The tree-lined avenue in this location consists of low small-leaved lime trees (*Tilia cordata*), which account for 100% of the species structure of the avenue, growing in 2 × 2 m planting beds between the road and the pavement. There are 100 trees along a 700-metre section, which gives an average of 143 trees per kilometre, resulting in a canopy cover of approximately 6%.


**Figure 2.** Tree inventory locations and identification numbers on selected street segments: Marszałkowska, Puławska, and Żwirki i Wigury in Warsaw (Source: Own elaboration based on aerial imagery © GUGiK, Geoportal.gov.pl).

Another section formed by a triple row of small-leaved lime trees (*Tilia cordata*) was designated along Żwirki i Wigury Street, where the two-lane road is crossed by one of the rows of trees. Small-leaved lime trees (*Tilia cordata*) account for 100% of the trees in this avenue. The selected section is adjacent to military grounds, multi-family residential buildings, and allotment gardens. It is the main thoroughfare connecting the southern part of Warsaw with Chopin Airport and the city centre. The area along the street is located in a green belt and is more densely covered than in the first section, with grassy vegetation under the tree crowns. There are 187 trees along the 700 m section, which gives an average of 267 trees per kilometre, i.e., a crown cover ratio of approx. 31%.

The third section is located on Puławska Street, where the road consists of three lanes in each direction and is adjacent to multi-family residential buildings, a market, and commercial buildings. It is the main thoroughfare connecting the city centre with the southern part of Warsaw and is also the main exit road to towns located within the Warsaw agglomeration. The habitat conditions of the trees are varied: some of them have designated tree pits, 97% grow in designated cobblestone strips, and the remaining 3% are located in the strip next to the pavement. The predominant species on Puławska Street is *Fraxinus*, which accounts for 76.3% of the species structure. There are 79 trees per 700 m on this section, which gives an average of 112 trees per kilometre and a Tree Canopy Cover index of 19%.

According to traffic measurements by the City of Warsaw, the selected areas are characterized by similar traffic intensity and have comparable geometry, i.e., they are straight sections without bends or curves. In addition, all avenues run from north to south. On this basis, it was assumed that the conditions related to air movement are similar in all locations. They were selected for analysis due to their diversity in terms of canopy cover.

### 2.1. Tree Inventory

As already mentioned, the tree inventory was carried out in three locations in July 2022 when the trees on Marszałkowska, Puławska, Żwirki, and Wigury Streets were in full leaf. The data was collected in accordance with the i-Tree Eco User Manual [39]. Measurements were carried out using a measuring tape and a Bosch GLM120c rangefinder. The trees within the scope of the study were described in detail, and their species and exact location were determined. Dendrometric measurements such as the diameter at breast height (DBH), total tree height (TOTAL TREE HEIGHT), live tree height (LIVE TREE HEIGHT), crown base height (CROWN BASE), crown width from north to south (CROWN WIDTH N-S), crown width from east to west (CROWN WIDTH E-W), crown loss (CROWN%MISS), crown health (CROWN HEALTH), and light exposure (CROWN LIGHT EXPOSURE) were taken.

The quantitative structure of the trees in the studied locations is shown in Figure 3.

| Street | Frequency | Percent |
|---|---|---|
| Marszałkowska | 99 | 29.5% |
| Puławska | 78 | 23.2% |
| Żwirki i Wigury | 159 | 47.3% |
| total | 336 | 100% |

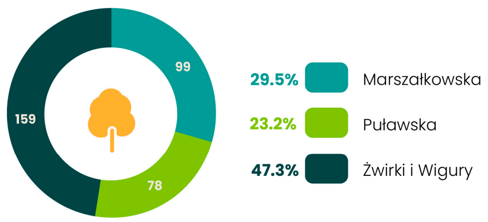



**Figure 3.** Number and percentage of inventoried street trees recorded along the three study locations: Marszałkowska, Puławska, and Żwirki i Wigury in Warsaw (Source: Own elaboration).

The average diameter of the tree trunks (DBH) on Marszałkowska Street was 17.20 cm, the average tree height was 5.2 m, and the average crown dieback was 12.2%. The average diameter of the trees on Żwirki i Wigury Street was 39.95 cm, the average tree height was 11.3 m, and the average crown dieback was 13.5%. For Puławska Street, the values are as follows: the average tree diameter was 46.37 cm, the average tree height was 12.3 m, and the average crown dieback was 18.3% (Figure 4).

| Street | Tree diameter (DBH) | Average tree height | Average crown dieback (ACD) | Predominant tree species (with %) |
|---|---|---|---|---|
| Marszałkowska | 17.20 cm | 5.20 m | 12.2% | *Tilia cordata* (100%) |
| Puławska | 46.37 cm | 12.30 m | 18.3% | *Fraxinus sp.* (76%) |
| Żwirki i Wigury | 39.95 cm | 11.30 m | 13.5% | *Tilia cordata* (100%) |

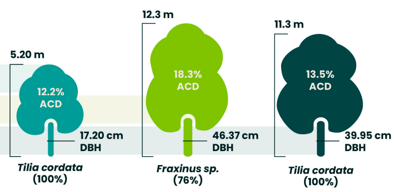



**Figure 4.** Average dendrometric parameters and predominant tree species on three inventoried streets in Warsaw (Source: Own elaboration).

Based on the inventory, it can be concluded that the largest trees are located on Puławska Street, while the smallest are on Marszałkowska Street. Crown dieback is at a similar level in all locations. The conclusions from the inventory form the basis for estimating the $PM_{10}$ and $PM_{2.5}$ absorption capacity of the plants.

### *2.2. The i-Tree Eco Model*

The analysis using the i-Tree Eco model utilized weather data and air quality data from monitors located in Warsaw [39]. The results were obtained on the basis of inventoried data, as well as the Data Base i-Tree, which has access to meteorological data and air quality data. After running the model, results were obtained on the removal of pollutants by trees located in the study areas. Variable amounts of PM absorbed depending on the month or season were taken into account, which may be caused by, among other things, factors like the lack of leaves on trees for part of the year.

### *2.3. Assessment of Suspended Particulate Matter Accumulation Using Laboratory Methods*

#### 2.3.1. Plant Material and Data Harvesting

The content of water-insoluble PM deposited on leaves, individual trees, and entire rows was assessed. Plant material from locations analysed by i-Tree Eco was harvested in July 2023 at the end of growing season. Harvesting was preceded by six days of no precipitation and strong winds and during a high PM concentration event, ensuring a sufficient number of pollutants deposited on leaves for analysis. To ensure data comparability, leaf samples (500 $cm^2$) with petioles were collected from the entire circumference of the plant and branches 1.5–2.0 m above the ground. Efforts were made to select leaves of similar age. For each species and location, material was harvested from four individual trees, with each tree serving as a biological replicate. The data were collected in accordance with the method presented in a publication by Przybysz [40].

#### 2.3.2. Quantitative Assessment of PM per $cm^2$ of Leaf

The plant material (150 $cm^2$) was first washed for 60 s with 200 mL distilled water (PM water washable from leaf surfaces) and then for 45 s with 100 mL chloroform (PM retained in leaf wax). The fractionation was performed sequentially. The wash solutions were filtered through a 10 µm paper filter (Whatman, Maidstone, Kent, UK, type 91), followed by a 2.5 µm paper filter (Whatman, Maidstone, Kent, UK, type 42), and finally, a 0.2 µm Polytetrafluoroethylene membrane filter (Whatman, Maidstone, Kent, UK). Filtration was performed using a filtration set equipped with a 47 mm glass filter funnel (PALL Corp. Port, Washington, DC, USA; New York, NY, USA) connected to a vacuum pump. Two fractions of PM were collected and analysed: 0.2–2.5 µm (fine; $PM_{2.5}$) and 2.5–10 µm (coarse; $PM_{2.5–10}$). The sum of both PM fractions was designated as $PM_{10}$ (total; 0.2–10 µm). The filters were dried at 60 °C for 45 min (KCW-100, PREMED, Marki, Poland), stabilized in the weighing room for 45 min, and weighed before and after filtration (balance XS105DU, Mettler-Toledo International Inc., and deionizer gate, HAUG, both Greifensee, Switzerland). For each species and location, material was harvested from four individual trees, with each tree serving as a biological replicate. Blind samples were used to validate the results. Filters were prepared and treated with solvents following the procedure, and one blind sample was analysed for every five experimental samples. The leaf area of the plant samples was measured (Image Analysis System equipped with Vista Protos CCTV camera (Vista CCTV, Reading, Berkshire, UK and Skye-Leaf v2 software, both Skye Instruments Ltd. Llandrindod Wells, Wales, UK).

