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Mikro- og nanoplast i boligers indeklima – forekomst, metoder og sundhedsmæssige perspektiver

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Forord

Mikro- og nanoplast er i de senere år blevet et voksende forskningsfelt inden for både miljø, eksponering og sundhed. I takt med at plastmaterialer indgår i stadig flere produkter, overflader og byggematerialer i hverdagen, er der også opstået øget opmærksomhed om, hvordan disse materialer over tid kan nedbrydes og bidrage til forekomsten af fine plastpartikler i det indendørs miljø. I boliger kan sådanne partikler potentielt stamme fra blandt andet tekstiler, møbler, maling, coatinger, plastbaserede forbrugerprodukter og andre polymerholdige materialer. Samtidig er boligen et sted, hvor mennesker opholder sig en stor del af døgnet, og hvor samspillet mellem materialer, støv, aktiviteter og ventilation har stor betydning for den luft, der indåndes til daglig. Mikro- og nanoplast i indeklimaet er derfor ikke alene et spørgsmål om materialenedbrydning, men også et spørgsmål om eksponering, målelighed og mulig sundhedsmæssig relevans.

Selv om forskningen på området er i hastig udvikling, er der fortsat væsentlige videnshuller. De mindste plastpartikler er vanskelige at identificere og kvantificere med de analysemetoder, der typisk anvendes i dag, og dette gælder især partikler, der er mindre end 1 mikrometer. Det betyder, at den nuværende dokumentation sandsynligvis kun belyser en del af det samlede billede. Samtidig er det vanskeligt at skelne plastpartikler fra andre organiske, mineralske og biologiske komponenter i komplekse prøver fra virkelige indendørsmiljøer. På sundhedssiden peger den eksisterende litteratur på, at fine plastpartikler kan være biologisk aktive, særligt i relation til luftvejene og hjertekarsygdomme, men datagrundlaget er endnu ikke tilstrækkeligt til at drage sikre konklusioner om risikoen ved almindelig eksponering i boliger.

Nærværende rapport er udarbejdet for at skabe et mere samlet og fagligt funderet grundlag for at forstå mikro- og nanoplast i boligers indeklima. Rapporten er rettet mod forskere, rådgivere og andre fagpersoner, der arbejder med indeklima, byggeri, eksponering og sundhed, og den har til formål at belyse både forekomst, mulige kilder, analysemetoder og sundhedsmæssige perspektiver. Rapporten forbinder et litteraturbaseret overblik med eksperimentelle analyser af fine luftbårne partikler og en sundhedsfaglig risikovurdering. Dermed søger den både at styrke forståelsen af, hvordan mikro- og nanoplast kan opstå og optræde i boliger, og at tydeliggøre de metodiske udfordringer, der fortsat begrænser sikker dokumentation og vurdering.

Rapportens indhold er struktureret, så læseren føres fra den overordnede problemforståelse til de mere konkrete analytiske og sundhedsfaglige spørgsmål. Først præsenteres en gennemgang af det aktuelle vidensgrundlag om nanoplast i boligers indendørsmiljø, herunder definitioner, kilder, transport mellem luft og støv samt metodiske udfordringer ved identifikation og måling. Dernæst beskrives den eksperimentelle undersøgelse af fine luftbårne partikler i indendørs og udendørs $PM_{2.5}$-prøver, hvor forskellige prøveforberedelses- og analysemetoder er blevet afprøvet med henblik på at vurdere forekomsten af polymerrelateret materiale. Afslutningsvis sættes resultaterne ind i en sundhedsmæssig sammenhæng gennem en risikovurdering, der diskuterer, hvad den nuværende viden gør det muligt at sige om betydningen af inhalation af fine plastpartikler i indeluft. Rapporten afrundes med perspektiver for videre forskning, herunder behovet for mere følsomme og

specifikke analysemetoder, bedre eksponeringsdata og et stærkere grundlag for fremtidig vurdering af mikro- og nanoplast i boligers indeklima.

Rapporten er udarbejdet med finansiel støtte fra Realdania og Grundejernes Investeringsfond, hvis bidrag har gjort det muligt at gennemføre projektet og samle den tværfaglige viden, som rapporten bygger på.

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MIKRO- OG NANOPLAST I BOLIGERS INDEKLIMA – FOREKOMST, METODER OG SUNDHEDSMÆSSIGE

Danish Abstract

Projektet undersøger mikro- og nanoplast i boligers indeklima med fokus på, hvordan disse partikler opstår, hvordan de kan identificeres, og hvilken mulig betydning de har for menneskelig eksponering og sundhed. Arbejdet forbinder tre perspektiver: den eksisterende viden om kilder og forekomst i indendørsmiljøer, de metodiske udfordringer ved at analysere partiklerne i fine luftbårne støvfraktioner, og den nuværende forståelse af deres potentielle sundhedsmæssige relevans. Gennemgangen peger på, at mikro- og nanoplast sandsynligvis er mere udbredt i boliger, end den nuværende dokumentation umiddelbart antyder, især fordi de mindste partikler fortsat er vanskelige at måle med tilstrækkelig sikkerhed. De eksperimentelle analyser viser samtidig, at identifikation af plast i realistiske indeklimaprøver er kompliceret, fordi partiklerne forekommer sammen med biologiske, mineralske og andre organiske komponenter, som kan give overlappende signaler i de tekniske analyser. På den sundhedsfaglige side tyder den eksisterende evidens på, at fine plastpartikler kan være biologisk aktive, særligt i relation til inflammatoriske reaktioner i luftvejene og hjertekarsygdomme, men datagrundlaget er endnu ikke stærkt nok til at give sikre konklusioner om risikoen ved almindelig indendørs eksponering. Projektet peger derfor på behovet for mere følsomme og specifikke analysemetoder samt bedre eksponeringsdata, hvis mikro- og nanoplast i boligers indeklima skal kunne vurderes med større præcision og faglig sikkerhed.

English Abstract

This project examines micro- and nanoplastics in residential indoor environments, with a focus on how these particles arise, how they can be identified, and what their possible implications may be for human exposure and health. The work brings together three perspectives: existing knowledge on sources and occurrence in indoor environments, the methodological challenges involved in analysing these particles in fine airborne dust fractions, and the current understanding of their potential health relevance. The review suggests that micro- and nanoplastics are likely more widespread in homes than the present evidence immediately indicates, particularly because the smallest particles remain difficult to detect with sufficient certainty. The experimental analyses also show that identifying plastics in realistic indoor samples is challenging by the fact that these particles occur alongside biological, mineral and other organic components that may produce overlapping signals in the analyses. From a health perspective, the available evidence suggests that fine plastic particles may be biologically active, especially in relation to inflammatory responses in the airways and cardiovascular diseases, although the current evidence base is still too limited to support firm conclusions about the risks associated with typical indoor exposure. The project therefore highlights the need for more sensitive and specific analytical methods, as well as improved exposure data, if micro- and nanoplastics in residential indoor environments are to be assessed with greater precision and scientific confidence.

CONTENTS

1 INDLEDNING

Projektet undersøger mikro- og nanoplast i boligers indeklima med det formål at skabe et mere sammenhængende billede af, hvordan disse partikler opstår, hvordan de kan identificeres, og hvilken betydning de kan have for menneskelig eksponering og sundhed. Udgangspunktet er, at mikro- og nanoplast i indendørsmiljøer endnu kun er delvist belyst, ikke mindst fordi de mindste partikler er vanskelige at måle med de metoder, der typisk anvendes i dag. Arbejdet forbinder derfor tre perspektiver, som tilsammen belyser feltet fra kilde og forekomst til analyse og risikovurdering.

Den første del samler den eksisterende forskningsbaserede viden om nanoplast i boliger og peger på, at disse partikler sandsynligvis forekommer oftere, end den nuværende dokumentation umiddelbart giver indtryk af. Forklaringen ligger i høj grad i de analytiske begrænsninger, der fortsat præger feltet, især når det gælder partikler der er mindre end 1 µm (nanoplast) og 100 nm (nanostørrelse). Gennemgangen viser, at nanoplast kan dannes ved gradvis nedbrydning af almindelige polymerholdige materialer i hjemmet, herunder tekstiler, møbler, maling, coatinger og plastbaserede forbrugerprodukter. Når sådanne materialer over tid udsættes for slid, friktion, varme, ultraviolet stråling og kemisk aldring, kan de fragmenteres til stadig mindre partikler, som efterhånden bliver en del af det indendørs partikelfelt. Husstøv indgår i denne sammenhæng som et aktivt reservoir, der både kan opsamle partikler og senere frigive dem til indeluften igen ved almindelige aktiviteter som gang, rengøring og bevægelse i boligen. Dermed bliver eksponeringen ikke alene et spørgsmål om primære kilder, men også om, hvordan partikler cirkulerer mellem overflader, støv og luft i det daglige indeklima.

Den anden del af projektet retter sig mod de praktiske og metodiske udfordringer ved at undersøge mikro- og nanoplast i fine luftbårne partikler fra virkelige indendørsmiljøer. Med udgangspunkt i $PM_{2.5}$-prøver fra indendørs og udendørs miljøer blev der udviklet procedurer til prøveforberedelse, redispergering og analyse, så materialet kunne undersøges med flere komplementære teknikker. Analyserne viste, at prøverne består af komplekse blandinger af fibre, partikler og aggregater, hvor enkelte fund kunne være forenelige med plastmateriale, men hvor mange signaler samtidig kunne stamme fra biologiske, mineralske eller andre organiske komponenter. Denne kompleksitet gør sikker identifikation vanskelig og understreger, at realistiske indeklimaprøver adskiller sig markant fra rene laboratorieprøver. Termogravimetriske analyser og optiske metoder som hyperspektral mikroskopi og fluorescensfarvning viste, at det er muligt at finde indikationer på polymerlignende materiale, men også at de nuværende metoder stadig er begrænsede af manglende specificitet, interferens fra baggrundsmatricen og usikkerhed i fortolkningen. Projektets eksperimentelle del peger derfor mindre på et endeligt kvantitativt svar og mere på, hvor de væsentligste metodiske barrierer ligger, hvis feltet skal bringes videre.

Den tredje del sætter disse resultater ind i en sundhedsmæssig sammenhæng ved at vurdere, hvad den nuværende viden gør det muligt at sige om risikoen ved indånding af fine plastpartikler i indeluft. Her trækkes der på både humane studier, eksperimentelle dyreforsøg og den bredere viden om luftbåren partikelforurening. Gennemgangen viser, at der endnu ikke findes et fuldt etableret metodisk grundlag for human risikovurdering af mikro- og

nanoplast, men også at den eksisterende evidens peger på, at fine plastpartikler kan være biologisk aktive. Særligt inflammatoriske reaktioner i luftvejene fremstår som et tilbagevendende fund i eksperimentelle studier, mens nyere humane observationelle undersøgelser antyder, at plastpartikler også kan være relevante i relation til kardiovaskulære sygdomsprocesser. Samtidig er eksponeringsdata for indendørsmiljøer fortsat præget af betydelig usikkerhed, især fordi de mindste og mest respirable partikler endnu ikke måles tilstrækkeligt pålideligt. Det betyder, at risikovurderingen nødvendigvis må forblive forsigtig og foreløbig. Der er tegn på, at mikro- og nanoplast i indeluft bør tages alvorligt som et potentielt indeklima- og sundhedsspørgsmål, men datagrundlaget er endnu ikke stærkt nok til at give sikre konklusioner om den faktiske risiko ved de niveauer, mennesker typisk udsættes for i boliger.

Projektet peger dermed på et tydeligt behov for mere følsomme og mere selektive analysemetoder, bedre karakterisering af mikro- og nanoplast partikler i indeluft og en tættere kobling mellem målinger, eksponeringsforhold og biologiske effekter. Det er først, når disse elementer udvikles i sammenhæng, at det bliver muligt at vurdere mikro- og nanoplast i boligers indeklima med den præcision og sikkerhed, som både forskningen og den sundhedsfaglige vurdering kræver.

2 BESKRIVELSE AF APPENDIX I

Appendix I omhandler nanoplast i boligers indendørsmiljø og undersøger, hvordan disse partikler kan dannes, hvilke kilder der kan bidrage til deres forekomst, hvordan de fordeler sig mellem indeluft og husstøv, samt hvilke metodiske udfordringer der knytter sig til deres identifikation og vurdering. Bilaget er udarbejdet som et state-of-the-art review med det formål at samle og diskutere den eksisterende forskningsbaserede viden på en systematisk og analytisk måde. Et gennemgående perspektiv i teksten er, at nanoplast i boliger sandsynligvis er langt mere udbredt, end den nuværende dokumentation umiddelbart antyder. Dette hænger især sammen med, at de mest anvendte analysemetoder fortsat har begrænsninger, når det gælder partikler i den submikrone (under 1 µm) og nanopartikulære størrelsesorden. Fraværet af tydelig dokumentation bør derfor ikke uden videre tolkes som fravær af nanoplast, men snarere som et udtryk for, at forskningen endnu ikke råder over tilstrækkeligt robuste metoder til at kortlægge de mindste plastpartikler i komplekse indendørs miljøer.

Appendix I diskuterer også den fortsatte uklarhed omkring selve definitionen af nanoplast. I nogle dele af litteraturen anvendes den aerosol- og nanomaterialebaserede afgrænsning på 1–100 nm, mens andre studier og institutionelle rammer arbejder med en bredere forståelse, der omfatter partikler op til 1 µm. Denne variation er ikke blot en terminologisk detalje, men har væsentlig betydning for, hvordan resultater kan sammenlignes, og hvordan eksponering og potentiel sundhedsrelevans vurderes. Når grænserne mellem mikroplast og nanoplast forskydes fra studie til studie, bliver det vanskeligt at etablere et fælles vidensgrundlag, og bilaget peger derfor på behovet for mere harmoniserede og operationelle definitioner, der bedre afspejler de faktiske forhold i miljø- og eksponeringsforskningen.

I forhold til kilder beskriver bilaget, hvordan nanoplast i boliger må forstås som resultatet af en gradvis nedbrydning af almindelige polymerholdige materialer og produkter, der findes i hjemmet. Det gælder blandt andet tekstiler, møbler, plastbaserede forbrugerprodukter, maling, coatinger og forskellige byggematerialer. Når disse materialer over tid udsættes for slid, friktion, varme, ultraviolet stråling og kemisk aldring, kan større plaststrukturer fragmenteres til mindre partikler, som efterhånden kan nå mikro- og nanoskala. Nanoplast fremstår dermed ikke som et særskilt eller ekstraordinært fænomen, men som en naturlig del af de nedbrydningsprocesser, der foregår i det indendørs miljø. Denne forståelse styrkes af eksperimentelle studier, der viser, at især maling og overfladebehandlinger kan afgive partikler i nanostørrelse, eksempelvis under tørring eller som følge af aldring. Sådanne resultater peger på, at overflader og materialer i boligen ikke alene udgør passive baggrundselementer, men i visse tilfælde også kan fungere som direkte kilder til ultrafine partikler i indeluften.

Et væsentligt element i Appendix I er desuden husstøvs rolle i det indendørs kredsløb af plastpartikler. Husstøv beskrives ikke blot som et sted, hvor partikler aflejres, men som et dynamisk reservoir, der både kan opsamle, opkoncentrere og senere frigive partikler til indeluften igen. Almindelige aktiviteter som gang, rengøring og bevægelse i boligen kan føre til resuspension, hvor partikler på ny hvirvles op i luften og dermed bliver tilgængelige for inhalation. På den måde bliver samspillet mellem luft og støv centralt for

forståelsen af, hvordan nanoplast kan ophobes, cirkulere og potentielt bidrage til eksponering i hjemmet. Bilaget fremhæver samtidig, at de mindste plastpartikler i høj grad opfører sig som ultrafine aerosoler snarere end som almindeligt støv, idet de lettere forbliver svævende og transporteres med luftbevægelser i rummet. Det gør deres adfærd særlig relevant i relation til indeluftkvalitet og inhalationseksponering.

Metodisk bygger Appendix I på en struktureret gennemgang af den videnskabelige litteratur, hvor relevante studier er identificeret gennem søgninger i centrale internationale databaser og udvalgt på baggrund af klart definerede kriterier. De inkluderede undersøgelser er analyseret med fokus på blandt andet partikelstørrelser, kildetyper, nedbrydningsmekanismer, analysemetoder og eksponeringsforhold. Dette giver bilaget en solid faglig forankring og gør det muligt at tegne et nuanceret billede af et forskningsfelt, som fortsat er under udvikling, men som samtidig rummer væsentlige perspektiver for forståelsen af indendørs partikelforurening. Appendix I peger dermed på, at der er et klart behov for fremtidige studier, som mere direkte retter sig mod partikler under 1 µm og kobler målinger sammen med forhold som ventilation, aktivitet og støvresuspension, så eksponeringen i boliger kan beskrives med større sikkerhed og præcision.

3 BESKRIVELSE AF APPENDIX II

Appendix II omhandler den eksperimentelle del af projektet og har fokus på, hvordan mikro- og nanoplast kan undersøges i boligers indeklima på baggrund af analyser af fint luftbårent støv. Bilaget tager udgangspunkt i $PM_{2.5}$-prøver indsamlet indendørs og udendørs ved svenske boliger og beskriver det metodiske arbejde med at forberede, karakterisere og analysere disse prøver for at vurdere, om de indeholder en plastrelateret fraktion. Hvor Appendix I først og fremmest belyser det eksisterende vidensgrundlag gennem litteraturen, retter Appendix II opmærksomheden mod de praktiske og analytiske udfordringer, der opstår, når man forsøger at påvise mikro- og nanoplast i komplekse prøver fra virkelige indendørsmiljøer.

Et centralt element i bilaget er udviklingen af en prøveforberedelsesmetode, der gjorde det muligt at redispergere det opsamlede støv og fordele materialet til flere typer analyser uden at tilføre unødige forstyrrelser eller kontaminering. Dette arbejde fremstår som en vigtig del af undersøgelsen, fordi prøverne bestod af meget små og heterogene mængder materiale, som samtidig havde været gennem flere tidligere håndteringstrin. Appendix II viser dermed, at selve prøvebehandlingen ikke blot er en teknisk detalje, men en afgørende forudsætning for, om det efterfølgende overhovedet er muligt at opnå brugbare resultater.