### 2.3.3. Quantitative Assessment of PM per Tree and All the Trees in the Avenue

The total leaf areas of each tree and the entire spatial arrangement were obtained from i-Tree Eco. PM accumulation recorded in Section 2.3.2 was converted to tree and plant community levels, and then to the entire growing season, taking into account the length of the ecological functionality periods of individual plants (from the moment leaves develop on trees to the moment they lose their leaves) and precipitation washing PM off plant surfaces. It was assumed that rainfall of less than 5 mm, 5–10 mm, 10–20 mm, and more than 20 mm washes away 5%, 10%, 20% and 25% of PM deposited on plants, respectively [40]. The same weather data as in Section 4 was used.

### 2.3.4. Statistical Analysis

The variables related to pollution absorption underwent a Kolmogorov–Smirnov test to assess the normality of the distribution. The test revealed a lack of normality in the examined variables, necessitating non-parametric tests. In comparisons of the pollution absorption values in different group (street, tree species) tests, an independent-sample Kruskal–Wallis Test with a Dunn post-hoc test was employed. Additionally, a non-parametric Spearman correlation was conducted between the laboratory measurement method and the i-Tree Eco model, as well as between the absorption values of $PM_{10}$ and $PM_{2.5}$ in the i-Tree Eco method. All analyses were performed using the statistical software IBM SPSS v30.

## 3. Results

### *3.1. i-Tree Eco*

The highest total $PM_{10}$ absorption value was recorded in August on Żwirki i Wigury Street (2.264 kg), Puławska Street (1.474 kg), and on Marszałkowska Street (1.097 kg). The highest $PM_{2.5}$ absorption values were recorded in September on PuławskaStreet (0.288 kg), and in October on Żwirki i Wigury Street (0.399 kg) and on Marszałkowska Street (0.128 kg). Figure 5 shows the average $PM_{10}$ and $PM_{2.5}$ absorptions throughout the year.

**Monthly total of pollutant removal (kg)**

| | Marszałkowska $PM_{2.5}$ | Marszałkowska $PM_{10}$ | Puławska $PM_{2.5}$ | Puławska $PM_{10}$ | Żwirki i Wigury $PM_{2.5}$ | Żwirki i Wigury $PM_{10}$ | sum: |
|---|---|---|---|---|---|---|---|
| January | 0.026 | 0 | 0.129 | 0 | 0.23 | 0 | 0.39 |
| February | 0.046 | 0 | 0.154 | 0 | 0.452 | 0 | 0.65 |
| March | 0.058 | 0 | 0.281 | 0.002 | 0.387 | 0.003 | 0.73 |
| April | 0.175 | 0.014 | 1.018 | 0.139 | 0.986 | 0.168 | 2.50 |
| May | 0.137 | 0.024 | 1.251 | 0.085 | 0.874 | 0.305 | 2.68 |
| June | 0.148 | 0.009 | 1.184 | 0.069 | 1.083 | 0.014 | 2.51 |
| July | 0.170 | 0.011 | 0.989 | 0.047 | 1.262 | 0.014 | 2.49 |
| August | **0.213** | 0.007 | **1.474** | 0.051 | **2.264** | 0.092 | 4.10 |
| September | 0.139 | 0.032 | 1.053 | **0.288** | 0.704 | 0.37 | 2.59 |
| October | 0.146 | **0.032** | 1.393 | 0.251 | 1.168 | **0.399** | 3.39 |
| November | 0.041 | −0.002 | 0.187 | −0.019 | 0.429 | −0.024 | 0.61 |
| December | 0.028 | 0 | 0.167 | 0 | 0.232 | 0 | 0.43 |
| sum: | 1.33 | 0.13 | 9.28 | 0.91 | 10.07 | 1.34 | |

**Figure 5.** Monthly total of $PM_{2.5}$ and $PM_{10}$ removal (kg) by street trees on three urban streets in Warsaw. Highlighted values indicate maximum removal recorded for each location (Source: Own elaboration).

On Marszałkowska Street, *Tilia cordata* absorbs 99.7% of $PM_{10}$ and 99.6% of $PM_{2.5}$. The percentage absorption of $PM_{10}$ and $PM_{2.5}$ by *Tilia tomentosa* is 0.002, while *Quercus robur* absorbs 0.0006% of $PM_{10}$ and 0.001% of $PM_{2.5}$. Average pollution removal value by street measured is also presented (Figures 6–8).

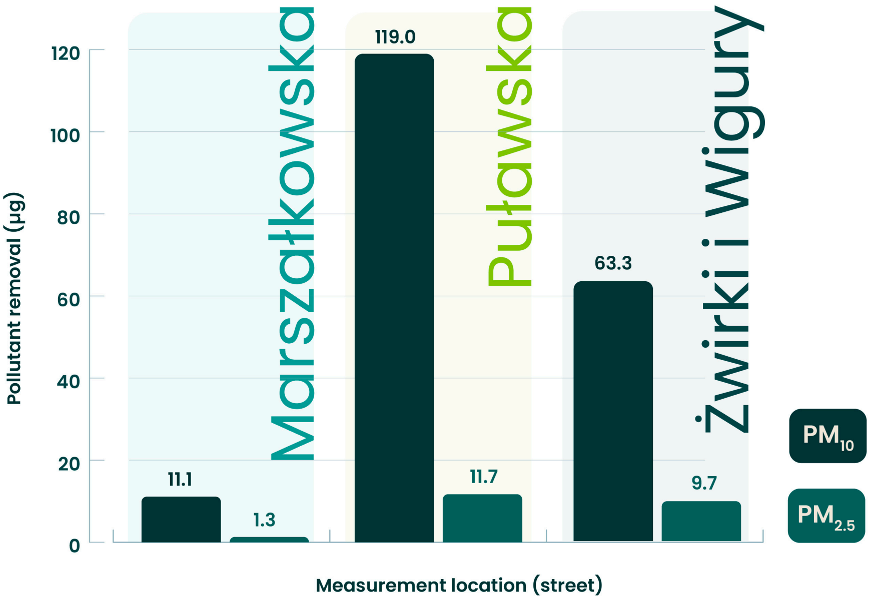



**Figure 6.** Pollution removal values for $PM_{10}$ and $PM_{2.5}$ on three inventoried streets in Warsaw, expressed in micrograms (µg) due to method sensitivity (Source: Own elaboration).

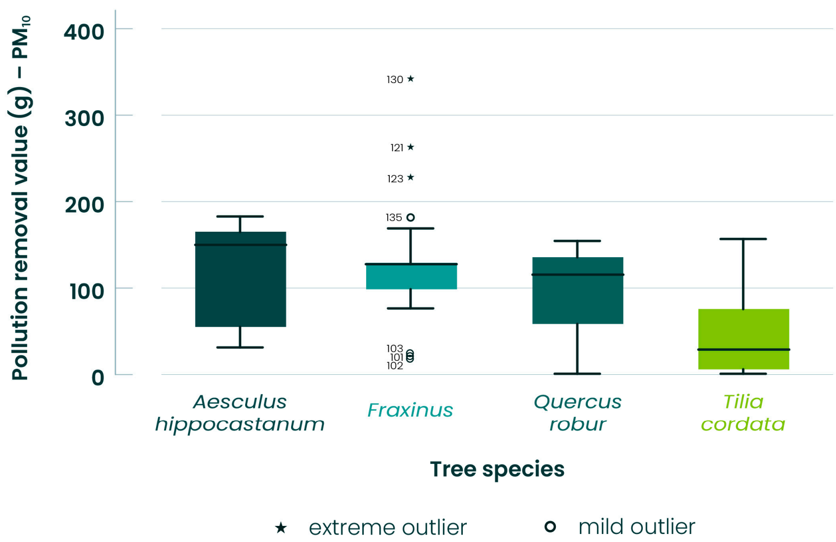



**Figure 7.** Boxplot showing the average annual $PM_{10}$ removal per tree by species, based on calculations from the i-Tree Eco model (Source: Own elaboration based on inventory and model output).