Bilaget beskriver herefter en række mikroskopiske analyser, som blev anvendt til at opnå en første karakterisering af partiklerne i prøverne. Polarisationsmikroskopi og skanningelektronmikroskopi viste, at både de indendørs og de udendørs prøver indeholdt et komplekst blandingsbillede af opake og transparente partikler, fibre, aggregater og kulstofholdige strukturer. I de indendørs prøver blev der observeret flere fibre end i de udendørs, og enkelte af disse havde egenskaber, som kunne pege i retning af plastmateriale. Samtidig stod det klart, at en stor del af de observerede fibre og partikler også kunne stamme fra biologiske materialer, mineraler eller andre organiske kilder. Netop denne usikkerhed er vigtig i bilaget, fordi den understreger, at partiklernes udseende alene ikke er tilstrækkeligt til en sikker identifikation af plast i realistiske indeklimaprøver.

En væsentlig del af Appendix II er viet til TGA-MS-analyser, hvor prøvernes termiske nedbrydningsprofiler blev undersøgt for at identificere tegn på polymerlignende materiale. For at kunne fortolke resultaterne blev der først etableret et bibliotek over referencematerialer, herunder forskellige plasttyper, cellulose og carbon black. Sammenligningen mellem prøverne og disse referencer viste, at især den indendørs prøve havde massetab i temperaturintervaller, som kunne være forenelige med plastmaterialer, og at denne prøve i flere henseender adskilte sig fra udendørsprøven. Bilaget gør imidlertid samtidig klart, at sådanne termiske signaler ikke kan tilskrives plast med sikkerhed, fordi også andre organiske og biogene materialer kan nedbrydes i de samme temperaturintervaller. TGA-MS fremstår derfor som en metode, der kan pege på tilstedeværelsen af polymerlignende materiale, men ikke som en metode, der alene kan dokumentere eller kvantificere mikro- og nanoplast entydigt i autentiske miljøprøver.

Appendix II behandler også forsøg med mere plastspecifikke optiske metoder, herunder hyperspektral mikroskopi og fluorescensfarvning med Nile Red, som ofte er anvendt i litteraturen. Disse analyser blev gennemført med

henblik på at forbedre mulighederne for at identificere små plastpartikler i de komplekse støvprøver, men resultaterne viste samtidig, hvor vanskeligt dette er i praksis. Ved hyperspektral mikroskopi viste det sig, at selv kontrolprøver og procesrelaterede urenheder kunne give signaler, der lignede referencenanoplast. Tilsvarende viste fluorescensfarvningen, at mange partikler i indeklimaprøverne bandt farvestoffet uspecifikt, og at andre støvkomponenter kunne give autofluorescens, som gjorde tolkningen usikker. Bilaget peger dermed på, at de eksisterende metoder endnu ikke er tilstrækkeligt selektive og robuste til sikker identifikation af nanoplast i prøver, hvor baggrundsmatricen er sammensat og interferens fra andre materialer er betydelig.

Appendix II giver derfor først og fremmest et metodisk indblik i, hvor vanskelig påvisning af mikro- og nanoplast i boligers indeklima er, når analyserne udføres på prøver fra virkelige miljøer frem for under kontrollerede laboratorieforhold. Bilaget viser, at der findes indikationer på polymerlignende materiale i både indendørs og udendørsprøverne af opsamlet $PM_{2.5}$ og at luften indendørs kan være en mere relevante kilde til eksponering for mikroplast end udendørs. Samtidig fremgår det tydeligt, at usikkerheder knyttet til både prøvebehandling, kontaminering, baggrundsmateriale og metodernes specificitet fortsat begrænser, hvor sikkert resultaterne kan fortolkes. Det er netop denne metodiske afklaring, der gør Appendix II væsentligt: ikke fordi bilaget giver et endeligt svar på mængden af mikro- og nanoplast i indeklimaet, men fordi det tydeliggør, hvilke barrierer der skal overvindes, og hvilke analytiske forbedringer der er nødvendige, hvis fremtidige undersøgelser skal kunne beskrive plastfraktionen i indendørs $PM_{2.5}$ med større præcision og troværdighed.

4 BESKRIVELSE AF APPENDIX III

Appendix III omhandler den sundhedsmæssige risikovurdering af fine plastpartikler i indeluft og sætter projektets tekniske og analytiske resultater ind i en bredere eksponerings- og helbredsmæssig sammenhæng. Hvor de foregående bilag især beskæftiger sig med forekomst, kilder og målemetoder, retter dette bilag opmærksomheden mod det mere overordnede spørgsmål om, hvad den nuværende viden faktisk gør det muligt at sige om risikoen ved indånding af mikro- og nanoplast i boliger. Teksten er bygget op efter en klassisk risikovurderingsramme med fokus på fareidentifikation, farekarakterisering, eksponeringsvurdering og risikokarakterisering, men samtidig er et vigtigt udgangspunkt, at feltet fortsat er præget af betydelige videnshuller. Bilaget gør det derfor klart fra begyndelsen, at der endnu ikke findes en fuldt accepteret metode til egentlig human risikovurdering af mikro- og nanoplast, og at vurderingen derfor nødvendigvis må baseres på den bedst tilgængelige, men stadig ufuldstændige evidens.

En væsentlig del af Appendix III handler om at placere fine plastpartikler i en partikel- og luftforureningsmæssig kontekst, som allerede er velkendt fra miljø- og arbejdsmiljøforskningen. Bilaget redegør for forskellige partikelstørrelser, fra total suspenderet støv til PM_{10}, PM2.5, PM_1 og ultrafine partikler, og understreger, at netop de fine og ultrafine fraktioner er de mest relevante, når spørgsmålet er, hvor dybt partiklerne kan trænge ned i luftvejene. På den baggrund argumenterer bilaget for, at mikro- og nanoplast ikke bør forstås som et helt isoleret problem, men som en særlig type partikulær eksponering, der på flere punkter deler karakteristika med anden luftbåren partikelforurening. Der peges blandt andet på, at både almindelige luftforureningspartikler og plastpartikler kan bestå af en partikelkerne med tilknyttede kemiske forbindelser, og at de i biologisk sammenhæng kan være forbundet med mekanismer som oxidativt stress, inflammation og vævsskade. Denne kobling er vigtig, fordi den giver et fagligt grundlag for at bruge den etablerede viden om partikler og luftforurening som et indirekte referencepunkt, når de mere specifikke data om plastpartikler endnu er begrænsede.

I den del af bilaget, der omhandler farekarakterisering, gennemgås både humane og eksperimentelle studier. De humane data er stadig få, men bilaget fremhæver, at nyere undersøgelser har påvist mikro- og nanoplast i menneskelige væv og i forbindelse med kardiovaskulære sygdomstilstande, blandt andet i blodkar med åreforkalkning. Disse studier dokumenterer ikke i sig selv en entydig årsagssammenhæng, men de peger på, at eksponering for plastpartikler kan have biologisk og klinisk relevans. Samtidig viser bilaget, at dyreforsøg mere konsekvent peger i retning af en inflammatorisk effekt i lungerne efter eksponering for forskellige typer mikro- og nanoplast. På tværs af polymerer som polyethylen, polypropylen, polyvinylchlorid og polystyren beskrives en række studier, hvor eksponering er blevet sat i forbindelse med neutrofil influx, forhøjede niveauer af proinflammatoriske markører, histopatologiske forandringer og i visse tilfælde tegn på fibrose. Det afgørende i bilagets fremstilling er ikke, at alle polymerer vurderes ens, men at evidensen på tværs af studier peger mod, at fine plastpartikler i luftvejene har potentiale til at udløse biologiske reaktioner, som er relevante for både luftvejs- og hjerte-kar-sygdomme.

Appendix III lægger samtidig stor vægt på, at denne evidens skal fortolkes med forsigtighed. Mange af de eksperimentelle studier bygger på relativt høje doser og på eksponeringsformer som intratrakeal instillation eller aspiration, som ikke uden videre svarer til den måde, mennesker udsættes for partikler på i dagligdagen. Bilaget gør derfor opmærksom på, at der er en tydelig forskel mellem, det at påvise et toksisk potentiale under kontrollerede forsøgsbetingelser, og det at kunne vurdere en reel sundhedsrisiko ved almindelig indendørs eksponering. Denne nuancering er central for teksten, fordi den forhindrer både en undervurdering og en overfortolkning af den eksisterende forskning. Risikoen afvises ikke, men den beskrives heller ikke mere skråsikkert, end datagrundlaget tillader.

I eksponeringsdelen samler bilaget resultater fra undersøgelser af luftbårne mikroplastpartikler i forskellige indendørs miljøer, herunder boliger, lejligheder, skoler og andre opholdsrum. Gennemgangen viser, at mikroplast i indeluft er påvist i en lang række studier, men også at de rapporterede koncentrationer varierer meget betydeligt. Denne variation forklares blandt andet med forskelle i prøvetagningsstrategier, analytiske metoder, detektionsgrænser og størrelsesområder. Bilaget understreger, at mange af de eksisterende målinger i praksis hovedsageligt omfatter partikler større end 1 µm, mens de mindste fraktioner fortsat er vanskelige at måle pålideligt. Det betyder, at den del af eksponeringen, som potentielt kan være mest relevant ud fra et toksikologisk perspektiv, nemlig de fine og ultrafine plastpartikler, stadig er utilstrækkeligt kortlagt. Dermed opstår der en væsentlig usikkerhed i enhver risikovurdering: vi ved, at mennesker udsættes for luftbårne plastpartikler indendørs, men vi kender endnu ikke med sikkerhed den fulde størrelse, sammensætning og størrelsesfordeling af den inhalerbare og respirable fraktion.

En vigtig pointe i Appendix III er, at vurderingen af risiko på nuværende tidspunkt i høj grad må baseres på massen af partikler snarere end på partikelantal, fordi de tilgængelige data for nanoplast og plastiske nanopartikler stadig er utilstrækkelige. Bilaget sammenholder de rapporterede koncentrationer af mikroplast i $PM_{2.5}$ og PM_{10} med WHO's luftkvalitetsretningslinjer for partikulær luftforurening og bemærker, at de højeste rapporterede masseniveauer for mikroplast i indeluft ligger under WHO's vejledende niveau for $PM_{2.5}$. Denne sammenligning viser, at de nuværende målte niveauer ikke umiddelbart overskrider kendte grænser for partikelmasse, men bilaget understreger samtidig, at en sådan sammenligning har klare begrænsninger. Plastpartikler adskiller sig fra klassiske forureningspartikler ved både polymerstruktur, additiver og potentielt adsorberede kemiske stoffer, og WHO's retningslinjer er ikke udviklet specifikt til at vurdere mikro- og nanoplast. Derfor bruges denne reference først og fremmest som et foreløbigt orienteringspunkt og ikke som et endeligt grundlag for at konkludere, at eksponeringen er uproblematisk.

Det, Appendix III i sidste ende bidrager med, er derfor en forsigtig, men fagligt velbegrundet risikoforståelse. Bilaget peger på, at den nuværende viden ikke giver grundlag for at konkludere, at fine plastpartikler i indeluft udgør en dokumenteret høj sundhedsrisiko ved de niveauer, der indtil videre er målt, men det peger heller ikke på, at spørgsmålet kan anses for afklaret. Tværtimod fremhæves det, at der er en troværdig biologisk plausibilitet for effekter, særligt i luftvejene og muligvis også i det kardiovaskulære system,

og at den største svaghed i den nuværende risikovurdering ligger i manglen på pålidelige eksponeringsdata for de mindste partikler. Teksten fremstår derfor som en nøgtern og vigtig afgrænsning af, hvad der kan siges med rimelig sikkerhed nu, og hvad der fortsat kræver bedre data, mere realistiske eksponeringsstudier og mere målrettede metoder til at måle nanoplast i indeluft.

Acknowledgements:

Projektet er finansieret af Realdania og Grundejernes Investeringsfond. Forfatterne takker for den støtte, som har gjort det muligt at gennemføre projektet og belyse mikro- og nanoplast i boligers indeklima.

Appendix I

Reconsidering Nanoplastics in Residential Indoor Environments

AAU: Alireza Afshari, Haider Latif, Mohammad Kiani-Moghaddam

Abstract

This state-of-the-art review examines nanoplastics in residential indoor environments, with a focus on how they form, how they move between air and dust, how they are measured, and why they may matter for indoor exposure. Thirty-one peer-reviewed articles were reviewed, spanning definitions and size frameworks, polymer weathering and fragmentation mechanisms, indoor chamber emission studies, dust reservoir and resuspension dynamics, and current analytical capabilities and limitations. In addition, recent institutional reports were considered to clarify how definitions of nanoplastics have evolved from traditional nanomaterial frameworks toward broader operational size ranges used in environmental research.

Across these studies, a consistent picture emerges. Even when research is framed around microplastics, reported size distributions frequently extend into submicron ranges that overlap with operational definitions of nanoplastics. Mechanistic evidence from polymer aging and laboratory degradation supports the plausibility of nanoscale fragment generation from common indoor polymer sources, including paints, coatings, textiles, and consumer products. Chamber studies show that indoor materials, particularly architectural paints during drying, can emit ultrafine particles in the nanometer range, while house dust appears to act as both a sink and a remobilizable reservoir, enabling repeated transfer back to indoor air during everyday activities. Recent institutional frameworks increasingly recognize that environmentally relevant plastic particles may extend beyond the strict nanoscale boundary (1–100 nm) into the broader submicron range approaching 1 μm, reflecting advances in environmental detection and exposure assessment.

The main conclusion is that nanoplastics in residential air and dust are likely underdetected rather than absent, largely because routine field methods have limited ability to chemically identify and quantify particles below one micrometer. The review therefore recommends prioritizing measurement strategies that explicitly target the submicron fraction, integrating air and dust sampling with nanoscale-capable analytical tools, and linking observations to indoor dynamics such as activity patterns, air movement, and ventilation that shape breathing zone exposure. Clarifying and harmonizing operational size definitions will also be important for improving comparability across future studies of indoor nanoplastics.

State-of-the-art review

Nanoplastics (NPs) are generally described as plastic particles within the nanoscale to submicron size range. Early environmental and toxicological studies often adopted conventional nanomaterial definitions, classifying nanoplastics as particles between approximately 1 and 100 nm. However, more recent environmental research and institutional frameworks increasingly recognize a broader operational size range extending up to 1 μm (1–1000 nm), reflecting advances in analytical detection methods and the recognition that environmentally generated plastic

fragments frequently occur within the submicron domain. Submicron particles are expected to form through fragmentation of larger plastics; however, the chemical composition of particles below 1 µm remains difficult to identify and quantify using current analytical methods [1,2]. Table 1 is adapted and reconstructed from the size-classification framework presented in literature [1], which highlights the substantial variability in how plastic debris size categories are defined across scientific literature. The comparison illustrates inconsistencies in lower and upper size thresholds, particularly at the nano–micro boundary, underscoring the lack of harmonized definitions and the resulting challenges for cross-study comparability and exposure assessment [1].

Table 0.1 Variations in Size-Based Classification of Plastic Debris in Scientific Literature [1]

References	Year	Nanoplastics Definition	Microplastics Definition	Mesoplastics Definition	Macroplastics Definition
[1]	2003	—	67–500 µm	—	1–15 cm
[3]	2007	<1 µm	1–1000 µm	—	>5 mm
[4]	2008	—	<5000 µm	—	>5 mm
[5]	2009	—	<2000 µm	2–20 mm	>2 cm
[6]	2010	—	<1000 µm	—	—
[7]	2014	—	1–5000 µm	—	—
[8]	2014	<20 µm	20–5000 µm	5–25 mm	>2.5 cm
[9]	2015	1–100 nm	Up to 5000 µm	—	>5 mm
[10]	2015	<1 µm	1–1000 µm	1–25 mm	2.5–100 cm
[11]	2017	<335 µm	335–5000 µm	—	>5 mm
[12]	2009	—	<5000 µm	—	—
[13]	2011	1–100 nm	—	—	—
[14]	2013	—	20–5000 µm	5–25 mm	>2.5 cm
[15]	2015	<1 µm	1–5000 µm	1–25 mm	2.5–100 cm
[16]	2016	1–100 nm	0.1–5000 µm	—	—

The definitions summarized in Table 1 illustrate the considerable variability in size-based classification of plastic debris across the scientific literature. Early environmental studies often applied thresholds derived from nanomaterial science (1–100 nm) or broader operational limits extending into the micrometer scale, reflecting mainly limitations in analytical detection methods. In recent years, however, institutional and regulatory bodies have begun to formalize these classifications in the context of environmental monitoring and exposure assessment. As shown in Table 2, several international organizations now recognize a broader operational nanoscale range extending toward approximately 1 µm (1–1000 nm) in order to capture environmentally relevant submicron plastic particles.

Notably, EFSA [17] largely retains the traditional nanomaterial-based definition of 1–100 nm, whereas other institutions increasingly acknowledge the practical need to include particles up to 1 µm within the nanoplastics category. Together, these

developments reflect the evolving scientific understanding of plastic fragmentation processes and the growing need for harmonized definitions in nanoplastics research. Beyond these definitional frameworks, recent reviews highlight that particles in the nanoscale and submicron range (<100–500 nm, and in some cases up to approximately 1000 nm) behave differently from larger microplastics. These small particles have high diffusivity, and their movement is dominated by Brownian motion rather than sedimentation or buoyancy. They also have high surface reactivity because a large proportion of their molecules are located at the surface. As a result, nanoplastics behave more like ultrafine aerosols in indoor air and are more likely to remain suspended, contributing to the ultrafine (<100 nm) particulate matter fraction relevant to indoor air quality (IAQ) [21,22].

Organisation	**Nanoplastics Definition**	**Microplastics Definition**	**Interpretation**
EFSA (European Food Safety Authority)	~1–100 nm	0.1–5000 µm	EFSA maintains a nanoscale definition aligned with conventional nanomaterial frameworks used in regulatory risk assessment [17]
European Commission / EU Science for Environment Policy	Often considered up to 1 µm (1000 nm) in environmental studies	<5 mm	EU reports acknowledge the absence of a universal boundary and note that many environmental studies operationally define nanoplastics as particles below 1 µm [18].
WHO (World Health Organization)	Not strictly defined; nanoscale particles considered within the nano–micro continuum	<5 mm	WHO emphasizes that particles smaller than 10 µm, particularly nanoscale particles, are most relevant for biological uptake and human exposure assessment [19].
US EPA (United States Environmental Protection Agency)	Nanoplastics defined as <1 µm (1000 nm)	<5 mm	EPA describes nanoplastics as a subset of microplastics smaller than 1 µm in environmental monitoring frameworks. [20]

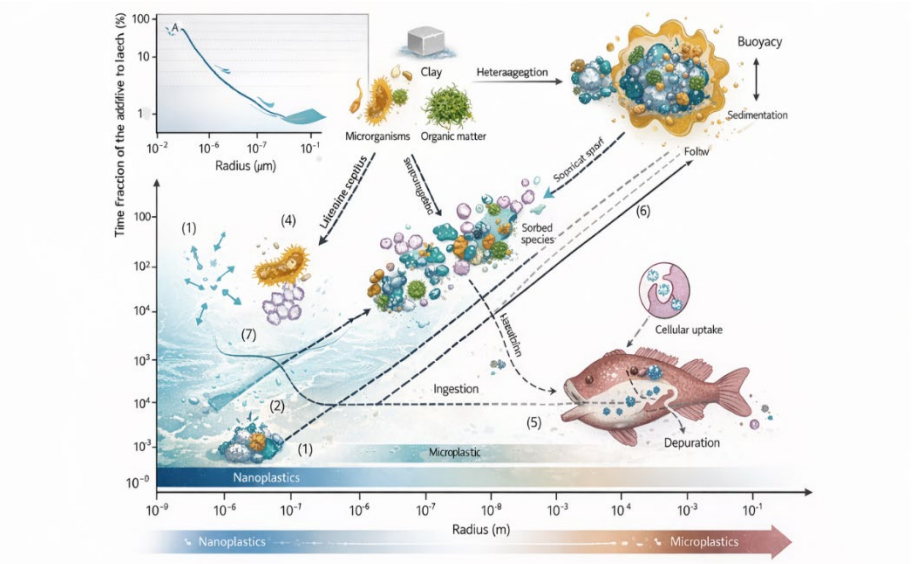

Figure 0.1 Conceptual overview of the transformation and environmental behavior of plastic debris from microplastics to nano plastics. The figure highlights size-dependent fragmentation, additive leaching, aggregation, transport processes, and biological interaction [5]

Figure 0.1 illustrates the transformation and environmental behavior of plastic debris across size scales, from microplastics to nanoplastics. It shows how weathering processes such as UV exposure, mechanical abrasion, and chemical degradation fragment bulk plastics into progressively smaller particles, while environmental interactions influence their transport, buoyancy, and sedimentation. The diagram also highlights size-dependent processes including additive leaching, sorption of contaminants, ingestion by aquatic organisms, cellular uptake, and depuration. Importantly, it emphasizes that smaller particles (nanoplastics) exhibit distinct physicochemical behavior, including enhanced surface reactivity and altered mobility compared to larger microplastics [5].

In residential indoor environments, nanoplastics are likely present in mixed forms. These include fibers with nanoscale fibrils, aged plastic fragments, and particles carrying chemical additives. They originate from textiles, furniture, coatings, household dust, and everyday human activities. In indoor air, micro- and nanoplastics are typically reported as “particles and fibers.” Indoor dust and limited air circulation can lead to higher indoor levels compared to outdoors. Air-conditioning filters may act both as sinks and as secondary sources, as particles can be released back into indoor air when the system operates. In addition, plastic additives attached to these particles may increase their exposure relevance [23].

Synthetic textiles such as polyester clothing, carpets, curtains, and upholstered furniture are recognized as a significant indoor source of micro- and nanoplastics (<1 μm). Mechanical abrasion releases fibers and small plastic fragments that accumulate in house dust. Microfibers can also be directly emitted into indoor air during daily wear [2,6]. Although routine textile use mainly releases micrometer-sized fibers, repeated friction, washing, and aging create internal stresses that lead to cracking and fragmentation. Over time, these processes reduce particle size, allowing nanoplastics to form from aged microplastics. Laboratory studies show that UV degradation of polyethylene can generate particles within the 1–1000 nm range [24,25]. Nano-sized debris can accumulate in settled indoor dust. Continued mechanical stress within the dust matrix can further reduce particle size. Dust therefore acts not only as a sink but also as a secondary source. Particles trapped in dust can become airborne again through resuspension during walking, cleaning, or other activities[2,26]. In this way, indoor dust contributes to repeated exposure cycles. Consumer polymer products such as packaging, plastic containers, and household goods can also generate secondary nanoplastics during degradation. UV exposure, heat, and mechanical wear progressively fragment these materials, potentially producing particles in the nanoscale range [2,25].

Controlled chamber studies demonstrate that nano-sized particles can be directly emitted from polymer-based building materials. During drying of interior paints, particles between 5.6 and 560 nm have been measured [27]. Dominant emission peaks vary by paint type and pigmentation. Reported modes include 9.31 nm for solvent-borne alkyd paints and 6.04 nm for certain pigmented water-borne acrylic paints, with other paints showing maxima between 29.4 and 34 nm [27]. Although instrumentation cannot distinguish whether particles are solid, volatile, or semi-volatile, these emissions clearly overlap with the ultrafine particle fraction relevant to indoor air quality. Once airborne, particles smaller than 1 μm—and especially those below 100 nm—behave as ultrafine aerosols. Their movement is dominated by Brownian diffusion rather than gravitational settling. As a result, they can remain suspended for extended periods, increasing the likelihood of inhalation and potential translocation across biological membranes [21,22]. Indoor airflow patterns, occupant activity,

and ventilation conditions influence how these particles redistribute within rooms and reach the breathing zone[21,26].

Polymer-based wall paints and coatings are increasingly recognized as potential secondary sources of nanoplastics. These materials often contain synthetic binders such as acrylates. Mechanical wear, UV exposure, and thermal oxidation cause chain scission, embrittlement, and surface cracking. Crack propagation can initiate fragmentation cascades that reduce materials from bulk polymers to micro- and nanoscale particles [2,28]. Accelerated weathering experiments confirm the formation of secondary plastic particles ranging from 30 nm to 60 µm under combined UV and thermal stress[24,29]. These findings support the mechanistic plausibility of nanoscale particle generation from indoor polymer-containing materials.

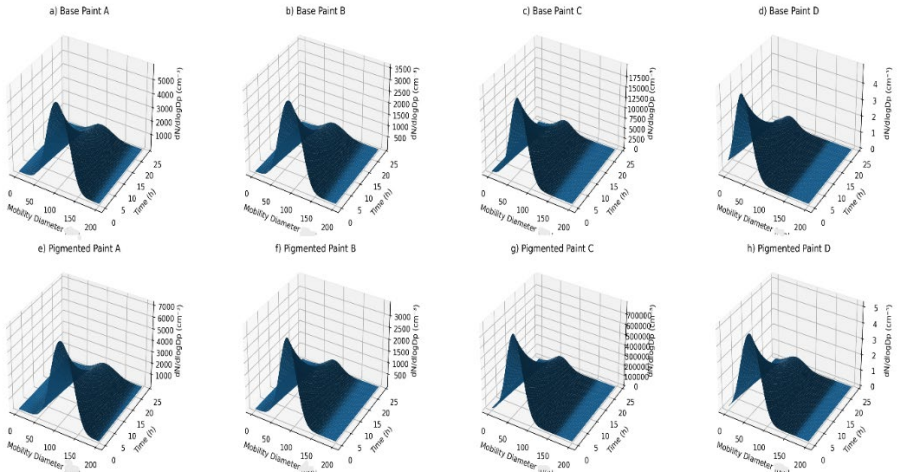

Figure 0.2 (a-h) Three-dimensional surface plots showing time-resolved particle number size distributions (dN/dlogDp) as a function of mobility diameter during drying of base and pigmented paints [10]

Figure 0.2 presents the temporal evolution of particle number concentration (dN/dlogDp) as a function of mobility diameter during drying of base (a–d) and corresponding pigmented paints (e–h). The surfaces illustrate size-dependent emission patterns, with distinct peak modes and decay over time, indicating formulation-specific differences in ultrafine particle generation. Pigmented and base variants show variations in intensity and dominant particle sizes, highlighting the influence of paint composition on nanoscale emission dynamics. Routine field measurements of indoor plastics are limited by methodological constraints at the nanoscale. Optical techniques such as micro-Raman, micro-FTIR, and brightfield microscopy are restricted by the Abbe diffraction limit (~200 nm), making reliable detection of smaller particles difficult. For this reason, advanced methods such as electron microscopy, field-flow fractionation (FFF), dynamic light scattering, and FFF coupled with pyrolysis are increasingly recommended for nanoplastic characterization [22,24,30]. However, nanoplastics in environmental samples remain largely unquantified. No current method can definitively confirm their presence in complex environmental matrices. As a result, nanoplastics are likely underreported rather than absent in residential air and dust [22,24,30].

Settled indoor dust contains measurable amounts of microplastics (MP; reported ranges of 10–635 and 62–3861 MPs g^{-1}). Dust acts as both a sink and a transformation reservoir. Mechanical stress and friction within the dust matrix can further reduce particle size, potentially generating nanoscale fragments. At the same time, dust particles can be resuspended during normal activities, reintroducing plastics into indoor air [2,30]. Nanoplastics smaller than 100 nm behave as ultrafine inhalable

particles. When inhaled, they can reach and deposit in the alveolar region in the deep lung. The alveolar barrier is extremely thin (<1 μm), allowing nanosized particles to potentially penetrate into the capillary blood system [6,13]. In addition, aging paints and coatings may continuously release small particles indoors. These particles can carry hydrophobic contaminants or leachable additives, increasing their potential health relevance [9,24,31].

Although most indoor studies use the term “microplastics,” reported size distributions frequently extend into the submicron range; i.e. the nanoplastics range as explained above [22]. Therefore, when microplastic datasets include submicron fractions, they are likely to contain a nanoscale component—even if it is not explicitly identified or quantified.

Methodology

This study was designed as a structured and methodologically state-of-the-art literature review to systematically evaluate current evidence on the occurrence, formation pathways, emission sources, indoor behavior, analytical detection, and exposure relevance of nanoplastics in residential environments. The study design followed a predefined review protocol that specified search strategy, eligibility criteria, and analytical categorization procedures prior to screening. A comprehensive search was conducted across four major scientific databases—Web of Science, Scopus, PubMed, and ScienceDirect—using predefined Boolean search strings combining nanoplastic-related terms (“nanoplastics,” “submicron plastics,” “ultrafine plastic particles”), indoor environment descriptors (“indoor air,” “residential buildings,” “indoor dust,” “breathing zone”), source-related keywords (“paints,” “coatings,” “textiles,” “consumer products,” “polymer degradation,” “UV aging,” “abrasion”), and exposure-focused terms (“inhalation exposure,” “resuspension,” “bio-uptake”). Searches were restricted to peer-reviewed journal articles published in English to ensure scientific rigor and comparability of methodologies.

All retrieved records underwent structured screening against predefined inclusion and exclusion criteria. Studies were included if they explicitly addressed nanoplastics (<1 μm) or reported particle size distributions extending into the submicron range and demonstrated relevance to indoor or residential environments or indoor-relevant polymer sources, Studies focusing exclusively on marine or outdoor systems without transferable indoor relevance, addressing only macroplastics, or lacking size-resolved characterization were excluded. Following eligibility assessment, 31 articles met the selection criteria and were retained for qualitative synthesis.

For analytical consistency, included studies were systematically categorized into predefined residential source domains, including polymer-based building materials (e.g., interior paints and coatings), synthetic textiles and furnishings, consumer polymer products, indoor dust reservoirs, and secondary degradation processes (UV-induced oxidation, mechanical abrasion, and thermal aging). Structured data extraction was performed using a standardized framework capturing particle size definitions, reported size distributions, polymer types, emission or degradation mechanisms, analytical techniques employed, and exposure implications. Due to methodological heterogeneity and acknowledged nanoscale detection constraints, findings were synthesized qualitatively, emphasizing mechanistic convergence across polymer degradation science, aerosol physics, and indoor exposure research.

Discussion

The presence of a fraction <100nm-size indoors is consistent with what polymer science predicts. Weathering processes driven by light, oxygen, and heat trigger chemical changes that lead to chain scission, embrittlement, and surface cracking. Once the material becomes brittle, cracks propagate and fragmentation accelerates, producing progressively smaller debris from the original bulk polymer [28]. Nanoplastic focused reviews describe this as a fragmentation cascade that can extend beyond microplastics into the nanoscale, while also emphasizing that the surface chemistry of the resulting particles changes in ways that can affect their environmental behavior [22]. Under controlled UV exposure and other stressors, secondary fragments can be generated that extend into the tens of nanometers range, showing that generation of even <100nm-size nanoplastics is achievable under realistic degradation drivers even if the exact rate in homes remains uncertain [24,29]. Indoor materials provide plenty of opportunities for such processes to operate. Residential environments contain long lived polymer reservoirs in the form of wall paints, surface coatings, decorative films, textiles, furnishings, packaging, and numerous consumer products, see figure 0.3.

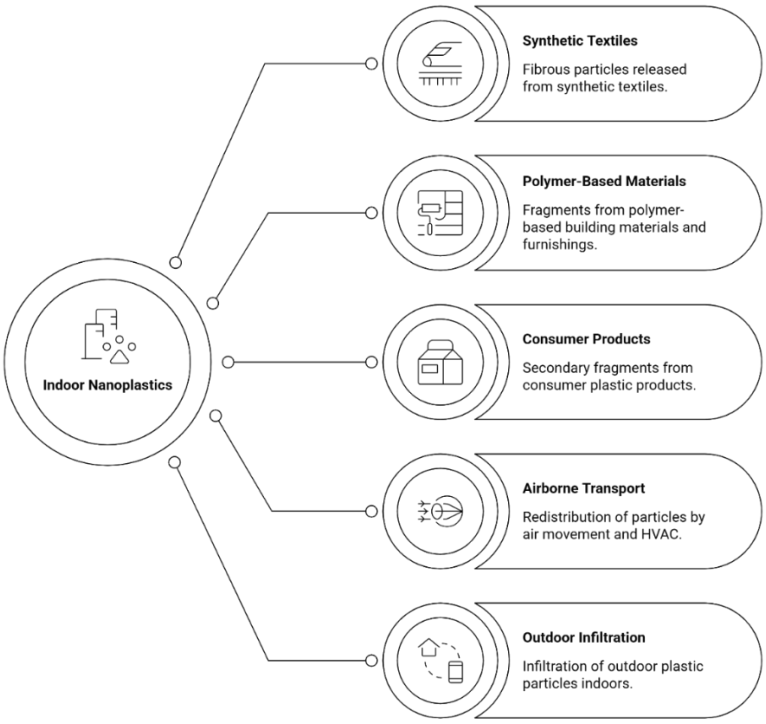

Figure 0.3 Conceptual overview of major sources and pathways contributing to nanoplastics in residential indoor environments

These materials experience routine abrasion, friction, handling, and cleaning, as well as intermittent heat and light exposure. Indoor environmental work emphasizes that fragments released from such sources tend to accumulate in house dust, and it explicitly frames indoor plastic contamination as a hygienic concern that deserves attention[2]. At the same time, the same literature makes clear why the nano fraction rarely appears in routine indoor datasets. Particles below one micrometer in particular, are difficult to chemically characterize using common optical approaches, which means the smallest fractions are systematically under captured [2,22]. Gigault and colleagues explain how diffraction limits constrain micro FTIR and micro-Raman

based identification at small sizes and why electron microscopy or other techniques are needed to image nanoplastics [22]. Method reviews similarly note that detection approaches for nanoplastics remain immature and that confirmed quantification in environmental samples is still limited, which makes underreporting a structural feature of the evidence base rather than a minor inconvenience [30].

Controlled indoor studies add another piece by showing that nano-sized particles can enter the air compartment directly from polymer containing building products. Chamber measurements of interior paints during drying report nano sized aerosol emissions across a size range from a few nanometers up to hundreds of nanometers, with dominant peaks in the ultrafine regime depending on paint formulation [27]. Even with the uncertainty about whether all measured particles are solid polymer fragments, the key implication is that polymer containing materials can generate ultrafine particle exposures in situations that are common in real homes, such as repainting or maintenance [27]. Field and exposure work further indicates that indoor particle concentrations vary with occupant activities and cleaning practices and that breathing zone dynamics, including near body airflow, shape what is actually inhaled [26]. This is consistent with the idea that settled material can become airborne again, which is particularly relevant for dust. House dust acts as both storage and a source. Dust measurements show that plastics are present at substantial levels, and the indoor literature states directly that particles contained in dust can be mobilized by resuspension [2]. Mechanistic discussions reinforce that when plastics embrittle, friction and other external forces can contribute to the formation of small particles at the surface, including in the nano and micro size ranges [30]. In a practical sense, this means dust does not simply collect what has already been emitted. It can also participate in the persistence of exposure by repeatedly feeding particles back into indoor air during routine movement and cleaning.

The case for paying attention to the smallest fraction is strengthened by aerosol physics and toxicological plausibility. Nanoplastics in the sub 100 nm range are described as more likely to remain suspended and to contribute to the ultrafine particulate matter fraction, with transport dominated by Brownian diffusion [22]. The comparison presented in table 1 highlights the substantial inconsistency in size-based definitions of plastic debris across scientific frameworks. In particular, the boundary between nanoplastics and microplastics varies widely, ranging from <100 nm to <1 µm, and in some cases extending into several hundred micrometers. Upper thresholds for microplastics also differ, although 5 mm is commonly adopted. These definitional discrepancies complicate cross-study comparisons, exposure assessments, and regulatory harmonization. The lack of a standardized size framework therefore represents a structural limitation in nanoplastic research and underscores the need for clearer operational definitions in indoor environmental studies [1, 3-16]. Table 2 indicates that more recent institutional reports are beginning to move toward a broader and more operationally useful interpretation of nanoplastics. EFSA appears to retain the nanomaterial-based definition of approximately 1–100 nm [17], while the European Commission and the US EPA increasingly acknowledge the practical relevance of a broader 1–1000 nm range for environmental particles [18-20]. This shift is scientifically important because environmentally generated plastic fragments do not necessarily conform to the stricter nanoscale definitions originally developed for engineered nanomaterials. The older definition is useful for regulatory consistency with nanomaterial science, but it may be too restrictive for environmental exposure studies, particularly in indoor settings where fragmentation processes, resuspension, inhalation behavior, and analytical limitations all point to the importance

of submicron plastic particles beyond 100 nm. By contrast, the newer broader range captures the continuum of environmentally relevant plastic fragments in a better way and aligns more closely with current analytical practice, where many detection methods can identify particles within the submicron range but not reliably below the strict nanoscale cutoff. In this sense, the newer definition does not replace the older one entirely but rather expands it to better reflect the realities of environmental occurrence, exposure assessment, and measurement.

Reviews also discuss the thin alveolar barrier and the potential for nanosized particles to interact with deep lung regions and potentially translocate beyond the respiratory tract, even though health risk assessment for plastic nanomaterials is still developing [24,31]. At the same time, nanoplastics may carry chemical burdens because small particles have high surface area and can adsorb hydrophobic chemicals or act as vectors for additives and degradation products, which raises the possibility that exposure is not purely particulate but also chemical [30].