At the Puławska Street location, the most effective species is *Fraxinus sp.*, which is the predominant species in the area, and is responsible for absorbing 81.3% of both $PM_{10}$ and $PM_{2.5}$. The species that absorbs the least PM at the location is Robinia sp. It absorbs only 0.001% of both types of PM.

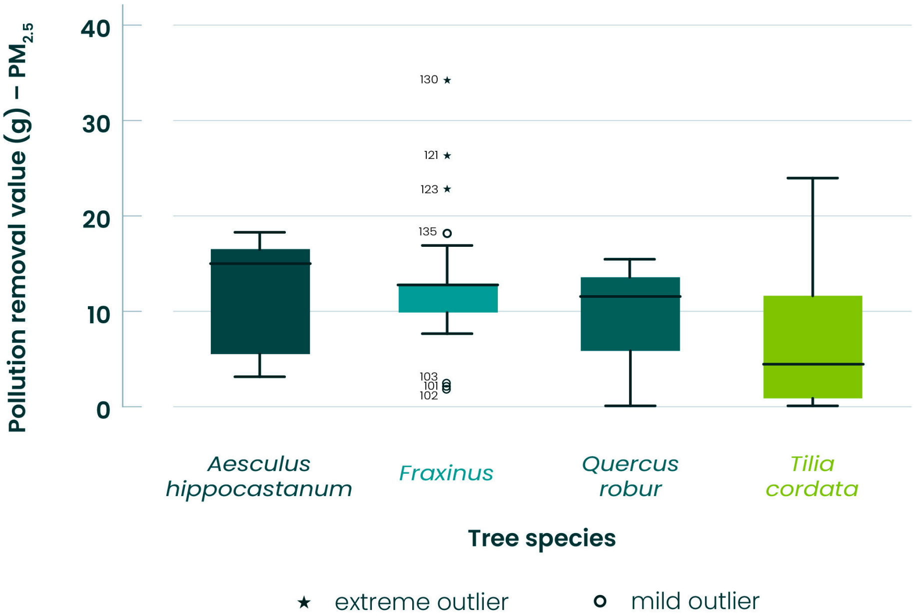



**Figure 8.** Boxplot showing the average annual $PM_{2.5}$ removal per tree by species, based on calculations from the i-Tree Eco model (Source: Own elaboration based on inventory and model output).

In the case of the study area at Żwirki i Wigury Street, the trees of the *Tilia cordata* species are 100% responsible for absorbing both types of PM.

Absorption capacities on individual streets and for specific species were calculated to identify those that are most effective, and the average for a single tree was calculated. It was shown that the most effective trees are on Pulawska Street, with an average of 119.0 g $PM_{10}$/tree (total uptake of 9280.9 g $PM_{10}$/street) and 11.7 g $PM_{2.5}$/tree (total uptake of 914.3 g $PM_{2.5}$/street), followed by those on Żwirki i Wigury Street, with an average of 63.3 g $PM_{10}$/tree (total uptake of 10,071.5 g $PM_{10}$/street) and 9.7 g $PM_{2.5}$/tree (total uptake of 1540.9 g $PM_{2.5}$/tree). Trees located along Marszałkowska Street are the least effective in absorption, with an average of 11.0 g $PM_{10}$/tree (total absorption of 1097.7 g $PM_{10}$/street) and 1.28 g $PM_{2.5}$/tree (total absorption of 128.20 g $PM_{2.5}$/street) (Figure 5).

An analysis of the pollutant uptake capacity for each species is shown in Figure 9. It was noted that *Aesculus hippocastanum* removes an average of 116.6 g $PM_{10}$/tree and 11.5 g $PM_{2.5}$/tree. For *Fraxinus excelsior*, this figure is 123.7 g $PM_{10}$/tree and 12.2 g $PM_{2.5}$/tree, while *Quercus robur* absorbs an average of 90.0 g $PM_{10}$/tree and 8.9 g $PM_{2.5}$/tree. The last species analysed was *Tilia cordata*, with an average $PM_{10}$ uptake of 50.5 g/tree and 7.6 g $PM_{2.5}$/tree.

| | empirical method - g/tree (individual) | | iTree Eco - g/tree (individual) | | empirical method (%) | | iTree Eco (%) | | empirical method g/all trees (species total) | | iTree Eco g/all trees (species total) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $PM_{10}$ | $PM_{2.5}$ | $PM_{10}$ | $PM_{2.5}$ | $PM_{10}$ | $PM_{2.5}$ | $PM_{10}$ | $PM_{2.5}$ | $PM_{10}$ | $PM_{2.5}$ | $PM_{10}$ | $PM_{2.5}$ |
| Tilia cordata | 15.1 (±1.82) | 2.54 (±0.30) | 11.08 | 1.29 | 100 | 100 | 100 | 100 | 1 494.9 | 251.4 | 1 096.9 | 127.7 |
| Fraxinus | 548.2 (±54.5) | 246.7 (±24.7) | 127.90 | 12.60 | 82.6 | 87.9 | 81.3 | 81.3 | 32 343.8 | 14 555.3 | 7 546.1 | 743.4 |
| Aesculus hippocastanum | 550.5 (±65.1) | 120.6 (±11.5) | 116.56 | 11.49 | 12.2 | 6.34 | 11.0 | 11.3 | 4 954.5 | 1 085.4 | 1 049.0 | 103.4 |
| Quercus robur | 292.9 (±31.0) | 122.5 (±22.1) | 134.8 | 13.3 | 1.44 | 1.43 | 3.0 | 2.9 | 585.8 | 245.0 | 269.6 | 26.6 |
| Tilia cordata | 60.9 (±5.32) | 24.0 (±2.10) | 19.65 | 1.95 | 0.30 | 0.28 | 1.0 | 0.4 | 121.8 | 48.0 | 39.3 | 3.9 |
| Populus alba | 432.7 (±37.4) | 148.2 (±7.77) | 147.70 | 14.60 | 1.07 | 0.87 | 2,7 | 2,8 | 865.4 | 296.4 | 295,4 | 29.2 |
| Acer platanoides | 264.1 (±22.2) | 176.1 (±14.8) | 96.60 | 9.50 | 0.65 | 1.03 | 0.01 | 0.01 | 528.2 | 352.2 | 193,.2 | 19.0 |
| Acer negundo | 625.1 (±74.4) | 341.0 (±40.6) | 125.10 | 12.30 | 1.54 | 1.99 | 1.0 | 1.3 | 625.1 | 341.0 | 125.1 | 12.3 |
| Robinia | 41.6 (±8.60) | 20.8 (±3.64) | 7.90 | 0.80 | 0.10 | 0.12 | 0.001 | 0.001 | 41.6 | 20.8 | 7.9 | 0.8 |
| Tilia cordata | 120.5 (±7.61) | 30.4 (±1.92) | 53.86 | 8.24 | 100 | 100 | 100 | 100 | 19 159.5 | 4 833.6 | 8 563.7 | 1 310.2 |

Marszałkowska Puławska Żwirki i Wigury

**Figure 9.** Comparison of $PM_{10}$ and $PM_{2.5}$ removal by tree species using empirical and i-Tree Eco methods (Source: Own elaboration).

A Kruskal–Wallis test was performed and showed that there were significant differences between the $PM_{10}$ uptake of *Tilia cordata* versus *Aesculus hippocastanum* and *Tilia cordata* versus *Fraxinus excelsior*, and significant differences in $PM_{2.5}$ uptake for *Tilia cordata* versus *Fraxinus excelsior*.

### 3.2. Comparison of Methods

The results obtained for both the empirical study and those synthesised from the i-Tree Eco simulation were the starting data for the comparative analysis of the two methods. The combined results for both methods are shown in Figure 9. The comparison for individual tree species and both methods is shown in Figure 9.

When comparing the mean annual $PM_{10}$ accumulation for individual tree species of the *Aesculus hippocastanum* species, the mean result for the laboratory method is 59.2 g/tree, and for i-Tree Eco it is 116.6 g/tree; for the *Fraxinus* species, the mean $PM_{10}$ uptake result for the laboratory method is 58.9 g/tree and for i-Tree Eco it is 123.7 g/tree. For the species *Quercus robur*, the average accumulation calculated using the laboratory method is 21.1 g/tree and for i-Tree Eco it is 90.0 g/tree. The last species for which a comparison was made is *Tilia cordata*—the result of the mean annual accumulation with the laboratory method is 12.0 g/tree and with the i-Tree Eco method it is equal to 43.6 g/tree.

A similar comparison was made for $PM_{2.5}$ uptake. The results obtained in the $PM_{2.5}$ comparison were much closer to each other than for $PM_{10}$. Accordingly, the following results were obtained for the species *Aesculus hippocastanum*—the average annual $PM_{2.5}$ accumulation obtained with the laboratory method was 13.0 g/tree, while with the i-Tree Eco method, it was 11.5 g/tree. For *Fraxinus*, the average annual $PM_{2.5}$ uptake obtained with the laboratory method was 13.8 g/tree and with the i-Tree Eco method it amounted to an average of 12.2 g/tree. For the *Quercus robur* species, the following results were obtained—the $PM_{2.5}$ uptake with the laboratory method is 8.8 g/tree and with the i-Tree Eco method 8.9 g/tree. The last species that was analysed was *Tilia cordata*—the result obtained with the laboratory method was 3.0 g/tree and with the i-Tree Eco method it was 6.5 g/tree. This was the case in which the largest difference in results was obtained.

## 4. Discussion

### 4.1. Technical Aspects of the Methods Analysed

Studies of urban PM air pollution are currently largely shaped by the i-Tree Eco model [41,42]. A comparison of the results obtained from an analysis using the i-Tree Eco model and the analytical method has only been performed in a study by Pace et al. [24]. The model has the advantage of being able to assess and value factors other than European Union air purification, while the laboratory method used in our study focuses on one type of pollution—the removal of PM by trees [27,28].

However, for analytical methods, the determination of the actual amount of pollutant on the plants and the precision of the measurement is an important advantage [43]. In addition, the possibility to select experimental sites taking into account the distance from the pollutant source, the location of the tree in the community, and the location of the sample on the plant, is a major benefit. This, with the support of the Leaf Area Index (LAI), allows a more accurate estimation of the amount of PM deposition on the plant at the time of the study [44]. In contrast to the i-Tree Eco method, an experiment analysing the role of weather factors can be carried out with the inclusion of rainfall data to ensure the washed PM values are accurately captured. In addition, empirical methods allow measurements to be made on a variety of objects and not just trees, as is the case with i-Tree Eco.

The disadvantages of laboratory analyses include their poor availability compared to i-Tree Eco software, as well as them being labour-intensive and high in costs. Furthermore, particle extraction with solvents can cause contamination of the samples [45]. This leads to a risk of interfering with the results by said contamination or the use of very poorly dissociated acids [46,47].

The i-Tree Eco model, which is the most popular tool used to assess ecosystem services, is based on procedures relating to deposition rates and resuspension rates for all tree species on the basis of a total leaf count and wind speed [24]. Various methods are used in laboratory studies, including random sampling, the replicate method, determination of PM by differential weighting, and the analysis of leaf constituents by optical measurements at specific wavelengths [48].

The i-Tree Eco model uses standardised technologies and is based on a peer-reviewed methodology supported by field research; moreover, the application is freely available to the public and offers technical support [49]. These should be considered its significant advantages, as should the short time needed to obtain results [50].

One of the main disadvantages of the i-Tree Eco model is the need to determine the effects and values of urban forests through modelling approaches, as they are difficult to define and measure directly in the field. The dynamics of change in urban forests and the results being dependent on precise field and ancillary data and important aspects (e.g., pollution data) cause the values obtained in the model not to be absolute [51]. The differences between the methods are shown in Table 1.

**Table 1.** Comparison of key characteristics of the empirical method (based on Przybysz et al. [52]) and the i-Tree Eco model for estimating PM accumulation.

| Element/Step | i-Tree Eco | Empirical Laboratory Method |
|---|---|---|
| Data source | Tree inventory (dendrometric measurements), meteorological data, air quality (Warsaw) | Leaf samples (500 $cm^2$), collected from 4 trees/species across 3 urban locations |
| Analytical approach | Ecosystem modelling based on USDA data and i-Tree database | Laboratory: PM quantification by fractionation and gravimetric analysis |
| PM type analyzed | $PM_{2.5}$ and $PM_{10}$ (simulated values across the vegetative season) | $PM_{2.5}$ and $PM_{10}$ (actual deposited mass on leaves) |
| Time reference | Modelled for full vegetative season | Actual state during sampling (following high PM episode in July 2023), calculated per full vegetative season based on i-Tree Eco and precipitation data |
| Rainfall consideration | Yes—simulated wash-off based on precipitation data | Yes—seasonal extrapolation using literature-based wash-off coefficients (Przybysz et al. [52]) |
| Seasonal variability | Included (e.g., leaf presence, precipitation, temperature) | Not included—single sampling timepoint |
| Output | Simulated PM absorption per tree/alley/season | Measured PM mass per tree, extrapolated to vegetative season |
| Strengths | Rapid assessment, applicable to large-scale urban areas | High local accuracy, based on real environmental exposure |
| Limitations | Calibrated for US data; potential mismatch with local conditions | Labor-intensive; sensitive to sampling timing and individual tree selection |

When collecting field data for use in the i-Tree Eco model, it would be beneficial to take into account factors affecting the ability to consider terrain factors influencing pollutant absorption, which would improve the accuracy of the results. Construction works carried out within the root system of trees have a negative impact on soil condition, causing mechanical damage and soil compaction [53–55]. It is assumed that these conditions have a negative impact on tree growth, limiting their potential to only a few years of vegetation [56]. An additional burden on the well-being of urban trees is soil contamination with heavy metals and elevated pH levels [57,58]. Other signs of poor tree health in urban conditions include the necrosis of entire leaves and leaf margins, abnormal growth and development of the root system [59], as well as vigour, twig dieback, twig growth, and the extent and severity of leaf chlorosis and leaf scorch [60]. These properties, mainly due to leaf loss, are directly related to the lower value of the ecosystem services provided. The proposed solutions include the use of conversion factors in the calculations in order to obtain more comprehensive information about the habitat. The i-Tree Eco model processes information about the division of the tree crown area into impervious and shrubby areas [39]; however, it would also be worth including impermeable site types in the calculations. Impermeable sites may differ in terms of the available space for root development [60] and in the modification of the habitat using, among other things, structural soil mixtures [61], which should be taken into account when entering values for the algorithm.

### *4.2. Differences in the Results Obtained with the Two Methods–Model and Empirical Method*

The i-Tree Eco method was based on empirical measurements. The $PM_{10}$ uptake efficiency of the i-Tree Eco method was found to be overestimated when calculated for all species. A comparison of the average annual $PM_{10}$ accumulation for individual tree species for *Tilia* sp. showed a laboratory value of 24% of the $PM_{10}$ uptake efficiency claimed by i-Tree Eco, while for *Fraxinus* sp.., the empirical study indicated an efficiency of 47.6% compared to that claimed by i-Tree Eco; meanwhile, for *Aesculus* sp. it was 50.77% and for *Quercus robur* 23.4% of the efficiency claimed by i-Tree Eco. No significant overestimation was found for $PM_{2.5}$ when comparing results obtained by the i-Tree Eco method and empirically. The differences in results ranged from 12% to 46% for the species studied, with the 46% difference being recorded for only one species.

### *4.3. Potential Reasons for Differences Between Methods*

The i-Tree Eco method does not take into account the habitat stress factor—the condition is expressed by the percentage of dead branches in the crown at the time of the inventory [39]; it does not take into account phenology, such as the earlier leaf drop of trees [58] or reduction in leaf area [62] under stress conditions. Trees growing under habitat stress shed their leaves before the end of the growing season and differences between stressed and non-stressed trees can reach up to 30 days [63]. It seems important in the analyses to include the habitat stress factor in the calculation of PM uptake levels. The results obtained show a variety of pollutant uptake by linden trees in different locations. The results showed that environmental and, above all, habitat conditions are important. Despite the fact that, along with other urban conditions, PM negatively affects the photosynthetic process—so the efficiency of air purification will also be conditioned by the concentration of PM in the air [64]—it can be concluded that this is a necessary action to improve the habitat conditions of plants so that they can provide ecosystem services at a high level.