When these strands are read together, the most defensible interpretation is not that nanoplastics are missing from residential air and dust, but that they sit below the effective detection floor of many standard methods. Submicron fractions are repeatedly present in datasets labeled as microplastics, the physics and chemistry of polymer weathering support continued size reduction, chamber studies show that indoor products can generate ultrafine particle emissions, and method reviews openly acknowledge why nanoscale identification remains difficult [2,22,24,26–31]. The next generation of indoor studies will need measurement strategies that are explicitly built around the submicron regime, paired with realistic descriptions of indoor dynamics such as activity patterns, air movement, and ventilation, because those processes determine what reaches the breathing zone and what remains in reservoirs such as settled dust [2,22,26,27,30].

Conclusion

This review brings together current evidence on the presence, formation, behavior, and potential exposure relevance of nanoplastics in residential indoor environments. Findings from polymer degradation studies, indoor chamber experiments, dust investigations, and aerosol exposure research collectively suggest that nanoscale plastic fragments are a plausible component of indoor particulate matter. Fragmentation processes driven by UV exposure, thermal oxidation, and mechanical abrasion can gradually reduce larger plastic materials to micro- and nanoscale particles. Common residential materials such as paints, coatings, textiles, and consumer products therefore act as ongoing sources, while indoor dust functions both as a sink and a reservoir that can release particles back into the air through resuspension.

At the same time, current analytical methods still struggle to reliably identify particles at the nanoscale. Because many optical techniques are limited by resolution constraints and interference, particles below one micrometer are also difficult to chemically confirm, which means that nanoplastics are likely underdetected rather than absent in indoor air and dust. Reported microplastic size distributions often extend into the submicron range, suggesting that a nanoplastic fraction is already embedded within existing datasets. Recent scientific and institutional frameworks also increasingly recognize a broader operational size range approaching 1 µm (1–1000 nm), reflecting a growing understanding of fragmentation processes and environmental particle behavior.

Given their ultrafine aerosol properties, high surface reactivity, and potential to interact with deep lung regions, nanoplastics deserve greater attention within indoor air quality research. Future studies should therefore focus on size-resolved sampling below 1 μm, apply analytical methods capable of detecting nanoscale particles, and link measurements with indoor processes such as ventilation, occupant activity, and dust resuspension in order to better understand breathing-zone exposure and possible health implications.

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Appendix II

Projekt: Forundersøgelse af mikro- og nanoplast i boligers indeklima

NFA: Keld Alstrup Jensen, Yahia Kembouche, Trine Berthing, Anders Brostrøm, Ulla Vogel

Formål

At undersøge andelen af den potentielle mikro- og nanoplast (MNP) fraktion i fint luftbåret støv ($PM_{2.5}$; som er massen af partikler mindre end 2,5 µm opsamlet med cyklon) i indeklimaet sammenlignet med en parallel $PM_{2.5}$ prøve fra udendørsmiljøet.

For at gennemføre projektet blev der opsat fire analytiske delmål.

1. Udvikling af metode til at dispergere prøverne og fordele dem til de planlagte analyser
2. Udvikle og teste plast-specifikke mikroskopimetoder
3. Etablering af databibliotek med relevante plastmaterialer til termogravimetrisk til plastanalyse
4. Karakterisere og udføre analyserne på prøverne

Prøvematerialet

Det var valgt, at projektet skulle undersøge indendørs og udendørs $PM_{2.5}$ opsamlet i og udenfor 15 forskellige svenske hjem i et tidligere projekt (Wierzbicka et al., 2022). Prøverne var udvasket fra PTFE-filtre med opsamlet indendørs og udendørs $PM_{2.5}$ støv. Filteret fra hvert hjem blev ekstraheret vha. 30 minutters ultralydsbad 2 gange i 30 mL ethanol. Prøverne for hhv. indendørs og udendørs $PM_{2.5}$ blev derefter poolet, sonikeret, og overført til 50 mL glas og ethanolen (ca. 20 mL) dampet af i vacuum (150 mbar) ved 35°C. Indendørs- og udendørsprøverne blev resuspenderet vha sonikering i ethanol, poolet og sonikeret igen og endelig fordelt i 10 mL prøveglas og inddampet som før. Prøverne i vores projekt var derfor støv udfældet i prøveglas. Dette var en udfordring, der skulle løses i forhold til de planlagte analyser, der til mikroskopi kræver veldispergerede partikler uden brug af detergenter samt overførsel en repræsentativ fra prøveglas til en Alumina-prøveholder til termiske analyser.

Dispergeringsmetode underdeling

Flere ekstrations- og sonikeringsmetoder (ultralyd og probe-sonikering og forskellige tider tid) og vand med forskellige ethanolkoncentrationer blev testet for at de-aggregere materialet. Vi endte med en protokol, hvor de oprindelige prøveglas blev tilføjet 3 mL 1% ethanol i Nanopure vand, ultralydsbehandlet efterfulgt af mekanisk løsning af det indtørrede prøvemateriale med en stålspatel. Det løsnede materiale blev herefter overført til en scintilationsglas og dispergeret vha. probe sonikering i 1% (v/v) ethanol (96%) i nanopure vand. Ved at poole to underdelte oprindelige

prøver fra hhv. indendørs og udendørs kunne vi få tilstrækkeligt materiale til de forventede analyser, hvor de termiske analyser har det største materialebehov. Den optimale sonikeringstid var til 3 x 5 minutter adskilt af 1-2 minutters pause for at forhindre at prøven blev for varm.

Herefter blev 2 mL af den sonikerede dispergering overført til at TGA Alumina prøvekop, som blev indtørret igen (ca. 30-60 minutter) ved 100°C på en varmeplade placeret i en LAF-bænk (BioSafety Cabinett Type II). Prøvekoppen var overdækket perforeret stanniol for at undgå kontaminering.

Resten af materialet blev brugt til at lave forskellige mikroskopi præparater.

Alle materialer og glas blev rengjort i 1% ethanol Nanopure vand før brug. Der blev anvendt glaspipetter for at undgå potentielt bidrag fra plast pipettespidser.

Generel prøvekarakterisering

Prøverne blev analyseret overordnet ved hjælp af optisk polarisationsmikroskopi og skanning elektron mikrokopi for at få en generel forståelse for partiklerne i prøverne.

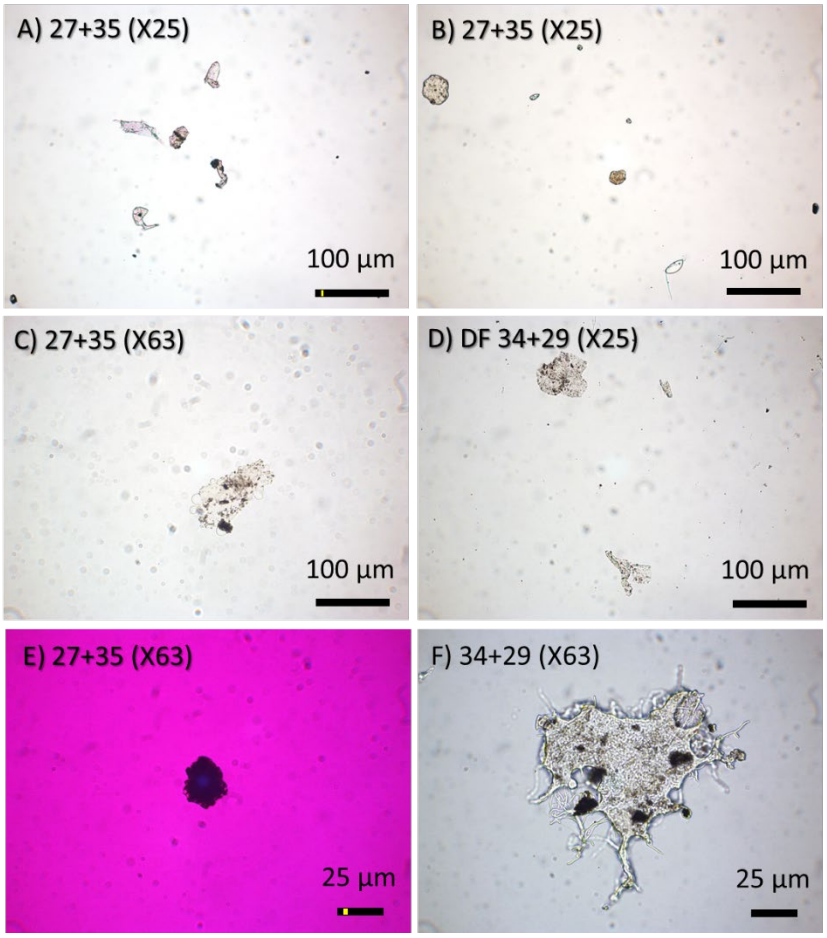
Optisk polarisationsmikroskopi

Støvprøverne blev karakteriseret med optisk polarisations mikroskopi for at få et overblik over de resuspenderede partikler i prøven, og for at undersøge, om der blandt de store partikler var særlige partikeltyper der potentielt kunne være plastmaterialer.

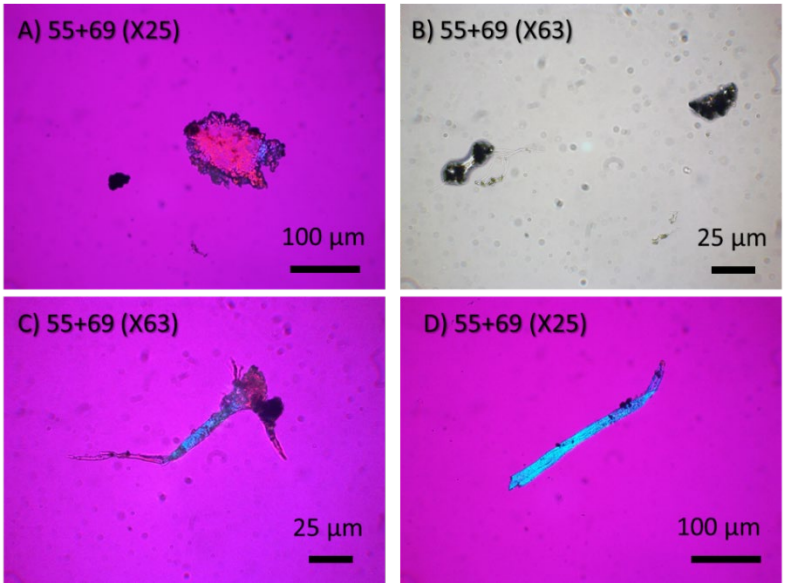
Optisk polarisationsmikroskopi er en metode, hvor den suspenderede prøve analyseres i et lysmikroskop, hvor lyset er polariseret i et plan. Prøven er suspenderet og dryppet ud på et ultrarent objektglas og tildækkes en tynd glasplade (ultrarent dækglas). Man analyserer generelt prøven i planpolariseret lys samt ved at indsætte endnu en polarisator, hvor dobbeltbrydende gennemskinnelige partikler lyser op i en ”udslukket” (ikke dobbeltbrydende) væske. Hvis man indsætter et såkaldt gipsblad i lysgangen, forskydes lysets bølgelængde 550 nm, så den mørke væskebaggrund bliver lyserød og de andre farver forskydes tilsvarende op eller ned afhængig af partiklernes optiske egenskaber. Der vises billeder af disse forskellige typer i gennemgangen herunder.

Indendørs og udendørsprøverne bestod begge overvejende af opake (ikke gennemskinnelige) og transparente (gennemskinnelige) partikler og aggregater med op mere end 100 µm størrelse. De transparente partikler kunne både forekomme som optisk rene partikler og partikler med inklusioner og sammenklumpninger med opake partikler (Figur 0.1 og Figur 0.2). Prøverne indeholdt også forskellige typer fibre. Nogle af fibrene var insekt og plantefragmenter (Figur 0.2C, D og Figur 0.3) mens andre potentielt kunne være tekniske organiske fibre (fx cellulose og lignin) og komme fra tekstiler og andre materialer (Fx Figur 0.4A-F). Enkelte fibre fremstod med glatte overflader og inhomogen udslukningsmønster i polariseret lys, hvilket kan være plastmateriale (Figur 0.4G). Indendørsprøven indeholdt en større andel af fibre end udendørsprøven. Fibrene i indendørsprøven omfattede umiddelbart både fremstillede/bearbejdede og naturlige materialer, inklusive plantefragmenter. Det skal bemærkes, at der blev undersøgt to resuspenderede delprøver fra indendørsmiljøerne. Den ene af disse prøver (34+29) havde et større indhold af fibre end den anden (27+35). I prøven 34+29 blev der observeret mange fine fibre, som kunne stamme fra større fiber bundter, men de kan også potentielt have biologisk oprindelse.

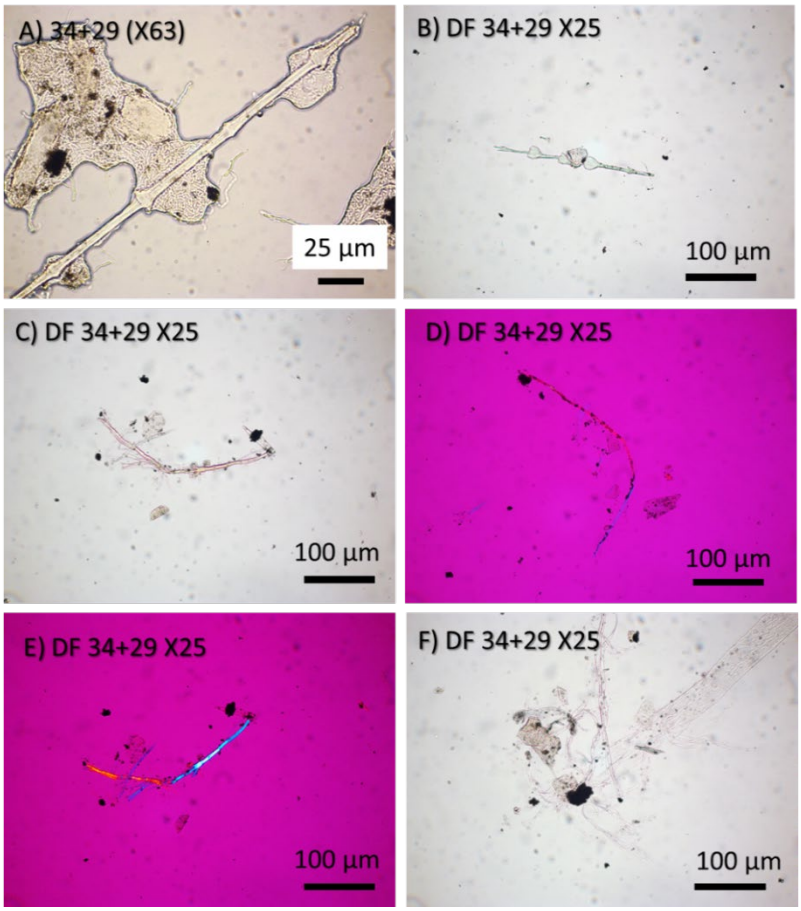
Størrelsen på de største partikler overskrider langt 50% cut-of-værdien på 2,5 µm for opsamlingen af $PM_{2.5}$ og de længste store fibre er flere hundrede µm lange. Figur 0.1A og E viser med en gul skala på den sorte bjælke størrelsen på en 2,5 µm objekt ved de to forstørrelser i lysmikroskopet. De store partikler kan dels forklares ved at være resuspenderede som aggregater af partikler og udfældede opløste stoffer fra de inddampede prøver. Denne mekanisme kan dog ikke forklare tilstedeværelsen af de store fiber-objekter, idet opsamlingseffektiviteten er nærmest 0% for en 5 µm sfærisk partikel med en densitet på 1 g/cm^3 ved opsamling med en $PM_{2.5}$ forudskiller. Disse store fibre antages derfor at stamme fra tilfældige indsugede fibre under opsamlingen og potentiel kontaminering under de forskellige ekstraktions, sub-sampling, og redispergeringsprocesser, som prøverne har været igennem.



Figur 0.1. Polarisationsmikroskopibilleder af de typisk forekommende transparente og opakke partikler i resuspenderede indendørsprøver. Billede A, B, C, D og F er taget i planpolariseret lys; billede E er taget med krydsede polarisatorer og indsat gipsblad. Prøven i D markeret med DF er densitetsfraktioneret for partikler med en densitet > 1.5 g/cm^3.



Figur 0.2. Polarisationsmikroskopibilleder af de typisk forekommende transparente og opakke partikler i resuspenderede udendørsprøver. Billede B er taget i planpolariseret lys; billede A, C, D er taget med krydsede polarisatorer og indsat gipsblad.



Figur 0.3. Polarisationsmikroskopibilleder af antagede biogene partikler og fibre i indendørsprøven. Prøven i B-F markeret med DF er densitetsfraktionerede for partikler med en densitet > 1.5 g.

Skanning elektron mikrokopi

Skanning elektron mikroskopi (SEM) er en metode, hvor en prøve analyseres ved hjælp af en fokuseret elektronstråle som skannes hen over et afgrænset analyseområde. Elektroner fra elektronstrålen kastes tilbage til en detektorchip, som omdanner

signalet til et 2-dimesionelt billede af overfladen med en opløsning ned til nanometer skala. I vores tilfælde blev de suspenderede prøver dryppet ud på et elektron mikroskopi Cu-grid pålagt en tynd carbon film. Prøven placeres i en holder og føres ind i mikroskopets vakuumkammer. Ud over at tage billeder af partiklerne, så kan de analyseres med en energidispersiv røntgendetektor i mikroskopet for at få et estimat af partiklernes grundstofsammensætning eller grundstoffordelingen over et område (mapping).

SEM af indendørsprøven understøttede resultaterne fra polarisationsmikroskopien. I SEM kunne vi se mikropartikler og større aggregater med kulstof-baseret matriks med lav Si-koncentration. Dertil blev der fundet en relativ stor andel af partikler af oxider med Fe-, Fe-Ni-Cr og ti. Der blev observeret enkelte meget store fibre. Fibrene inkluderede cellulose-lignende materiale, kulstof-baserede biogene fibre med lave koncentrationer af Si, P og alkalimetaller. Der blev fundet en kulstof-baseret fiber med glat overflade, der kunne være af plast (Figur 0.5D). Figur 0.6 viser et overbliksbillede et agglomerat af partikler og fibre over samt fordelingen af grundstoffer deri.

I udendørsprøven (70+62) bestod partiklerne overvejende af karbon-baserede partikler med lave koncentrationer af S, Cl, alkalimetaller og nogle gange Si (typisk for biogene partikler), forskellige jordmineraler (fx alumina/silika/alkali-aluminium-silikat, og en mindre andel Ti-, Fe-, Fe-Ni oxider). Der blev observeret diverse salte (alkali sulfater) samt enkelte større kulstof-baserede partikler med alkalimetaller, Cl og S. Vi fandt ikke fibre i den udtagne udendørsprøve. Figur 0.7 viser en oversigt over de typiske partikeltyper.