Research by Staples et al. highlights the importance of ecosystem restoration to increase biodiversity and consequently improve ecosystem services such as habitat creation and carbon sequestration [65]. Quigley [66], in his study, found that urban trees had smaller trunk diameters than rural trees of the same age, influenced by proximity to impervious areas, showing reduced growth rates and, consequently, reduced final size. In the case of deteriorated habitat conditions (small tree pits surrounded by the impermeable areas of Marszałkowska Street) and consequently weakened root systems, trees are in poorer condition due, for example, to the depletion of biodiversity within the rhizosphere [67], resulting in lower PM uptake values. Achieving a high level of ecosystem services therefore involves improving habitat conditions and enabling the potential to clean the air of PM but also to perform other ecosystem services independent of the species. The i-Tree Eco method only considers visual crown loss (the number of lost branches) and the visual percentage loss of leaves without taking specific stress factors into account when conducting the analyses.

### *4.4. Benefits of Urban Tree Planting*

A significant trend in contemporary research is focused on assessing the ecological benefits of urban tree planting, with particular emphasis on air purification. In his research, Zhang [68] points to the benefits in terms of air quality improvement. Similar results were obtained in studies conducted by Riondato [69], which pointed to the potential of urban trees to remove $PM_{2.5}$ when compared to a tree-free avenue. Absorption results were significantly higher in the tree-lined avenue than in the tree-free avenue.

Furthermore, biodiversity studies indicate links between health benefits and biodiversity. Studies conducted by Fuller [70] and Van der Berg [71] point to a link between biodiversity and mental health benefits. In addition, research conducted by Hanski [72] proved the impact of biodiversity on minimising the effects of allergies. Health risks caused by the inability of trees to purify the air and shade the area have also been linked to the possibility of heart attacks and asthma attacks [73]. In the above studies, Hopkins demonstrated the negative impact of the lack of trees on the increased incidence of these health risks. In summary, tree planting with biodiversity in mind should be particularly recommended to decision makers involved in the planning and approval of urban planting projects.

The study suggests that the compared methods have different applications. i-Tree Eco allows for research to be conducted in a broader spatio-temporal perspective. Laboratory methods are definitely more effective in small-scale case studies and when studying processes related to phytoremediation of PM from the air, e.g., PM retention on plants, the impact of PM on plants, etc. However, the results of laboratory studies should be used to improve i-Tree Eco models and to validate them.

## 5. Conclusions

Analysing the two methods, we can conclude that the i-Tree Eco method is limited by the risk of error due to, amongst other things, the lack of consideration of the local conditions in a wider context or the possibility of an error by the field worker during the collection of the inventory data. The main limitations of the empirical method, on the other hand, are the lack of standardisation and the dependence of the results on weather conditions.

A comparison of the results obtained with the two methods showed significant differences in the results for $PM_{10}$. The differences in the results obtained occur in both directions—this means that the rule that i-Tree Eco over- or underestimates the results when compared with the laboratory method has not been confirmed. At the same time, biodiversity in tree-lined avenues enhances ecosystem services, which should be considered when planning plantings.

The results obtained indicate that trees which grow in the right habitat can guarantee a higher value of ecosystem services—the results obtained on Żwirki i Wigury confirm this assumption. The difference in habitat conditions is most evident on Marszałkowska Street, where the planted trees are not provided with the optimal conditions for growth and the uptake values are much lower than for the other streets. The *Tilia cordata Mill.* species planted in two different habitats behaves quite differently in terms of $PM_{10}$ and

$PM_{2.5}$ uptake efficiency also due to the phytosanitary condition of the plants, which most likely influences their growth potential and thus their air purification efficiency.

To make the PM uptake result more realistic, one possible approach is to leverage the strengths of both methods, i.e., to compare the relatively easy-to-obtain i-Tree Eco results and the results obtained with the laboratory method. A comparison of this kind makes it possible to take local conditions, for example, habitat conditions, into account in the analysis and thus to 'calibrate' the i-Tree Eco model to a certain extent. It seems that the urban forest management process requires periodic verification of the PM uptake efficiency of urban forests using laboratory methods, especially in climate change dynamics.

Further research may focus on comparative analyses between the i-Tree Eco algorithms and both local habitat and the trees' physiological conditions.

**Author Contributions:** Conceptualization, K.K.; Methodology, K.K. and A.P.; Software, K.K.; Validation, A.P.; Formal analysis, K.K.; Investigation, K.K.; Writing—original draft, K.K., M.S., O.B. and A.P.; Writing—review & editing, K.K., M.S., O.B. and A.P.; Visualization, O.B.; Supervision, M.S. and A.P.; Project administration, M.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Guyatt, A.L.; Cai, Y.S.; Doiron, D.; Tobin, M.D.; Hansell, A.L. Air pollution, lung function and mortality: Survival and mediation analyses in UK Biobank. *ERJ Open Res.* **2024**, *10*, 00093-2024. [CrossRef]
2. Syuhada, G.; Akbar, A.; Hardiawan, D.; Pun, V.; Darmawan, A.; Heryati, S.H.A.; Siregar, A.Y.M.; Kusuma, R.R.; Driejana, R.; Ingole, V.; et al. Impacts of air pollution on health and cost of illness in Jakarta, Indonesia. *Int. J. Environ. Res. Public Health* **2023**, *20*, 2916. [CrossRef] [PubMed]
3. Brook, R.D.; Franklin, B.; Cascio, W.; Hong, Y.; Howard, G.; Lipsett, M.; Luepker, R.; Mittleman, M.; Samet, J.; Smith, S.C., Jr.; et al. Air pollution and cardiovascular disease: A statement for healthcare professionals from the expert panel on population and prevention science of the American Heart Association. *Circulation* **2004**, *109*, 2655–2671. [CrossRef] [PubMed]
4. Brook, R.D.; Rajagopalan, S.; Pope, C.A., 3rd; Brook, J.R.; Bhatnagar, A.; Diez-Roux, A.V.; Holguin, F.; Hong, Y.; Luepker, R.V.; Mittleman, M.A.; et al. Particulate matter air pollution and cardiovascular disease: An update to the scientific statement from the American Heart Association. *Circulation* **2010**, *121*, 2331–2378. [CrossRef]
5. Pope, C.A., III.; Dockery, D.W. Health effects of fine particulate air pollution: Lines that connect. *J. Air Waste Manag. Assoc.* **2006**, *56*, 709–742. [CrossRef]
6. Dockery, D.; Pope, C.; Xu, X.; Spengler, J.; Ware, J.; Fay, M. An association between air-pollution and mortality in 6 United-States cities. *N. Engl. J. Med.* **1993**, *329*, 1753–1759. [CrossRef] [PubMed]
7. Meng, X.; Ma, Y.; Chen, R.; Zhou, Z.; Chen, B.; Kan, H. Size-fractionated particle number concentrations and daily mortality in a Chinese city. *Environ. Health Perspect.* **2013**, *121*, 1174–1178. [CrossRef]
8. Stanaway, J.D.; Afshin, A.; Gakidou, E.; Lim, S.S.; Abate, D.; Abate, K.H.; Abbafati, C.; Abbasi, N.; Abbastabar, H.; Abd-Allah, F.; et al. Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks for 195 countries and territories, 1990–2017: A systematic analysis for the Global Burden of Disease Study 2017. *Lancet* **2018**, *392*, 1923–1994. [CrossRef]
9. Vos, T.; Slim, S.; Abbafati, C.; Abbas, K.M.; Abbasi, M.; Abbasifard, M.; Abbasi-Kangevari, M.; Abbastabar, H.; Abd-Allah, F.; Abdelalim, A.; et al. Global burden of 369 diseases and injuries in 204 countries and territories, 1990–2019: A systematic analysis for the Global Burden of Disease Study 2019. *Lancet* **2020**, *396*, 1204–1222. [CrossRef]
10. Pandey, A.; Behera, S.K.; Dwivedi, S.; Singh, V.K.; Pandey, V. Assessment of phytodiversity and phytoremediation potential of plants in the vicinity of a thermal power plant. *Int. J. Phytoremediat.* **2024**, *26*, 1863–1872. [CrossRef]

11. Mandal, M.; Popek, R.; Przybysz, A.; Roy, A.; Das, S.; Sarkar, A. Breathing fresh air in the city: Implementing avenue trees as a sustainable solution to reduce particulate pollution in urban agglomerations. *Plants* **2023**, *12*, 1545. [CrossRef]
12. Petrova, S. The added value of urban trees (*Tilia tomentosa* Moench, *Fraxinus excelsior* L. and *Pinus nigra* J.F. Arnold) in terms of air pollutant removal. *Forests* **2024**, *15*, 1034. [CrossRef]
13. Chen, D.; Yan, J.; Sun, N.; Sun, W.; Zhang, W.; Long, Y.; Yin, S. Selective capture of $PM_{2.5}$ by urban trees: The role of leaf wax composition and physiological traits in air quality enhancement. *J. Hazard. Mater.* **2024**, *478*, 135428. [CrossRef]
14. Saadat, O.; Teiri, H.; Mohammadi, F.; Hajizadeh, Y. Accumulation of heavy metals in the leaves of different tree species and its association with the levels of atmospheric PM2.5-bond heavy metals in Isfahan. *Int. J. Phytoremediat.* **2025**, *27*, 260–270. [CrossRef]
15. Steinparzer, M.; Schaubmayr, J.; Godbold, D.L.; Rewald, B. Particulate matter accumulation by tree foliage is driven by leaf habit types, urbanization-and pollution levels. *Environ. Pollut.* **2023**, *335*, 122289. [CrossRef]
16. Shan, Y.; Shen, Z.; Zhou, P.; Zou, X.; Che, S.; Wang, W. Quantifying air pollution attenuation within urban parks: An experimental approach in Shanghai, China. *Environ. Pollut.* **2011**, *159*, 2155–2163. [CrossRef] [PubMed]
17. Dazzi, C.; Lo Papa, G. Anthropogenic soils: General aspects and features. *Ecocycles* **2015**, *1*, 3–8. [CrossRef]
18. McDonald, A.G.; Bealey, W.J.; Fowler, D.; Dragosits, U.; Skiba, U.; Smith, R.I.; Donovan, R.G.; Brett, H.E.; Hewitt, C.N.; Nemitz, E. Quantifying the effect of urban tree planting on concentrations and depositions of PM10 in two UK conurbations. *Atmos. Environ.* **2007**, *41*, 8455–8467. [CrossRef]
19. Sicard, P.; Pascu, I.-S.; Petrea, S.; Leca, S.; De Marco, A.; Paoletti, E.; Agathokleous, E.; Calatayud, V. Effect of tree canopy cover on air pollution-related mortality in European cities: An integrated approach. *Lancet Planet. Health* **2025**, *9*, e527–e537. [CrossRef]
20. Li, Y.; Chen, X.; Sonne, C.; Lam, S.S.; Yang, Y.; Ma, N.L.; Peng, W. Reduction and control of air pollution: Based on plant-microbe interactions. *Environ. Pollut. Bioavailab.* **2023**, *35*, 2173657. [CrossRef]
21. Barnes, M.J.; Brade, T.K.; MacKenzie, A.R.; Whyatt, J.D.; Carruthers, D.J.; Stocker, J.; Cai, X.; Hewitt, C.N. Spatially-varying surface roughness and ground-level air quality in an operational dispersion model. *Environ. Pollut.* **2014**, *185*, 44–51. [CrossRef]
22. Mazur, J. Plants as natural anti-dust filters—Preliminary research. *Tech. Trans.* **2018**, *115*, 165–172. [CrossRef]
23. Nowak, D.J.; Crane, D.E.; Stevens, J.C. Air pollution removal by urban trees and shrubs in the United States. *Urban For. Urban Green.* **2006**, *4*, 115–123. [CrossRef]
24. Pace, R.; Guidolotti, G.; Baldacchini, C.; Pallozzi, E.; Grote, R.; Nowak, D.J.; Calfapietra, C. Comparing i-Tree Eco estimates of particulate matter deposition with leaf and canopy measurements in an urban Mediterranean holm oak forest. *Environ. Sci. Technol.* **2021**, *55*, 6613–6622. [CrossRef]
25. Vashist, M.; Kumar, T.V.; Singh, S.K. Assessment of air quality benefits of vegetation in an urban-industrial region of India by integrating air monitoring with i-Tree Eco model. *Clean-Soil Air Water* **2024**, *52*, 2300198. [CrossRef]
26. Satoshi, H.; Kroll, C.N.; Nowak, D.J.; Endreny, T.A. I-Tree eco dry deposition model descriptions. *Citeseer* **2012**, *36*, 1–43.
27. Nersisyan, G.; Przybysz, A.; Vardanyan, Z.; Sayadyan, H.; Muradyan, N.; Grigoryan, M.; Ktrakyan, S. Peculiarities of particulate matter absorption by urban tree species in the major cities of Armenia. *Sustainability* **2024**, *16*, 10217. [CrossRef]
28. Popek, R.; Roy, A.; Mandal, M.; Przybysz, A.; Drążkiewicz, K.; Romanowska, P.; Sarkar, A. Enhancing urban sustainability: How spatial and height variability of roadside plants improves pollution capture for greener cities. *Sustainability* **2024**, *16*, 11131. [CrossRef]
29. Roy, A.; Das, S.; Singh, P.; Mandal, M.; Kumar, M.; Rajlaxmi, A.; Vijayan, N.; Awasthi, A.; Chhetri, H.; Roy, S.; et al. Summer-time monitoring and source apportionment study of both coarse, fine, and ultra-fine particulate pollution in Eastern Himalayan Darjeeling: A hint to health risk during peak tourist season. *MAPAN* **2024**, *39*, 995–1009. [CrossRef]
30. Sgrigna, G.; Baldacchini, C.; Dreveck, S.; Cheng, Z.; Calfapietra, C. Relationships between air particulate matter capture efficiency and leaf traits in twelve tree species from an Italian urban-industrial environment. *Sci. Total Environ.* **2020**, *718*, 137310. [CrossRef]
31. Wang, L.; Gong, H.; Liao, W.; Wang, Z. Accumulation of particles on the surface of leaves during leaf expansion. *Sci. Total Environ.* **2015**, *532*, 420–434. [CrossRef]
32. Muhammad, S.; Wuyts, K.; Samson, R. Atmospheric net particle accumulation on 96 plant species with contrasting morphological and anatomical leaf characteristics in a common garden experiment. *Atmos. Environ.* **2019**, *202*, 328–344. [CrossRef]
33. Shao, F.; Wang, L.; Sun, F.; Li, G.; Yu, L.; Wang, Y.; Zeng, X.; Yan, H.; Dong, L.; Bao, Z. Study on different particulate matter retention capacities of the leaf surfaces of eight common garden plants in Hangzhou, China. *Sci. Total Environ.* **2019**, *652*, 939–951. [CrossRef]
34. Zhang, Y.; Tang, L.; Croteau, P.L.; Favez, O.; Sun, Y.; Canagaratna, M.R.; Wang, Z.; Couvidat, F.; Albinet, A.; Zhang, H.; et al. Field characterization of the $PM_{2.5}$ aerosol chemical speciation monitor: Insights into the composition, sources, and processes of fine particles in eastern China. *Atmos. Chem. Phys.* **2017**, *17*, 14501–14517. [CrossRef]
35. Poland in Numbers. The City of Warsaw in Numbers. Available online: https://www.polskawliczbach.pl/Warszawa (accessed on 3 August 2025).
36. Euractiv.pl. Available online: https://www.euractiv.pl/section/energia-i-srodowisko/news/mroz-smog-piec-warszawa-wroclaw-zanieczyszczenie-powietrze-miasta/ (accessed on 3 August 2025).