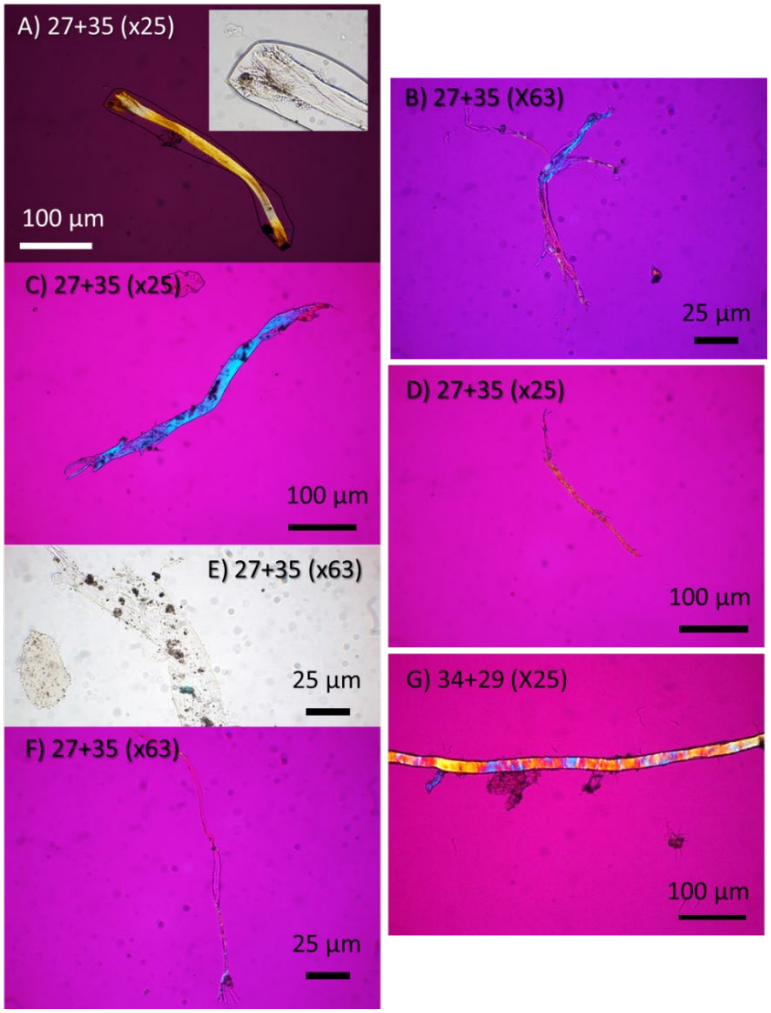
”Plastspecifikke” analysemetoder

TGA-MS (Termogravimetrisk Analyse koblet med et MasseSpektrometer)

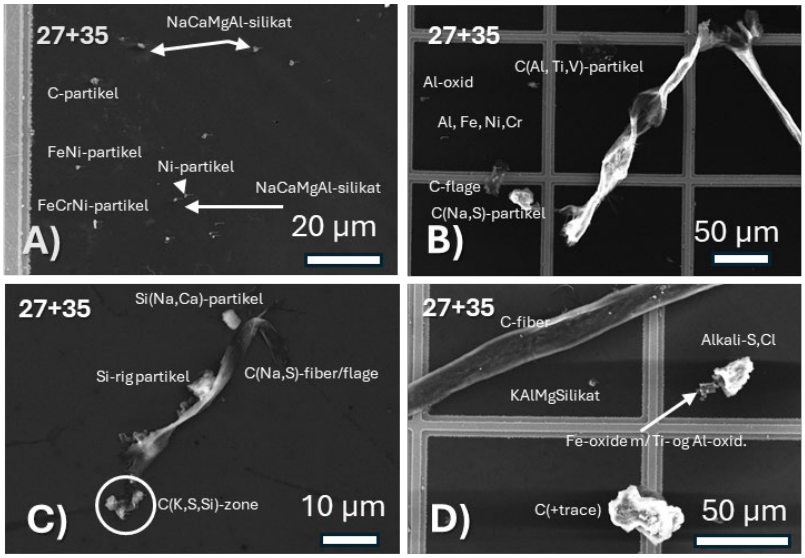
TGA-MS (Figur 0.8) blev anvendt til at bestemme den potentielle mængde af plastikmaterialer i prøverne. Metoden består grundlæggende i at opvarme en prøve i en Alumina-prøveholder under velkontrolleret opvarmning (2,5C°/min) fra 30/35°C til 1000°C i iltet luft (80% O_2/ 20% N_2). Undervejs vejes masse-ændringerne direkte på en meget fintfølende mikrovægt i TGA’en som funktion af temperatur (eller tid). Gasser, der frigives under opvarmningen, måles løbende vha. et massespektrometer, der kan måle relativt lette molekyler, ved at opsamle luften fra prøvekammeret vha. en ca. 300°C opvarmet opsamlingsslange. Princippet er anvendt i en række publikationer til analyse af plast alene eller i blandinger med affald (fx Gunasee et al., 2016; Das and Tiwari, 2019).

Arbejdet omfattede:

- Til analysearbejdet udbyggede vi et plast prøvebibliotek for at kunne identificere de relevante temperatur-intervaller, hvor forskellige plasttyper/materialer har et signifikant masse-stab samt om der var karakteristiske molekyler, der kunne bruges til kvantificering med metoden. Udbygningen blev foretaget med forskellige typiske plastmaterialer fra dagligdagen og husinstallationer (forskellige fødevareemballager, tekstilprøver, vandrør, gulvvarmerør).
- TGA-MS-analyse af prøverne fra de svenske hjem og analyse af de termiske spektre til potentiel kvantificering af plastandelen i prøven.

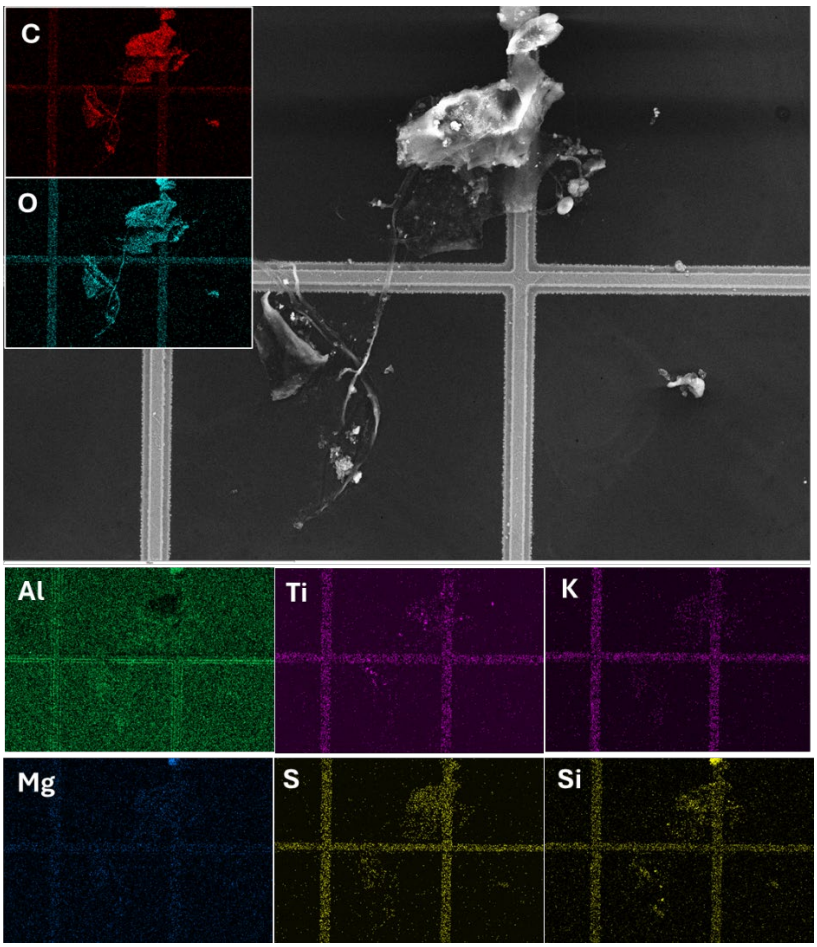


Figur 0.4. Polarisationsmikroskopibilleder af potentielt forarbejdede (A, B, C) og naturlige (D, E, F) fibre i indendørsprøven samt en formodet plastfiber (G). A) Billede taget med krydsede polarisator; B, C, D, F; og G) billede taget med krydsede polarisator og gipsblad, E) billede taget i planpolariseret lys.

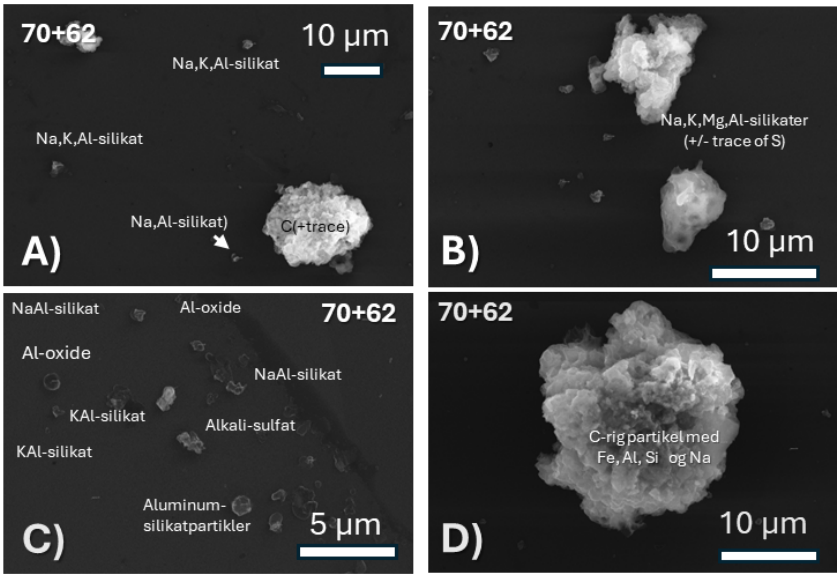


Figur 0.5. SEM billeder af partikler og fibre i indendørsprøven (27+35). Partikler og fibre fremstår som lyse områder på mørk baggrund af kulstof tyndfilm. På visse billeder ses kanterne af det Cu-grid som tyndfilmen er hæftet på. De individuelle partikeltyper i billederne er angivet ud fra deres kemiske karakteristika. A) Oversigtsbillede af mikropartikler i indendørsprøven. B) Stor fiber-bundt og diverse mikropartikler. C) Kulstof-

holdig fiber antaget af være organisk associeret med mikropartikler. D Store og små mikropartikler samt ca. 20 µm tyk kulstof-baseret fiber, der kan være en plastfiber. De mindste partikler i prøven er under 50% cut-point for opsamling af $PM_{2.5}$ og kan være originale luftbårne støvpartikler.

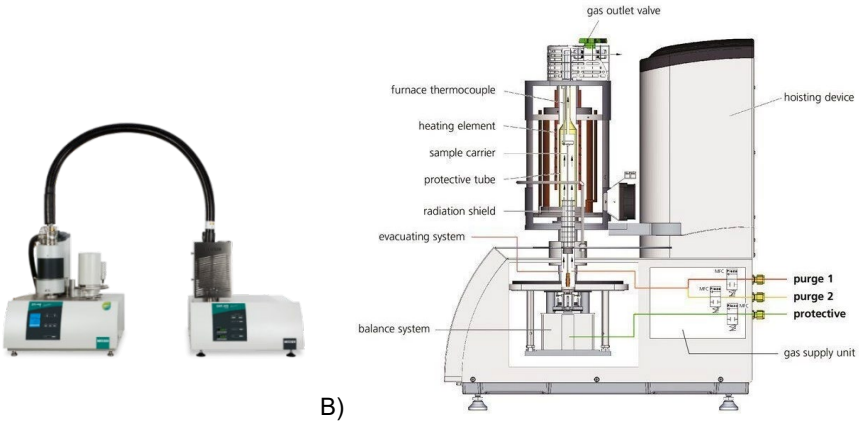


Figur 0.6. SEM-billede og kemisk arealfordeling af udvalgte grundstoffer (stærk farve er lig med høj koncentration i relativ skala) i en ansamling af fibre og partikler i indendørsprøven 27+35. Der ses fibre og flager som overvejende består af kulstof (C) med mindre mængder Si, S, K, og P. Enkeltpartikler består af fx TiO_2 og SiO_2, MgAl-silikat.



Figur 0.7. SEM billeder af typiske partikeltyper i udendørsprøven. De individuelle partikeltyper i billederne er angivet ud fra deres kemiske karakterstika. Overordnet var de analyserede prøve domineret af alkali-(magnesium)-aluminium- silikater mineraler og oxider (A, B, C) samt kulstof rige partikler med lave koncentrationer

af andre grundstoffer (A og D). De mindste partikler i prøven er under 50% cut-point for opsamling af $PM_{2.5}$ og kan være originale luftbårne støvpartikler.



A) B)

Figur 0.8. A) Billede af termogravimetrisk analyseapparat (TGA) sammenkoblet med et massespecktrometer (MS). Til højre samt den tekniske opbygning af en TGA.

Prøvebibliotek

Der blev lavet et TGA-MS prøvebibliotek baseret på 16 forskellige plast-prøvematerialer (14 vist Figur 0.9) samt cellulose (methyl cellulose (MCE-filtre)) og carbon black (Printex90), som surrogat for hhv. plantebaserede materialer/plantefragmenter og kulstofkernen i sodpartikler. Resultaterne viste at methyl cellulose afbrændte ved meget lavere temperatur end plastmaterialerne. Omvendt afbrændte carbon black ved væsentligt højere temperaturer end plastmaterialerne. Plastmaterialerne i sig selv begyndte ofte at have et massetab ved ca. 200°C (ca. 250°C for PS) og fuld afbrænding mellem 400 og 550°C. Resultaterne tyder på, at produkter af plastmaterialer i visse tilfælde afbrænder over et relativt stort temperaturspænd, sammenlignet med de rene plastpolymerer (fx prøverne PP, PET, MDPE of PS). Derfor analyserede vi også gasserne og materialernes peak-masse-tab under afbrændingen. Det vil sige peak-værdien for prøvens massetab som funktion af stigende temperatur. Den kurve kaldes differential thermogravimetrisk (DTG) kurve og afledes af data'ene bag kurverne i Figur 0.9.

Tabel 1 viser et overblik over peak-masse-tab for alle benchmark materialerne og relevante litteraturdata. Det skal bemærkes at opvarmningsraten i TGA-MS-protokollen, som er anvendt i dette studie, er langsommere end dem, der er anvendt i den fundne relevante litteratur. En højere opvarmningsrate medfører at peak-temperaturerne øges svagt per 10 grads stigning i rate. Derfor kan litteraturdataene ikke sammenlignes direkte med resultaterne i vores studie, men de giver en god indikation det relevante temperaturområde, hvor afbrændingen sker.

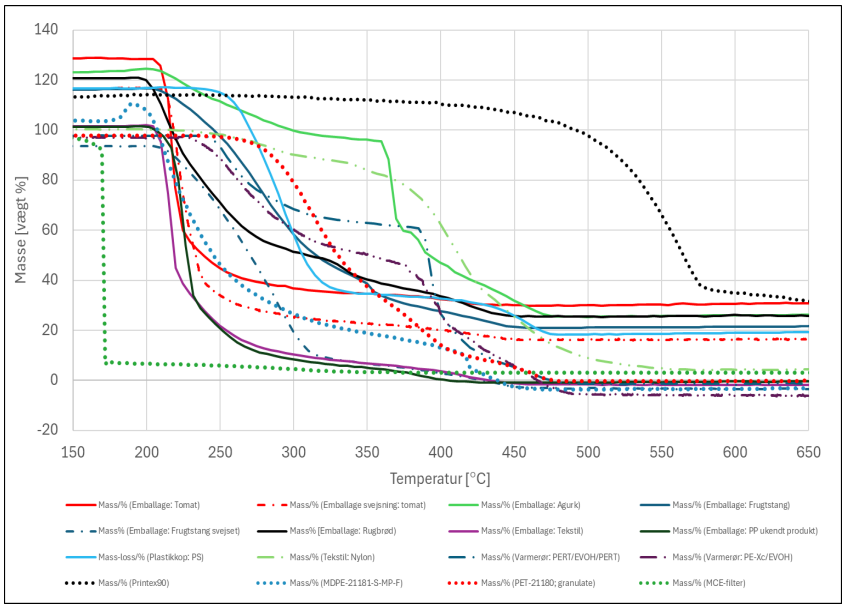
Peak-temperaturerne for afbrænding af de forskellige rene PP, MDPE og PET-plastmaterialer afveg generelt betragteligt fra de fundne litteraturdata (Tabel 1). Derimod ser det ud til at Methyl-cellulose afbrænder ved væsentligt lavere temperaturer end cellulose og lignin i litteraturen. Shen et al. (2013) viste et peak-massetab ved 326°C ved afbrænding af cellulose i 20% O_2 luft og en opvarmningsrate 20°C/min (4 gange hurtigere end i vores setup). Et studie af afbrænding af lignin fra lærk viste en peak afbrændingstemperatur på 447°C ved afbrænding i luft (ca. 20% O_2) og en opvarmningsrate på 10 °C/min (2 gange hurtigere end i vores setup; Li et al., 2002). Et andet studie, også ved 10°C/min, viste højere peak-afbrændingstemperaturer for

kraft lignin og hårdtræ lignin; hhv. 518°C (kraft; 228-518°C) og 478-480°C (hårdtræ; temperaturinterval: 214-480°C) (Pe III et al., 2023).

TGA-MS-analyse af $PM_{2.5}$ prøverne

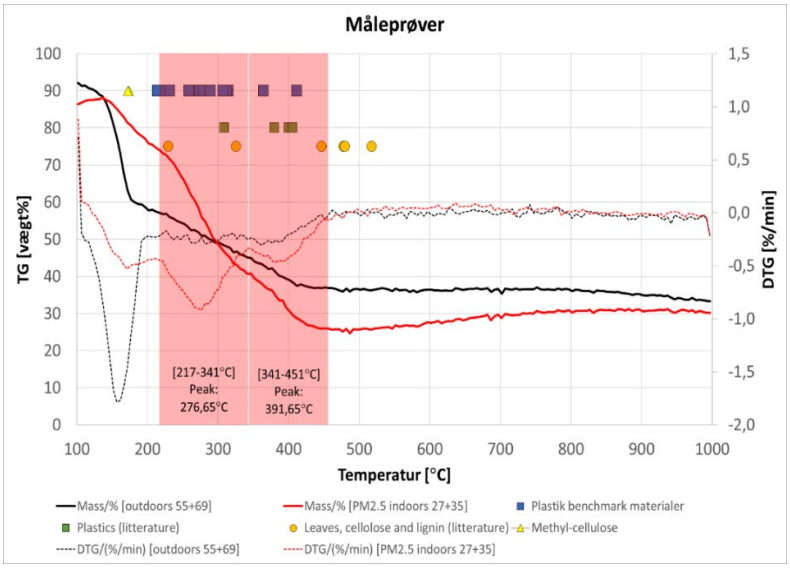
Figur 0.10 viser de termogravimetriske måleresultater for analysen af $PM_{2.5}$ prøverne. Det ses tre distinkte masse-tabs-begivenheder under opvarmningen. Den første event (1. event) sker ved ca. 150°C og er stærkest i udendørsprøven. Derefter følger to events ved hhv. 217-234°C (peak 276,65°C; 2. event) og 234-451°C (peak 391,65°C; 3. event), som er stærkest i indendørsprøven. Den første event tilskrives ikke plast, men kan potentielt tilskrives organisk / biogent materiale. I 2. event er det relative massetab 30,7% i indendørsprøven og 10,7 % i udendørsprøven. I 2. event er massetabet 14,7% i indendørsprøven og 9,1% i udendørsprøven.

Ved sammenligning med benchmark materialerne, ses det, at flere materialer har peak massetab i intervallet 217-234°C (peak 276,65°C). Enkelte plastmaterialer har også et peak massetab i det sidste 234-451°C (peak 391,65°C). Det var dog ikke muligt at identificere enkeltmaterialer i vores benchmark bibliotek, der matchede $PM_{2.5}$ kurverne præcist. Det kan skyldes, at vi ikke har det rigtige materiale i benchmark kataloget. Dog passer peak-temperaturen og TGA-profilen for afbrænding af emballagen til frugtstang godt med 2. event. Plasttypen er dog ikke identificeret i vores bibliotek. Der kan også være biogent materiale der afbrænder i samme temperaturinterval.



Figur 0.9. Prøvebibliotek over det procentvise termogravimetriske massetab mellem 150 og 1000°C for benchmark plastmaterialer: Medium-Density Polyethylene (MDPE); Polyethylene terephtalate (PET); variation af plastprodukter relevant for indeklimaet: forskellige plastemballager; svejsede plastemballager, emballage af Polypropylene (PP), polystyrenkop (PS), Nylon (baseret på PET), 3-5 lags (PERT/EVOH/PERT) varmerør af Polyethylene (with) Raised Temperature Resistance (PERT) og ethylene vinylalcohol (EVOH) og varmerør: Polyethylene rør med ethylen vinylalcohol (PE-Xc/EVOH), sammenlignet med Printex90 (elementært kulstof lig kerne i sodpartikler) og methyl-cellulose (MCE-filter).

Det konkluderes at der maksimalt er 45.4 vægt% polymer-lignende materiale i indendørsprøven og 19,5 vægt% i udendørsprøven. Det er dog ikke sandsynligt, at hele den masse skal tilskrives plast set ift. Mikroskopianalyserne (ovenfor og herefter).



Figur 0.10. Termogravimetrisk analyseresultat at den indendørs og udendørs $PM_{2.5}$ prøve anvendt i undersøgelsen. TG (hele linjer) viser massetabet under opvarmning mens DTG (stiplede linjer) viser massetabsraten som funktion af temperatur. Til sammenligning er figuren er tilført peak masse-tabs-rate for forskellige plastmaterialer, cellulose og lignin opgivet i Tabel 1.

Plast-specifik optisk mikroskopi

Ved projektets start fandtes der ikke gennemprøvede plast-specifikke optiske metoder til at analysere nanoplast (<1µm) og småt mikroplast (1-10µm) i indeklimaprøver. Derfor bestod en del af arbejdet i at afprøve og udvikle forskellige plast-specifikke mikroskopi-teknikker vha. hyperspektral- og fluoroscens mikroskopi, som er forklaret herunder.

Hyperspektral mikroskopi

Enhanced darkfield hyperspektral mikroskopi er en metode udviklet til at detektere partikler helt ned til nano-størrelse. Detektionen sker ved at opfange det lys der reflekteres fra partiklerne. Lyset opdeles i bølgelængder fra 400-1000 nm som svarer til hver partikels spektrale fingeraftryk. Ved at sammenligne partiklernes spektrale fingeraftryk med spektrene fra kendte materialer, kan vi skelne mellem forskellige materialer. Metoden er under udvikling med hensyn til at kunne detektere og differentiere plastpartikler i komplekse prøver såsom luftprøver (Rahman et al. 2022).

- Der er skannet 5 typer reference-nanoplast (Tabel 3, Figur 0.11) samt den svenske indendørs $PM_{2.5}$ prøve (Figur 0.12), med hyperspektral mikroskopi. Desværre viste almindelige proces-urenheder i kontrolprøver med laboratorie-vand et spektralt match med reference-nanoplast-partikler (Figur 0.11).
- Følgende optimeringer af processen er gennemgået: brug af reneste klasse laboratorievand (nanopure), alt arbejde udføres i sterilt miljø (LAF-bænk), syrevask af forskellige typer mikroskop-glas, brug af særlige ultrarene mikroskopglas. Udestående problemer: at immobilisere og forsegle partiklerne til skanning uden at tilføje urenheder.

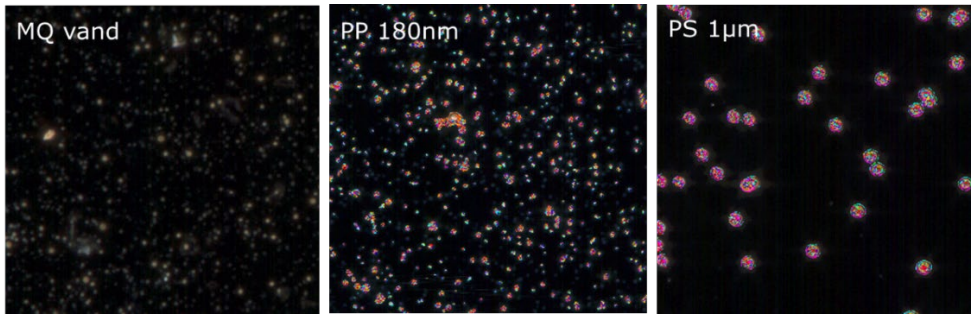
Tabel 0.1. Liste over event peak-temperaturer under afbrænding af plast referencematerialer, MCE og Printex 90 i dette studie sammenholdt med litteraturdata.

Materiale	Event 1 [°C]	Event 2 [°C]	Event 3 [°C]	Event 4 [°C]	DTA Rate (°C/min)	Reference
Emballage: Tomat	214,5				2,5	Dette studie
Emballage svejsning: tomat	222,8				2,5	Dette studie
Emballage: Agurk	364,6	384,6	459,6		2,5	Dette studie
Emballage: Frugtstang svejset	270,0	425,0			2,5	Dette studie
Emballage: Frugtstang	279,7				2,5	Dette studie
Emballage: Rugbrød	314,6	334,6			2,5	Dette studie
Emballage: Tekstil	214,7				2,5	Dette studie
Tekstil: Nylon	281,8	411,8	456,6		2,5	Dette studie
Plastikkop: PS	289,5	459,5			2,5	Dette studie
PS	400				20	Gunasee et al. (2016)
Emballage: PP ukendt produkt	226,7	381,5			2,5	Dette studie
PP	380				20	Gunasee et al. (2016)
Varmerør: PERT/EVOH/PERT	259,9	404,9			2,5	Dette studie
Varmerør: PE-Xc/EVOH	259,1	389,6	459,3		2,5	Dette studie
MDPE-21181-S-MP-F	232,0	414,5			2,5	Dette studie
PET-21180; granulate	312,4	*384,9*	459,9		2,5	Dette studie
PET 21182-SM-F	312,1	387,1	459,6		2,5	Dette studie
PET-21183-S-MP-F	167,6	307,7	385,2	462,6	2,5	Dette studie
PET (bottles)	406				5	Das and Tiwari (2019)
PVC	309	450*			20	Gunasee et al. (2016)
MCE-filter 25 mm	174,0				2,5	Dette studie
MCE-filter 37 mm	172,1				2,5	Dette studie
Leaves (LV)	230	430*			20	Gunasee et al. (2016)
Cellulose	326				20	Shen et al. (2013)
Lignin (lærk)	447				10	Pe III et al. (2019)
Lignin (”Kraft” – pulp lignin)	518				10	Pe III et al. (2019)
Lignin (hårdtræ; Accacia spp.)	478				10	Pe III et al. (2019)
Lignin (hårdtræ; mixed)	480				10	Pe III et al. (2019)
Printex90	561,6				2,5	Dette studie

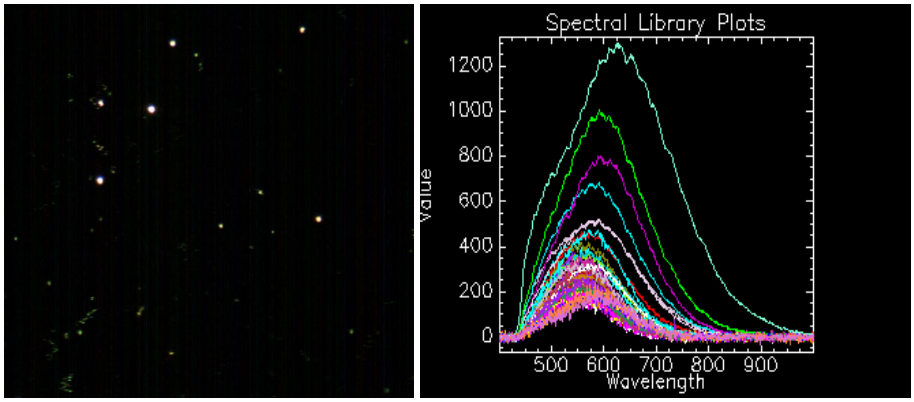
* Flere distinkte toppe observeret.

Tabel 0.2. Reference-plast til hyperspektral mikroskopi

Polymer	Diameter
PE	330 nm
PP	180.5 ± 5.8 nm
PET	1120 ± 140 nm, agglomerater 20-40 µm
PET	90 nm
PS	1 µm



Figur 0.11. Proces-relaterede urenheder i laboratorie vand (MQ (MilliQ-filtreret) vand) matcher spektralt med reference-nanoplast af bl.a. polypropylen (PP) og polystyren (PS). Spektralt match vises med farvede pixels. Enhanced darkfield hyperspectral microscopy.



Figur 0.12. Hyperspektralt skan af indendørs $PM_{2.5}$. De mindste partikler ligner streger på grund af bevægelse i opløsningen, da der mangler en metode til at immobilisere partiklerne uden at tilføje urenheder. Til højre ses spektrale fingeraftryk af indendørs $PM_{2.5}$.

Fluorescens-farvning og optisk mikroskopi

Nile Red er et farvestof som er kendt for at binde til plastpartikler, og som ændrer farve ved binding til forskellige typer plast (Shruti et al. 2022). Nile Red kan dog også binde til andre komponenter i indeklima, som fx hudceller fra mennesker og kæledyr eller olie-aerosoler fra madlavning. Derfor har vi arbejdet på en protokol med Nile Red og to kontrol-farver; DAPI der farver bl.a. DNA i fx hudceller og plantestøv, og Calcofluor White der farver bl.a. cellulose fra fx bomulds-, træ- og papirstøv (Taraf-dar et al. 2022). Derudover skal farvningen udføres med mindst mulig risiko for at påvirke plast-indholdet i prøverne. Udbredte metoder til større plast så som at opløse organisk materiale med syre eller enzymer, og at vaske overskydende farve ved størrelses-filtrering er ikke muligt med nanoplast. I 2024 udkom en artikel med en skånsom metode til at farve mikro- og nanoplast direkte i vandprøver (Peinador et al. 2024).

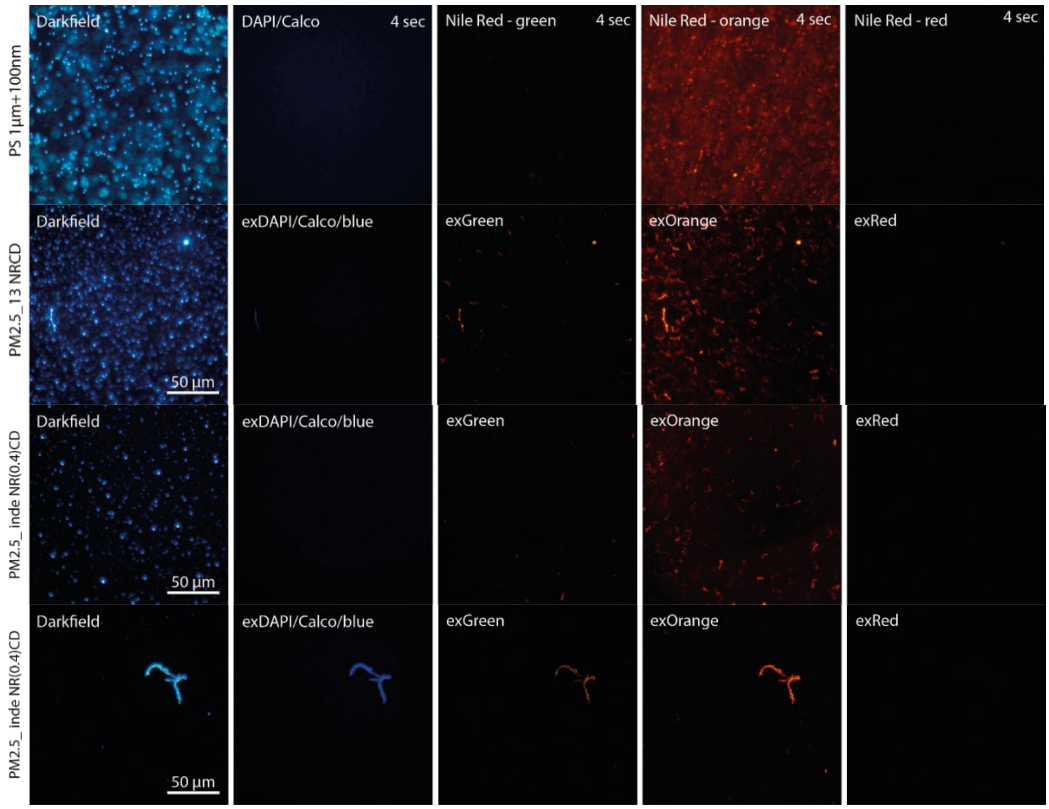
- En farve-protokol er udviklet og testet på polystyrenkugler i to størrelser, 1 µm og 100 nm (Figur 0.13). Fluorescens-signalet fra polystyrenkugler på 1 µm var kraftigt nok til at synliggøre kuglerne, selv i bevægelse, hvorimod 100 nm polstyrenkugler kræver at partiklerne immobiliseres for at kunne op-fange signalet.
- Forskellige metoder til immobilisering er testet: indstøbning i monteringsme-die, ladede mikroskopglas, nedkøling, samt udtørring. Ingen af disse meto-der er forenelig med Nile Red farvning. Nile Red farve-protokollen kan der-med ikke bruges til plast mindre end 1µm.
- Indendørs $PM_{2.5}$ farvet med Nile Red og de to kontrolfarver viste, at næsten alle partikler i prøven binder Nile Red (Figur 0.13). Det er usandsynligt at næsten alle partikler i indeklima er plast, derfor kræver det yderligere

optimering af farve-protokollen for at sikre en mere specifik farvning. Desværre var der også partikler i ufarvet indendørs støv, som udsender autofluorescens, der ligner Nile Red. Derfor vil farve-metoden skulle suppleres med en yderligere teknik til at bekræfte resultatet. I indendørs $PM_{2.5}$ fandt vi også enkelte små og store fibre, som blev blå-farvet med de to kontrolfarver, og som dermed ikke er plast-fibre, men sandsynligvis cellulose.

Konklusion og perspektivering.

Plast-specifik TGA-MS-analyse

TGA-MS-analyser af plast benchmark prøver viser, at forskellige plastmaterialer giver forskellige forbrændingsprofiler med forskellige peak-temperaturer. Forbrændingen og tilhørende massetab kan kobles med en stigning i CO_2 (m/z 44) målt med MS er en generel kontrolmarkør for afbrænding plast og øvrig kulstofholdige materialer, inklusiv organiske materialer. Det var ikke muligt at identificere plastspecifikke ioner i dette setup. Det skyldes til dels at den tilkoblede MS-linjen ikke kan måle tunge ioner (> 300 m/z), som er karakteristiske for plast polymerer. Litteratursøgning viste, at udover plast, så kan der ske for brænding af bla. cellulose og lignin samt andre biogene materialer i samme temperaturinterval, som plast dekomponerer i. Dette er et problem for indendørs og udendørsprøver opsamlet i autentiske miljøer. TGA-MS-analyse af $PM_{2.5}$ prøverne viste en afbrændingsprofil og peak masse-tabs temperaturer, der matcher karakteristiske temperaturer for en række plastmaterialer. Et større masse-tab skete i samme område (217-341°C) og profil svarende til TGA-MS-test af emballage til frugtstænger (plasttype ikke oplyst).



Figur 0.13. Fluorescens-farvning af referenceplast polystyren (PS) 1µm og 100nm (top) og $PM_{2.5}$ indendørs (midt, bund).

Baseret på TGA-MS-analyserne kan indeklimaprøven indeholde op mellem 30,7 og 45.4 vægt% polymer-lignende materiale og udendørsprøven 19,5 vægt%. Det er dog meget usandsynligt, at der forekommer så store mængder mikro- og nanoplast $PM_{2.5}$ i prøverne. Dog har vi med polarisationsmikroskopi, SEM og fluorescens mikroskopi observeret enkelte store fibre, i især indendørsprøven, som kunne være plast samt flere plante/cellulose-lignende fibre og flager. Grundet disse fibres og flagers størrelse antages disse at være tilfældig opsamling af "over-size" fibre under opsamlingen af $PM_{2.5}$ eller kontaminering i prøverne i de mange håndteringstrin, som de har været igennem siden opsamling. Disse store fibre kan hurtigt udgøre en stor masse-fraktion i en $PM_{2.5}$ prøve.