37. NOIZZ Ekologia. Available online: https://noizz.pl/ekologia/warszawa-gorsza-niz-kalkuta-jest-na-2-miejscu-miast-z-najgorszym-powietrzem/c3jn196 (accessed on 3 August 2025).
38. *Climate Change, Impacts and Vulnerability in Europe 2012*; EEA Report No 12/2012; An Indicator-Based Report; EEA: Copenhagen, Denmark, 2012; pp. 168–204.
39. i-Tree Eco User's Manual. Available online: https://www.itreetools.org/documents/275/EcoV6_UsersManual.2021.09.22.pdf (accessed on 3 August 2025).
40. Przybysz, A.; Nersisyan, G.; Gawroński, S.W. Removal of particulate matter and trace elements from ambient air by urban greenery in the winter season. *Environ. Sci. Pollut. Res.* **2019**, *26*, 473–482. [CrossRef] [PubMed]
41. Selmi, W.; Weber, C.; Rivière, E.; Blond, N.; Mehdi, L.; Nowak, D. Air pollution removal by trees in public green spaces in Strasbourg city, France. *Urban For. Urban Green.* **2016**, *17*, 192–201. [CrossRef]
42. Gong, C.; Xian, C.; Ouyang, Z. Assessment of no2 purification by urban forests based on the i-tree eco model: Case study in beijing, china. *Forests* **2022**, *13*, 369. [CrossRef]
43. Grandesso, E.; Ballesta, P.P.; Kowalewski, K. Thermal desorption GC–MS as a tool to provide PAH certified standard reference material on particulate matter quartz filters. *Talanta* **2013**, *105*, 101–108. [CrossRef] [PubMed]
44. Gaglio, M.; Pace, R.; Muresan, A.N.; Grote, R.; Castaldelli, G.; Calfapietra, C.; Fano, E.A. Species-Specific Efficiency in $PM_{2.5}$ Removal by Urban Trees: From Leaf Measurements to Improved Modeling Estimates. *Sci. Total Environ.* **2022**, *844*, 157131. [CrossRef] [PubMed]
45. Galvão, A.; Segers, I.; Smitz, J.; Tournaye, H.; De Vos, M. In vitro maturation (IVM) of oocytes in patients with resistant ovary syndrome and in patients with repeated deficient oocyte maturation. *J. Assist. Reprod. Genet.* **2018**, *35*, 2161–2171. [CrossRef]
46. Sarzanin, C. Recent developments in ion chromatography. *J. Chromatogr. A* **2002**, *956*, 3–13. [CrossRef]
47. López-Ruiz, B. Advances in the determination of inorganic anions by ion chromatography. *J. Chromatogr. A* **2000**, *881*, 607–627. [CrossRef] [PubMed]
48. Chaudhary, I.J.; Rathore, D. Dust Pollution: Its Removal and Effect on Foliage Physiology of Urban Trees. *Sustain. Cities Soc.* **2019**, *51*, 101696. [CrossRef]
49. Nowak, D.; Crane, D.; Stevens, J.; Hoehn, R.; Walton, J.; Bond, J. A Ground-Based Method of Assessing Urban Forest Structure and Ecosystem Services. *Arboric. Urban For.* **2008**, *34*, 347–358. [CrossRef]
50. Bagstad, K.J.; Semmens, D.J.; Waage, S.; Winthrop, R. A Comparative Assessment of Decision-Support Tools for Ecosystem Services Quantification and Valuation. *Ecosyst. Serv.* **2013**, *5*, 27–39. [CrossRef]
51. Kim, G. Assessing Urban Forest Structure, Ecosystem Services, and Economic Benefits on Vacant Land. *Sustainability* **2016**, *8*, 679. [CrossRef]
52. Przybysz, A.; Sæbø, A.; Hanslin, H.M.; Gawroński, S.W. Accumulation of Particulate Matter and Trace Elements on Vegetation as Affected by Pollution Level, Rainfall and the Passage of Time. *Sci. Total Environ.* **2014**, *481*, 360–369. [CrossRef]
53. Pike, K.; O'Herrin, K.; Klimas, C.; Vogt, J. Tree Preservation during Construction: An Evaluation of a Comprehensive Municipal Tree Ordinance. *Urban For. Urban Green.* **2021**, *57*, 126914. [CrossRef]
54. Suchocka, M.; Jankowski, P.; Błaszczyk, M. Tree Protection on Construction Sites—Knowledge and Perception of Polish Professionals. *Urban For. Urban Green.* **2019**, *46*, 126436. [CrossRef]
55. Watson, G.W.; Kelsey, P. The Impact of Soil Compaction on Soil Aeration and Fine Root Density of Quercus palustris. *Urban For. Urban Green.* **2006**, *4*, 69–74. [CrossRef]
56. Hilbert, D.R.; Roman, L.A.; Koeser, A.K.; Vogt, J.; van Doorn, N.S. Urban Tree Mortality: A Literature Review. *Arboric. Urban For.* **2019**, *45*, 167–200. [CrossRef]
57. Olchowik, J.; Suchocka, M.; Jankowski, P.; Malewski, T.; Hilszczańska, D. The ectomycorrhizal community of urban linden trees in Gdańsk, Poland. *PLoS ONE* **2021**, *16*, e0237551. [CrossRef]
58. Krzyżaniak, M.; Świerk, D.; Antoszewski, P. Factors Influencing the Health Status of Trees in Parks and Forests of Urbanized Areas. *Forests* **2021**, *12*, 656. [CrossRef]
59. Martinez, C.; Coelho-Duarte, A. Hazard indicators in urban trees. case studies on platanus x hispanica mill. ex münchh and morus alba l. in mendoza city-argentina. *Rev. De La Fac. De Cienc. Agrar. Uncuyo* **2023**, *55*, 152–165. [CrossRef]
60. Berrang, P.; Karnosky, D.F.; Stanton, B.J. The role of water stress in tree growth. *Arboric. Urban For.* **1985**, *11*, 185–189. [CrossRef]
61. Kociel, H.; Kalaji, H.; Suchocka, M.; Tuchowska, Ż. Structural soil as one of the pro ecological solutions for cities. *Ecol. Eng. Environ. Technol.* **2018**, *19*, 81–90. [CrossRef] [PubMed]
62. Suchocka, M.; Swoczyna, T.; Kosno-Jończy, J.; Kalaji, H.M. Impact of heavy pruning on development and photosynthesis of *Tilia cordata* Mill. trees. *PLoS ONE* **2021**, *16*, e0256465. [CrossRef]
63. Górka, M.; Bartz, W.; Skuridina, A.; Potysz, A. Populus nigra Italica Leaves as a Valuable Tool for Mineralogical and Geochemical Interpretation of Inorganic Atmospheric Aerosols' Genesis. *Atmosphere* **2020**, *11*, 1126. [CrossRef]

64. Popek, R.; Przybysz, A.; Gawrońska, H.; Klamkowski, K.; Gawroński, S.W. Impact of Particulate Matter Accumulation on the Photosynthetic Apparatus of Roadside Woody Plants Growing in the Urban Conditions. *Ecotoxicol. Environ. Saf.* **2018**, *163*, 56–62. [CrossRef] [PubMed]
65. Staples, T.; Dwyer, J.M.; Mayfield, M.M.; England, J.R. Productivity does not correlate with species and functional diversity in Australian reforestation plantings across a wide climate gradient. *Glob. Ecol. Biogeogr.* **2019**, *28*, 1003–1015. [CrossRef]
66. Quigley, M.F. Street trees and rural conspecifics: Will long-lived trees reach full size in urban conditions? *Urban Ecosyst.* **2004**, *7*, 29–39. [CrossRef]
67. Błońska, E.; Lasota, J.; Prażuch, W.; Ilek, A. Vertical variations in enzymatic activity and C:N:P stoichiometry in forest soils under the influence of different tree species. *Eur. J. For. Res.* **2025**, *144*, 83–94. [CrossRef]
68. Zhang, B.; Wang, W.; He, X.; Zhou, W.; Xiao, L.; Lv, H.; Wei, C. Urban forest characteristics and ecological services in Harbin. *Chin. J. Ecol.* **2017**, *36*, 951–961.
69. Riondato, E.; Pilla, F.; Sarkar Basu, A.S.; Sarkar Basu, B. Investigating the effect of trees on urban quality in Dublin by combining air monitoring with i-Tree Eco model. Sustain. *Cities Soc.* **2020**, *61*, 102356. [CrossRef]
70. Fuller, R.A.; Irvine, K.N.; Devine-Wright, P.; Warren, P.H.; Gaston, K.J. Psychological benefits of greenspace increase with biodiversity. *Biol. Lett.* **2007**, *3*, 390–394. [CrossRef]
71. van den Berg, M.; van Poppel, M.; van Kamp, I.; Andrusaityte, S.; Balseviciene, B.; Cirach, M.; Danileviciute, A.; Ellis, N.; Hurst, G.; Masterson, D.; et al. Visiting green space is associated with mental health and vitality: A cross-sectional study in four european cities. *Health Place* **2016**, *38*, 8–15. [CrossRef] [PubMed]
72. Hanski, I.; von Hertzen, L.; Fyhrquist, N.; Koskinen, K.; Torppa, K.; Laatikainen, T.; Karisola, P.; Auvinen, P.; Paulin, L.; Mäkelä, M.J.; et al. Environmental biodiversity, human microbiota, and allergy are interrelated. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 8334–8339. [CrossRef] [PubMed]
73. Hopkins, L.; January-Bevers, D.; Caton, E.I.; Campos, L. Prosty model sadzenia drzew w celu poprawy klimatu, zanieczyszczenia powietrza, zdrowia i upałów miejskich w lokalizacjach narażonych na zmiany klimatu z wykorzystaniem partnerów nietradycyjnych. *Plants People Planet* **2021**, *4*, 243–257. [CrossRef]

## 11. Oświadczenia współautorów

Warszawa, 25.10.2025 r.