Analyserne har vist, at TGA-MS ikke har tilstrækkelig sensitivitet til at påvise og kvantificere mængden af plast entydigt i en kompleks autentisk prøve. En række andre organiske materialer kan dekomponere eller afbrænde i de samme temperatur-intervaller. Udfordringerne med pålidelige plastanalyser er i stigende hast anerkendt i forskerkredse det sidste års tid. Der er behov for mere specifikke metoder, hvor polymer-ioner kan måles med høj opløsning og sensitivitet. En af de mest lovende metoder til kvantitative bestemmelser er Thermodesorption Pyrolyse koblet med Gas Chromatografi-Mass-Spectrometri (TD-Py-GC-MS) (se fx Analysis of PIP (3:1) in Plastic by Py/TD-GC-MS: SHIMADZU (Shimadzu Corporation)) og eller en mere avanceret High-Resolution (TD-Py-GC-HRMS). Disse apparater findes ikke tilgængeligt til plastanalyse i Danmark.

Plast-specifik mikroskopi

Mikro og nanoplast reference-partikler er synlige med enhanced darkfield mikroskopi, men ser ikke ud til at have et identificerbart spektralt fingeraftryk inden for bølgelængderne 400-1000 nm. Dermed kan enhanced darkfield hyperspektral mikroskopi med disse bølgelængder ikke umiddelbart bruges til at identificere plastpartikler blandt andre små støv-partikler i en indeklima-prøve. Farvning af indeklimaprøven med et kendt plast-farvestof gav problemer, da noget indeklima-støv er autofluorescerende med samme farve og en stor del binder plast-farven uspecifikt. De nyeste og måske mest lovende metoder til identificering af nanoplast kan blive Fourier-transformeret infrarød mikroskopi (μ-FTIR) og konfokal Raman mikroskopi (Casella et al. 2025, Fang et al. 2024).

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Appendix III

Peter Møller

Risk assessment of fine plastic particles in indoor air

The primary purpose of a risk assessment is to identify, analyze, and evaluate potential hazards of an exposure situation to prevent potential diseases or death. Presently, there is no acceptable methodology to perform human risk assessment for micro- and nanoplastics (MNPs) (1). The present risk assessment is based on the framework developed by the World Health Organization (WHO), covering hazard identification, hazard characterization, exposure assessment and risk characterization (2). The risk assessment focuses on potential health effects by exposure to plastic particles in indoor air.

Hazard identification

Particulate matter (PM) in aerosols is segregated into size fractions, which are not entirely consistent across different fields of environmental and occupational health. For the present assessment of human health risks due to inhalation of MNPs, there are six relevant particle size ranges of importance. The particle size range refers to the aerodynamic diameter, which is defined as the diameter of a hypothetical sphere with a density of 1 g/cm^3 (density of water) that settles in still air at the same terminal velocity as the actual particle in question.

- **Total Suspended Particles (TSP)** refers to all particles suspended in the air, often up to 100 µm in diameter. Note that total inhalable dust in occupational hygiene is defined by sampling with an inlet flow rate of 1.25 m/sec [https://www.retsinformation.dk/eli/lta/2025/1356].
- **PM_{10}** (also called inhalable particles) are particles with an aerodynamic diameter ≤ 10 µm. These can reach the upper respiratory tract. It should be noted that inhalable dust in occupational hygiene includes much coarser particles and collection efficiency of 50% cut-point for unit density spherical particles of 100 µm [EN481:1993].
- **Respirable particles** are typically considered to be smaller than 4-5 µm. The respirable particles are small enough to reach the lower respiratory tract, including the alveoli (gas exchange region). EN481:1993 prescribes a 50% collection efficiency at 4 µm in size. The Johannesburg convention defines it at 5 µm in size.
- **Fine Particles** (or **$PM_{2.5}$**) are sampled with a 50% collection efficiency at 2.5 µm, can penetrate deep into the lungs and entering the bloodstream. $PM_{2.5}$ is used for regulatory environmental monitoring and frequently used in indoor and outdoor air-quality research.
- **PM_1** (equivalent to **nanoplastics**) are smaller than 1 µm. They can penetrate deep into the lungs and enter the bloodstream. PM_1 is used for environmental monitoring and used in indoor and outdoor air-quality research.
- **Ultrafine particles** and nanoparticles are smaller than 0.1 µm (100 nanometers). In ambient environments, they often represent over 90% of all airborne pollutants by number, whereas they contribute little to the total mass. Regarding plastics, it has been suggested use the term “plastic nanoparticles” for particles that are less than 100 nm.

There is a paucity of studies on health effects caused by inhalation of MNPs in the human population. However, observation on health effects from exposures to outdoor air pollution particles can be used as a proxy-measure to identify the potentially relevant types of diseases caused by exposure to MNPs. Outdoor air pollution particles and MNPs have the same characteristics such as being a complex mixture, consisting of a core of PM as well as loosely bound (leachable) compounds. In addition, particles from plastics and air pollution sources have the same key mechanisms of action, including the potential to cause oxidative stress, inflammation and DNA damage. Based on disability-adjusted life years (DALY) calculations, the latest global burden of disease assessment of outdoor air pollution in the European Union (27 member states) has shown that health impacts in descending order are ischemic heart disease, stroke, diabetes, lung cancer, chronic obstructive pulmonary disease, and asthma in children/adolescents (European Environment Agency; https://www.eea.europa.eu/en/analysis/publications/harm-to-human-health-from-air-pollution-burden-of-disease-status-2025).

Hazard characterization/guidance or guideline value identification

Research on hazard characterization of MNPs is slowly evolving, including epidemiological findings and in vivo animal models. In the present case, the literature search for relevant studies on hazard characterization has focused on pulmonary inflammation (including fibrosis), genotoxicity in lung tissue, lung cancer and cardiovascular effects. At present, there are no studies on genotoxicity or cancer in lung tissue. The literature on health effects in the general human population encompasses a few epidemiological studies on cardiovascular effects, whereas animal models on airway exposure assess especially lung inflammation effects. Below, the studies are summarized study-by-study, followed by a short summary of the results from epidemiological and animal studies.

Human studies in the general population (epidemiology)

Marfella et al. (2024) (3) assessed associations between the concentration of MNPs in carotid atheromas and risk of cardiovascular events in a prospective study of patients with asymptomatic carotid stenosis (n = 304). The patients underwent carotid endarterectomy [surgical procedure to remove atherosclerotic plaques from the lining of narrowed or blooded arteries] and were subsequently followed up to 34 months after the surgery. Of the 257 patients who completed the follow-up, 150 patients had evidence of MNPs in carotid artery plaques (predominantly polyethylene and polyvinyl chloride), whereas 107 patients had no evidence of MNPs in plaques. Patients with MNPs in carotid artery plaques had higher risk of combined non-fatal myocardial infarction, non-fatal stroke and all-cause mortality (hazard ratio = 4.53, 95% CI: 2.00. 10.27). It should be noted that the study shows that patients with MPs in carotid artery plaques have a poor prognosis, but it does not demonstrate that exposure to MNPs causes cardiovascular disease.

Yang et al., (2024) (4) examined the presence of MPs in blood samples from patients who were admitted to hospitals with chest pain and subsequently diagnosed with acute coronary syndrome. MP concentrations were higher in patients with coronary artery syndrome (162 µg per gram of blood, n = 82) compared to healthy controls (100 µg per gram blood, n = 19). Subgroup analysis indicated that patients with myocardial infarction (≈178 µg per gram of blood, n = 34) had higher MP concentration than patients with unstable angina (≈109 µg per gram of blood, n = 48; estimated

from graphs). Unstable angina and myocardial infarction are both acute coronary syndromes caused by reduced blood flow, but they differ in severity and tissue damage. Unstable angina is typically regarded as a warning sign of temporary, partial blockage without permanent heart muscle damage, whereas myocardial infarction involves complete or sustained blockage resulting in irreversible myocardial damage. The study indicates an association between MP levels in blood and severity of coronary artery syndrome, but a cause-and-effect relationship cannot be assessed due to the cross-sectional study design.

In summary, the available evidence indicates the presence of MPs in atherosclerotic plaques. These observations are supported by other studies, showing the presence of MPs in (i) heart tissue of patients who received cardiac surgery (5), (ii) thrombi from patients with ischemic stroke, myocardial infarction and deep vein thrombosis (4), (iii) human coronary, carotid and aortic arteries with atherosclerotic plaques (6), and (iv) femoral artery plaques (7). The samples have been obtained from patients, and it cannot be ruled out that surgical procedures or other treatments are the main source of MPs. Nevertheless, it is noteworthy that there appears to be a linkage between MP levels and severity of cardiovascular endpoints.

Animal models

Several studies have assessed pulmonary effects of MNPs via exposure in the airways of animals, mainly mice and rats. The present summary of studies is restricted to pristine particles. Surface-modified plastic particles may be used in toxicology, but their relevance to the human exposure situations is uncertain. The exposure periods typically range from acute (days) to subchronic (few months) exposure. Acute inflammation is characterized by an initiation of the inflammatory cascade and rapid influx of neutrophils to the lung air space lumen. These cells and inflammatory mediators (cytokines) and commonly measured in bronchoalveolar lavage (BAL) fluid. Chronic inflammation is characterized by a sustained presence of macrophages and lymphocytes. In only few studies the authors established a no observed adverse effect level (NOAEL) and/or lowest observed adverse effect level (LOAEL). Below the studies are summarized according to the primary plastic polymer. The NOAEL and/or LOAEL are reported for the outcomes when the authors of the studies highlighted these doses, or they can be determined from the results in the studies.

Polyethylene

Jung et al., 2025 (8) exposed ICR mice by intratracheal instillation to polyethylene microplastics (size = 13.9 µm) as an acute single dose (24 h; 125, 250 or 500 µg), four exposures (two per week for two weeks; 125, 250 or 500 µg), or once a week for 13 weeks (5, 25 or 50 µg). Acute high-dose and repeated short-term exposures were associated with pulmonary inflammation (i.e. influx of neutrophils in bronchoalveolar lavage fluid). Repeated exposures by intratracheal instillation over 90 days (once a week for 13 weeks) were associated with pulmonary inflammation in terms of higher number of cells and pro-inflammatory cytokines in BAL fluid as well as histopathological findings in lung tissue. Overall, the results in the 90 days study indicate consistent inflammatory response at a dose of 25 µg/week. Statistically significant increases were not consistent across biomarkers of pulmonary inflammation in the group exposed to 5 µg/mouse, which might be due to small group size.

Dou et al., 2026 (9) exposed C57BL/6 mice to 100 and 1000 nm polyethylene particles by intratracheal instillation (10 mg/kg; four times, separated by 6 days). This

was associated with pulmonary inflammation (elevated TNFα and IL1β by immunofluorescence in epithelial cells) and pulmonary fibrosis (Masson trichrome staining and expression of α-SMA and collagen). Nanosized and microsized polyethylene particles generated the same level of pulmonary inflammation.

Kwabena Danso et al., 2024 (10) exposed to C57BL/6 mice to polypropylene particles (size = 21.3 µm) by intratracheal instillation (5 mg/kg every day for 14 days). The exposure was not associated with pulmonary inflammation response in terms of cellular influx and pro-inflammatory cytokines in BAL fluid.

Muhammad et al., 2025 (11) exposed Wistar rats by whole-body inhalation to polyethylene microplastics (size = 110 µm) for 28 days (15 mg/m^3, 4 h/day and 5 days/week). Histopathological examination showed a narrowing of alveolar spaces and thickened lung parenchyma (lung histology score of 3.6 ± 0.5 and 0.25 ± 0.43 in exposed and control rats, respectively). A pro-inflammatory response was inferred by increased NF-κB expression in lung tissue. Nevertheless, it should be noted that particles with a size of 110 µm might not reach the peripheral airways and the study did not assess deposition of microparticles in lung tissue.

Polyvinyl chloride

Richards et al., 1981 (12) exposed Spraque-Dawley rats to PVC-7 paste polymer (containing the detergent sodium dodecyl sulphate). The rats inhaled 10 mg/m^3 of particles for 15 weeks (6 h/day, 5 days/week). The mass median aerodynamic diameter was reported to be 1.7 µm. The exposure caused only minor inflammatory responses in lung tissue, and the effects were not present at 15 weeks post-exposure.

Tetley et al., 1981 (13) exposed Norwegian-hooded rats to PVC-7 paste polymer (containing the detergent sodium dodecyl sulphate) and an additive-free PVC. Rats were exposed by a single intratracheal instillation of 0.25, 2.5, 10 and 25 mg/kg and sacrificed at either 1-or 4-week post-exposure. The exposure was associated with a modest increase in total cells in BAL fluid at both 1 and 4 weeks post-exposure [differential counts are not reported, although it is stated that the extra cells are not polymorphonuclear cells].

Groth et al., 1981 (14) exposed Sprague-Dawley rats, Hartley guinea pigs and Cynomolgus monkeys to PVC (size = 1.5 µm) by inhalation (13 mg/m^3, 6 h/day, 5 days/week for up to 245 days for rats and guinea pigs and 464 for monkeys). Monkeys had PVC-laden macrophages aggregated into clusters in the lungs, whereas the lung function was unaltered and there was no sign of fibrosis. Rats and guinea pigs were less affected than monkeys.

Xu et al., 2004 (15,16) exposed Wistar rats by intratracheal instillation to PVC with or without additives (mean size = 2 µm). In one set of experiments, rats were exposed to 10 or 50 mg/kg as single dose and groups were subsequently sacrificed at days 2, 7, 28 and 90 post-exposures. There was a difference in pulmonary inflammation between PVC with and without additives. The exposure to 50 mg/kg was associated with increased influx of cells in BAL fluid at day 2 post-exposure (mainly neutrophils and eosinophils). The inflammatory results gradually subsided until day 90 post-exposure. On day 90 post-exposure, there were minor histopathological lesions, although fibrosis was not observed. In another set of experiments, the same total doses (10 and 50 mg/kg) were administered as repeated lower doses (1.4 and 7.1 mg/kg, seven times over a period of 21 days). Pulmonary inflammation was observed in rats after repeated intratracheal instillations of the highest dose of PVC. Overall, the results indicate that the highest dose of PVC induced limited acute and transient inflammation in the lungs (i.e. LOAEL).

Jin et al., 2024 (17) assessed pulmonary inflammation in Balb/c mice following intratracheal instillation of PVC (size = 6.5 µm) once a day for eight consecutive days (25 or 100 mg/kg). The exposure caused pulmonary inflammation, assessed by histopathology (thickening of pulmonary septum and infiltration of cells) and TNFα expression.

Polypropylene

Hesterberg et al., 1992 (18) exposed F344 rats to polypropylene fibers (geometric diameter = 1.6 µm, geometric length = 30 µm) by nose-only inhalation to 15, 30 or 60 mg/m^3 for 30 or 90 days (6 h/day 5 days/week). Lung pathology scores increased dose- and time-dependently (corresponding to "evidence of cellular damage"). The main histopathological finding was described as progression of macrophage infiltration in lungs. This effect persisted at 30 days post-exposure. There was no sign of pulmonary fibrosis after exposure to polypropylene fibers. The lowest concentration (15 mg/m^3) produced transient and mild indicators of pulmonary inflammation. Based on these data, the concentration of 15 mg/m^3 can be regarded as LOAEL.

Tomonaga et al., 2024 (19) exposed F344 rats to polypropylene (3 µm) by inhalation and intratracheal instillation. The rats were exposed in a chamber to 2 or 10 mg/m^3, 6 h/day, 5 days/week for 4 weeks, or by intratracheal instillation once (0.8 or 1 mg/kg). For both inhalation and intratracheal instillation exposures, rats were sacrificed at 3 days, 1 month or 3 months post-exposure. Pulmonary inflammation was strongest at three days post-exposure, including neutrophil influx in BAL fluid and expression of cytokine-induced neutrophil chemoattractant 1 (CINC-1; CXCL1), CINC-2/CXCL3 and myeloperoxidase activity in BAL fluid. The lowest concentration (2 mg/m^3) produced transient and mild effects at three days after exposure. Based on these data, the authors considered that 2 mg/m3 is the LOAEL in the study.

Woo et al., 2023 (20) exposed ICR mice to polypropylene at doses of 1, 1.25 or 5 mg/kg by intratracheal instillation five times per week for 4 weeks (size = 0.66 µm). This was associated with pulmonary inflammation, assessed by increased number of cells and pro-inflammatory cytokines (TNF, IL1β, IL-6, MCP-1 and KC) in BAL fluid, and altered lung histology (inflammatory cell infiltration, alveolar epithelial hyperplasia, foamy macrophage aggregates). These effects occur dose-dependently, with some effects even at the lowest dose.

Dou et al., 2026 (9) exposed C57BL/6 mice to 100 and 1000 nm polypropylene particles by intratracheal instillation (10 mg/kg; four times, separated by 6 days). This was associated with pulmonary inflammation (elevated TNFα and IL1β by immunofluorescence in epithelial cells) and pulmonary fibrosis (Masson trichrome staining and expression of α-SMA and collagen). Nanosized and microsized polypropylene particles generated the same level of pulmonary inflammation.

Kwabena Danso et al., 2024 (10) exposed to C57BL/6 mice to polypropylene particles (size = 6.4 µm) by intratracheal instillation (5 mg/kg every day for 14 days). The exposure was not associated with pulmonary inflammation response in terms of cellular influx and pro-inflammatory cytokines in BAL fluid.

Polystyrene

Tetley et al., 1981 (13) exposed Norwegian-hooded rats to polystyrene particles (particle size = 1.0 µm) by a single intratracheal instillation to 0.25, 2.5, 10 and 25 mg/kg and sacrificed at either 1 or 4 weeks post-exposure. The exposure was associated with a modest increase in total cells in BAL fluid at both 1 and 4 weeks post-

exposure [differential counts were not reported, although it is stated that polymorphonuclear cells were observed in BAL fluid of rats in the highest dose group].

Jung et al., 2026 (21) exposed ICR mice by pharyngeal aspiration to polystyrene (30 nm) at doses of 10, 25 or 50 µg/mouse, once a week for 13 weeks. There were dose-dependent increases in various indices of pulmonary inflammation, including increased number of cells and proinflammatory cytokines (CXCL-1, CCL2, CCL3, IL1β, TNFα, IL-6) in BAL fluid, and histopathological findings in lung tissue. Effects were observed at lowest dose (i.e. LOAEL).

Li et al., 2022 (22) exposed C57BL/6 mice to 1.25 or 6.25 mg/kg three times/week for 3 three weeks by intratracheal instillation of polystyrene particles (5 µm). This was associated with pulmonary inflammation (elevated TNFα and IL1β by immunofluorescence in epithelial cells) and pulmonary fibrosis (Masson trichrome staining and expression of α-SMA and collagen).

Dou et al., 2026 (9) exposed C57BL/6 mice to 100 and 1000 nm polystyrene beads by intratracheal instillation (10 mg/kg; four times, separated by 6 days). This was associated with pulmonary inflammation (elevated TNFα and IL1β by immunofluorescence in epithelial cells) and pulmonary fibrosis (Masson trichrome staining and expression of α-SMA and collagen). Nanosized polystyrene generated higher toxic effects than microsized particles.

Yang et al., 2024 (23) exposed C57BL/6 mice to 40 nm polystyrene beads at doses of 16, 40 or 100 µg/day for one week, one month or three months by oronasal aspiration [described as an inhalation situation where mice are exposed under normal breathing condition]. All exposure scenarios were associated with dose-dependent increases in pulmonary inflammation in terms of cellular influx and pro-inflammatory cytokines (IL6, TNFα, MCP-1) in BAL fluid. Effects were observed at lowest dose (i.e. LOAEL).

Chen et al., 2025 (24) exposed ICR mice by whole-body inhalation (6 h/day for 60 days) to 150,000 particles/m^3 of either nanosized (80 nm) or microsized (1000 nm) polystyrene spheres. Assessment of pulmonary inflammation demonstrated higher cellular influx and pro-inflammatory cytokine concentration (IL6, IL1β, TNFα) in BAL fluid after exposure to microsized polystyrene spheres as compared to nanosized particles. This parallel lung histochemical examination where hematoxylin/eosin, Sirius red and Masson's trichrome staining indicated stronger pulmonary fibrosis by microsized polystyrene as compared to nanosized particles.

Kwabena Danso et al., 2024 (10) exposed to C57BL/6 mice to polystyrene particles (size = 17.5 µm) by intratracheal instillation (5 mg/kg every day for 14 days). The exposure was associated with a modest pulmonary inflammation response in terms of cellular influx (neutrophils and eosinophils) and pro-inflammatory cytokines (IL1β, IL6, MCP-1, MIP-1α, MIP-2 and KC) in BAL fluid.

Hu et al., 2024 (16) exposed C57BL/6 mice by intratracheal instillation to 12.5 or 25 mg/kg once a day for seven consecutive days to 100 or 200 nm polystyrene beads. Polystyrene-induced lung toxicity was qualitatively described as signs of pulmonary inflammation, including atelectasis (partial/complete collapse of lung lobes due to e.g. blockage of air sacs), pulmonary hemorrhage and fibrosis (Masson trichrome staining).

In summary, the available evidence indicates that pulmonary exposure to MNPs is associated with inflammatory responses in animal lungs. Based on the available findings, it is not possible to rank MNP polymers according to inflammatory potential. Dose-response relationships have been observed in studies with multiple doses. High bolus exposures by intratracheal instillation (or pharyngeal aspiration) appear

to cause larger inflammatory responses than inhalation exposures. In general, relatively high exposures have been used and most studies have not established a NOAEL.

Exposure assessment

There are many studies on MPs in different indoor environments of workplaces, schools, and residential spaces (25). MPs have been collected by either passive sampling as settled dust or active sampling with an air pump in the breathing zone of humans. Table 1 lists a summary of studies that have analyzed MPs by active sampling from indoor air. One type of active sampling entails a collection of all particles from air on a filter. This is traditionally called TSP in gravimetric analysis, although it is slightly misleading in the context of measuring the particle number concentration of MNPs because the pores size allows small particles to pass through the filter and the detection methods have not detected small particles. Another type of active sampling method removes large particles before collection of smaller particles on a filter. A pioneering study from 2017 sampled air at 1.2 m height in the living room of apartments in Paris (France) for assessment of total particles/fibers and showed the presence of fibers (26). Typically for the measurement challenges, the optical microscopy assessment had a size resolution limit of 50 µm. Chemical characterization of 28 fibers, using FTIR microscopy, limit of detection (LOD) = 5 µm, showed the fibers were either natural material (67%, cotton, cellulose and wool) or plastic polymers (33%, polyamide, co-polymers of PP and PE) (26). Other studies have shown the presence of total MPs by active air sampling and light microscopy from living rooms or bedrooms in houses in Sri Lanca (0.13-0.90 MPs/m^3), Australia (0.47-0.87 MPs/m^3), and Spain (4.8 MPs/m^3) (27-29). Studies using fluorescence detection have shown higher total particle number concentrations in air from apartments/houses in Birmingham, UK (15.6 ± 5.4 MPs/m^3), Aveiro, Portugal (0.7-1.3 MPs/m^3) and Wenzhou City, China (1583 MPs/m3) (30-32). Studies with detection of MPs using µFTIR or µRaman have also generated mixed results. A study from Taichung City (Taiwan) reported indoor concentrations of 1.8 MP/m^3 in the living room air (33). The concentration was 1.7-16.2 MP/m^3 of particles with a diameter >11 µm in the living room air of apartments in Aarhus, Denmark (34). A refined analysis of MPs by µRaman spectroscopy (LOD = 1 µm), collected by active sampling in two home offices of private apartments in Denmark, yielded relatively high particle number concentration (185 and 548 MP/m^3 in new and old apartment, respectively) (35). Lastly, one study used a cascade impactor to collect different size fractions of MP (<0.65 µm to >7 µm in diameter) from apartments in Kuwait; the total particle number concentration was between 6.3 and 27.1 MP/m^3, with an inverse relationship between particle size and particle number concentration (36). Collectively, studies that have measured total airborne particles have consistently detected MPs in the indoor environment, but the mean concentrations differ by 2-3 orders of magnitude. The sampling equipment have collected particles that are larger than ≈1 µm (specific filter pore sizes are shown in Table 1), although the actual sizes of the analyzed particles are much larger because of limitations in the employed detection methods. While, the total particle number concentration is an indicator of exposure, it has limited relevance for potential human health risk because large particles do not reach the lower airways.

In pulmonary toxicology, it is acknowledged that particles with diameter smaller than 10 µm (PM_{10}) are inhalable into the lungs, whereas it is respirable fine particles (less than 2.5 µm or $PM_{2.5}$) that reach the lower airways. Sampling of $PM_{2.5}$ or PM_{10}

entails a two-step process where large particles are removed from the air flow by an inlet size selector and particles with diameters less than 2.5 or 10 µm are collected on a filter. A study from Toulouse (France) sampled PM_{10} in bedrooms and living rooms of apartments, measuring a median concentration of 528 MP/m^3 and approximately 50% of the particles in the size range from 1 to 4 µm (37). Recently, studies have used active sampling and Pyr-GC/MS to obtain mass concentrations of both PM_{10} (1.14 µg/m^3) and $PM_{2.5}$ (0.51 µg/m^3) in a laboratory environment (38). Lower mass concentrations were obtained for PM_{10} in classrooms in Estarreja, Portugal (21.8 ± 16.3 ng/m^3) (39). These levels of exposure are similar to $PM_{2.5}$ concentrations (2.27 ± 2.31 µg/m^3) by person-borne active samplers on subjects in Shanghai, China who spend approximately 20 h of the day indoors (40).

Table 1. Indoor microplastic number concentration and polymer type in studies with active air sampling in private houses, apartments and certain school classrooms

Location	Particle size	Number concentration, morphology and polymer type	Reference
France, Paris (n = 2, living room)	Total (filter pore size = 1.6 µm) 1.2 m above floor	• 5.4 fibers/m^3 (stereomicroscope, LOD = 50 µm) • 67% of the fibers are natural material (cotton) and 33% synthetic fibers (FT-IR, LOD = 5 µm). PA (nylon) with co-polymers of PE and PP (from carpet); PET not detected	(26)
Sri Lanca (residences, living room/area, n = 7)	Total (filter pore size = 1 µm) 1.2 m above floor)	• 0.13-0.90 MP/m^3 (mean = 0.49 MP/m^3, stereomicroscope) • Mean fiber length: 768 µm (67-4919 µm). most MP within sizes 100-500 µm (MP with sizes <50 µm not measured, stereomicroscope) • PET>>polyester/acrylic>PA/PP/PS (µFTIR)	(27)
Australia (living room in houses and bedroom in elder's home)	Total (filter pore size = 1 µm) 1.2 m above floor	• 0.47 (house) and 0.87 (bedroom) MP/m^3 (stereomicroscope, 20 to 5000 µm) • PET>>PE>PA>PP/PAN/PVC (µFTIR)	(28)
Spain, Barcelona (homes, living room, n = 6	Total (filter pore size = 20 µm) 0.7-0.75 m from floor	• 4.8 MP/m^3 (stereomicroscope) • 81% fibers (358 µm) and 19% fragments (114 µm) (µFTIR) • Natural fibers (e.g. cellulose), PA and polyester (µFTIR)	(29)
UK, Birmingham (homes; 21 houses and 9 apartments; locations within houses not specified)	Total (filter pore size = 1 µm)	• 15.6 ± 5.4 MP/m^3 (fluorescence microscope; carpeted floor main source) • Particle sizes: 10-25 (41%), 25-50 (37%), 50-100 (17% and >100 µm (5%) (stereo fluorescence microscope • PET>>PP/PE/PVC>PES/PA>PCTFE (µFTIR)	(30)
Portugal, Aveiro (n = 5 houses/apartments, living room)	Total (filter pore size = 2.2 µm)	• 0.7 MP/m^3 [range 0.7-1.3 MP/m^3; mainly fragments (fluorescence microscopy, Nile Red staining) • Smallest particle = 9.6 µm (LOD of method ≈2 µm)	(31)
China, Wenzhou City (apartments, living room, n = 5)	Total (filter pore size = 0.7 µm) 1.6 m above floor	• 1583 MP/m^3 (fluorescence microscopy, Nile Red staining) • Fragments (90%) and fibers (10%). Size ranges cover 5-30 µm (60%), 30-100 (29%) and >100 µm (11%) • Polyester>PA>>PP/PE>PS>PVC and other (µFTIR]	(32)
Taiwan, Taichung City (n = 10, living room)	Total (pore size = 0.2 µm) 1-1.2 m above floor	• 1.8 MP/m^3 (fragments, 3-50 µm) (µRaman) • PET most abundant (µRaman) • No seasonal variation (cold vs warm)	(33)
Denmark, Aarhus (n = 3 apartments, living room, three consecutive days)	Total (filter pore size = 0.8 µm) 1.1 m above floor (breathing manikin)	• 1.7-16.2 MP/m^3 (focal plane array µFTIR, LOD = 11 µm) • PE>>PE/nylon/PP (other less abundant synthetic polymers, (focal plane array µFTIR)	(34)

Kuwait (n = 6, apartments, location not specified)	Total (particles collected on cascade impactor in size fractions). Hight above floor level is not specified	• 6.3 -27.1 MP/m^3 (inverse association between size fraction and particle number concentration, fluorescence stereomicroscope) • Mainly fibers (fragments in smaller size ranges) • Polyester/nylon (fibers) and acrylic/polyurethane (fragments). Measured by µRaman spectrometry [authors express concern about the reliability of the results due to fluorescence interference]	(36)
Denmark (n = 2, old and new apartments, home office room)	Total (filter pore size = 1 µm) 1.6 m above floor	• 185 and 548 MP/m^3 (new and old flat respectively) (µRaman) • PA>PV/PE>PS>PEST>>PP (other polymers too, µRaman) • Median diameter = 6.2 µm (45% between 1-5 mm, µRaman)	(35)
France (n = 3, apartments; bedroom, home office, living room)	PM_{10} 1.6-1.7 m above in living room; 0.5 m in bedroom	• 528 particles/m^3; 1-28 µm, but mainly <10 µm (approximately 50% of the particles between 1 and 4 µm Raman) • PE>PA>PMMS/PP/PBT/PS/PET/ABS/PHS/PVC (Raman)	(37)
Auckland, Australia (laboratories)	$PM_{2.5}$ and PM_{10} 2 m above floor	• 1.14 µg/m^3 (PM_{10}) and 0.51 µg/m^3 ($PM_{2.5}$) [Pyr-GC/MS] • PE>PET>Nylon>PVC/PC>PMMA [Pyr-GC/MS]	(38)
Shanghai (university students)	$PM_{2.5}$ (24 h)	• 2.27 ± 2.31 µg/m^3 (personal; spend 20 h indoor on average) • PE>>PET/PS>PP/PMMA (Py-GC/MS)	(40)
Estarreja, Portugal (Classrooms, school)	PM_{10} 1.2 m above floor	• 21.8 ng/m^3 (MP in PM_{10}) [Spring higher than winter] (Pyr-GC/MS) • NBR>PVC>N66>PP>PS>PMMA (Pyr-GC/MS)	(39)
Spain (Madrid, urban; corridor on the 1st floor)	PM_{10}	• 124 MP/m^3 (88 and 122 MP/m^3 in warm and cold seasons, respectively) (µRaman) • PS>PE>PET/PMMA (µRaman, Pyr-GC/MS)	(41)

NBR: Nitrile butadiene rubber (copolymer in tires); PA: polyamide, PAN: polyacrylonitrile, PET: polyethylene terephthalate, PEST: polyethylene terephthalate and polybutylene terephthalate; PMMA: polymethyl methacrylate; PV: polyvinyl (including poly-vinyl acetate, poly-vinylrylate butyral, polyvinyl chloride, polyvinyl alcohol, polyvinyl pyrrolidone).

Risk characterization

The hazard characterization shows that pulmonary exposure in animals (mainly mice and rats) is associated with dose-dependent pulmonary inflammatory responses, irrespective of the type of investigated MNPs. The lowest exposure level is typically equivalent to LOAEL and the dosing regiments are generally too high to establish NOAELs. Presently, there are no studies that have assessed relationships between pulmonary exposure to MNPs and cardiovascular endpoints in animals (e.g. development of atherosclerosis). However, other studies have shown that 9-20 weeks of oral exposure to polystyrene with primary particles sizes ranging from 50 nm to 5 µm accelerated atherosclerosis in dyslipidemic ApoE or LDLr knockout mice (42-47). These observations are in line with findings of associations between MNP exposure and cardiovascular diseases in human studies, which in principle could encompass both airway and oral exposure routes. Collectively, observations from epidemiology, animal studies, and mechanistic evidence (cell cultures), suggest that pulmonary exposure to MNPs may be associated with risk of the same outcomes as air pollution particle, including diseases of the respiratory and cardiovascular system (48).

In animal studies, exposure by inhalation has higher relevance than studies using direct instillation of particles in the lungs. In particular, the inhalation studies of polypropylene in rats by Hesterberg et al., 1992 (18) and Tomonaga et al., 2024 (19) are

relevant for risk characterization. Both studies used subchronic exposures. They used MNPs with different dimensions (3 µm particles and fibers with diameter of 1.6 µm and length of 30 µm). The results indicate LOAELs of 2 mg/m3 (Tomonaga et al., 2024) and 15 mg/m3 (Hesterberg et al., 1992). In table 1, the study with highest particle mass concentration to humans reported levels of 2.27 ± 2.31 µg/m^3 by personal exposure (40). In risk characterization of health outcomes with a dose-response threshold, such as pulmonary inflammation, the margin of safety is typically set to be 100 between the NOAEL and actual exposure to consider uncertainties in difference between responses in animals and humans, and vulnerable groups in the human population. In cases where only the LOAEL is known, the margin of safety would be ≥1000. In the present dataset the margin of safety is 880 between the highest reported mass concentration and the lowest LOAEL.

The WHO air quality guideline proposes annual levels of 5 µg/m^3 for $PM_{2.5}$ (15 µg/m^3 for PM_{10}) in both outdoor and indoor air (49). It is well-established that exposure to outdoor $PM_{2.5}$ is associated with diseases of the respiratory and cardiovascular system, including chronic obstructive pulmonary disease (COPD), lung cancer, coronary heart disease and stroke (49). The highest reported mean particle mass concentration (2.27 ± 2.31 µg/m^3 by personal exposure (40)) is lower than the WHO air quality guideline for $PM_{2.5}$ (5 µg/m^3).

WHO has not proposed air quality guidelines for particle number concentrations, which are dominated by ultrafine particles (less than 0.1 µm). The studies on airborne particles in the indoor environment demonstrate presence of MNPs in the breathing zone (Table 1). The type of polymer and shape of material (particles, fragments, fibers) differ from environment to environment, reflecting the type of sources of plastics, textiles, carpeting and clothing. However, the assessment of particle number concentrations may not be an accurate estimate of the true exposure because nanoplastics and plastic nanoparticles are not measured. In fact, the very low particle number concentrations reported in table 1 (typically 1-1000/m^3) are lower than the background particle number concentration indoors. The measurement of nanoplastic or plastic nanoparticles is further complicated by the fact that everyday human activity and appliances are sources to high concentrations of ultrafine particles, such as cooking, cleaning, heating and combustion (fireplaces, candles, passive smoking) (50,51).

In summary, the available evidence suggests that indoor concentrations of MNPs do not exceed the WHO air quality guideline for $PM_{2.5}$ (based on mass concentration). However, this assessment does not consider differences in chemical composition (and additives) between MNPs and combustion-derived particles that is the primary focus of the WHO air quality guideline. Currently, there are no reliable measurements of the particle number concentration of MNPs in the indoor air.

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Denne rapport fungerer som et fagligt og praktisk grundlag for at forstå, identificere og vurdere mikro- og nanoplast i boligers indeklima. Rapporten samler den eksisterende viden om forekomst, kilder, adfærd, målemetoder og mulig sundhedsmæssig relevans af fine plastpartikler i indeluft og husstøv. Med dette udgangspunkt kombinerer rapporten et state-of-the-art litteraturstudie med eksperimentelle analyser af fine luftbårne partikelprøver samt en sundhedsfaglig risikovurdering. Dermed belyser rapporten både den grundlæggende forståelse af, hvordan mikro- og nanoplast dannes og cirkulerer i indendørsmiljøet, og de metodiske udfordringer, der er forbundet med at påvise og karakterisere disse partikler i komplekse, virkelige prøver. Rapporten følger en logisk og sammenhængende struktur, der indledes med en gennemgang af det aktuelle vidensgrundlag, efterfulgt af en eksperimentel undersøgelse af polymerrelateret materiale i indendørs og udendørs PM2.5-prøver, og afsluttes med en vurdering af de mulige sundhedsmæssige konsekvenser ved inhalation af fine plastpartikler. Afslutningsvis peger rapporten på behovet for videre forskning, herunder udvikling af mere følsomme analysemetoder, bedre karakterisering af eksponering og et stærkere grundlag for at vurdere mikro- og nanoplasts betydning i indeklimaet.