Karolina Kais
karolina_kais@sggw.edu.pl

Rada Dyscypliny Inżynieria
Środowiska, Górnictwo i
Energetyka
Szkoły Głównej Gospodarstwa
Wiejskiego w Warszawie

Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracach:

- Kais, K.; Gołaś, M.; Suchocka, M. Awareness of Air Pollution and Ecosystem Services Provided by Trees: The Case Study of Warsaw City. Sustainability 2021, 13, 10611 mój indywidualny udział polegał na konceptualizacji, opracowaniu metodyki, zarządzaniu danymi, walidacji, formalnej analizie, wizualizacji, pisaniu oryginalnej wersji pracy oraz jej edycji i recenzji.
- Kais, K.; Gołaś, M.; Suchocka, M.; Ziemiański, M.; Kalaji, H. M. The Role of Urban Trees in PM2.5 Mitigation: Air Quality Assessment and Absorption Capacity Comparison in Warsaw Alleys. JSPAE 2025, 4, 75–94 mój indywidualny udział polegał na konceptualizacji, opracowaniu metodyki, zarządzaniu danymi, walidacji, formalnej analizie, wizualizacji, pisaniu oryginalnej wersji pracy oraz jej edycji i recenzji.
- Kais, K.; Suchocka, M.; Balcerzak, O.; Przybysz, A. Street Trees as Sustainable Urban Air Purifiers: A Methodological Approach to Assessing Particulate Matter Phytofiltration. Sustainability 2025, 17, 7451 mój indywidualny udział polegał na konceptualizacji, opracowaniu metodyki, zarządzaniu danymi, walidacji, formalnej analizie, wizualizacji, pisaniu oryginalnej wersji pracy oraz jej edycji i recenzji.

Karolina Kais
..............................
(Podpis)

Warszawa, 25.10.2025 r.

Marzena Suchocka
marzena_suchocka@sggw.edu.pl

Rada Dyscypliny Inżynieria
Środowiska, Górnictwo i
Energetyka
Szkoły Głównej Gospodarstwa
Wiejskiego w Warszawie

Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracach:

- Kais, K.; Gołaś, M.; Suchocka, M. Awareness of Air Pollution and Ecosystem Services Provided by Trees: The Case Study of Warsaw City. Sustainability 2021, 13, 10611 mój indywidualny udział polegał na konsultacjach w procesie konceptualizacji, konsultacjach w opracowaniu metodyki, udziale w przeglądzie i redakcji artykułu oraz pozyskaniu funduszy.
- Kais, K.; Gołaś, M.; Suchocka, M.; Ziemiański, M.; Kalaji, H. M. The Role of Urban Trees in PM2.5 Mitigation: Air Quality Assessment and Absorption Capacity Comparison in Warsaw Alleys. JSPAE 2025, 4, 75–94 mój indywidualny udział polegał na konsultacjach w procesie konceptualizacji, konsultacjach w opracowaniu metodyki, udziale przeglądzie i redakcji artykułu oraz pozyskaniu funduszy.
- Kais, K.; Suchocka, M.; Balcerzak, O.; Przybysz, A. Street Trees as Sustainable Urban Air Purifiers: A Methodological Approach to Assessing Particulate Matter Phytofiltration. Sustainability 2025, 17, 7451 mój indywidualny udział polegał na konsultacjach w procesie konceptualizacji, konsultacjach w opracowaniu metodyki, udziale w przeglądzie i redakcji artykułu oraz pozyskaniu funduszy.

Marzena Suchocka
..........................................
(Podpis)

Warszawa, 25.10.2025 r.

Marlena Wójcik z d. Gołaś
marlena_golas@sggw.edu.pl

Rada Dyscypliny Inżynieria
Środowiska, Górnictwo i
Energetyka
Szkoły Głównej Gospodarstwa
Wiejskiego w Warszawie

Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracach:

- Kais, K.; Gołaś, M.; Suchocka, M. Awareness of Air Pollution and Ecosystem Services Provided by Trees: The Case Study of Warsaw City. Sustainability 2021, 13, 10611 mój indywidualny udział polegał na konsultacjach w procesie konceptualizacji, konsultacjach w opracowaniu metodyki, walidacji, udziale w analizie formalnej, udziale w pisaniu oryginalnej wersji pracy oraz udziale w jej edycji i recenzji.
- Kais, K.; Gołaś, M.; Suchocka, M.; Ziemiański, M.; Kalaji, H. M. The Role of Urban Trees in PM2.5 Mitigation: Air Quality Assessment and Absorption Capacity Comparison in Warsaw Alleys. JSPAE 2025, 4, 75–94 mój indywidualny udział polegał na konsultacjach w procesie konceptualizacji, udziale w pisaniu oryginalnej wersji pracy oraz udziale w jej edycji i recenzji.

Marlena Wójcik
.......................................
(Podpis)

Warszawa, 25.10.2025 r.

Arkadiusz Przybysz
arkadiusz_przybysz@sggw.edu.pl

Rada Dyscypliny Inżynieria
Środowiska, Górnictwo i
Energetyka
Szkoły Głównej Gospodarstwa
Wiejskiego w Warszawie

Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracach:

- Kais, K.; Suchocka, M.; Balcerzak, O.; Przybysz, A. Street Trees as Sustainable Urban Air Purifiers: A Methodological Approach to Assessing Particulate Matter Phytofiltration. Sustainability 2025, 17, 7451 mój indywidualny udział polegał na opracowaniu metodyki, walidacji, oryginalnej wersji pracy oraz jej edycji i recenzji.

A. Przybysz
.....................................
(Podpis)

Warszawa, 25.10.2025 r.

Hazem M. Kalaji
mohamed_kalaji@sggw.edu.pl

Rada Dyscypliny Inżynieria
Środowiska, Górnictwo i
Energetyka
Szkoły Głównej Gospodarstwa
Wiejskiego w Warszawie

Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracach:

- Kais, K.; Gołaś, M.; Suchocka, M.; Ziemiański, M.; Kalaji, H. M. The Role of Urban Trees in PM2.5 Mitigation: Air Quality Assessment and Absorption Capacity Comparison in Warsaw Alleys. JSPAE 2025, 4, 75–94 mój indywidualny udział polegał na pisaniu oryginalnej wersji pracy oraz jej edycji i recenzji.

Hazem Kalaji
......................................
(Podpis)

Warszawa, 25.10.2025 r.

Olga Balcerzak
olga_balcerzak@sggw.edu.pl

Rada Dyscypliny Inżynieria
Środowiska, Górnictwo i
Energetyka
Szkoły Głównej Gospodarstwa
Wiejskiego w Warszawie

Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracach:

- Kais, K.; Suchocka, M.; Balcerzak, O.; Przybysz, A. Street Trees as Sustainable Urban Air Purifiers: A Methodological Approach to Assessing Particulate Matter Phytofiltration. Sustainability 2025, 17, 7451 mój indywidualny udział polegał na wizualizacji, edycji i recenzji.

......................................
(Podpis)

Warszawa, 25.10.2025 r.

Maciej Ziemiański
maciej.ziemianski@bessons.pl

Rada Dyscypliny Inżynieria
Środowiska, Górnictwo i
Energetyka
Szkoły Głównej Gospodarstwa
Wiejskiego w Warszawie

Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracach:

- Kais, K.; Gołaś, M.; Suchocka, M.; Ziemiański, M.; Kalaji, H. M. The Role of Urban Trees in PM2.5 Mitigation: Air Quality Assessment and Absorption Capacity Comparison in Warsaw Alleys. JSPAE 2025, 4, 75–94 mój indywidualny udział polegał na pisaniu oryginalnej wersji pracy oraz jej edycji i recenzji.

..................................
(Podpis)