High positive forcing efficiency by modern wood stove aerosol emissions

Effects of photochemical aging and an electrostatic precipitator

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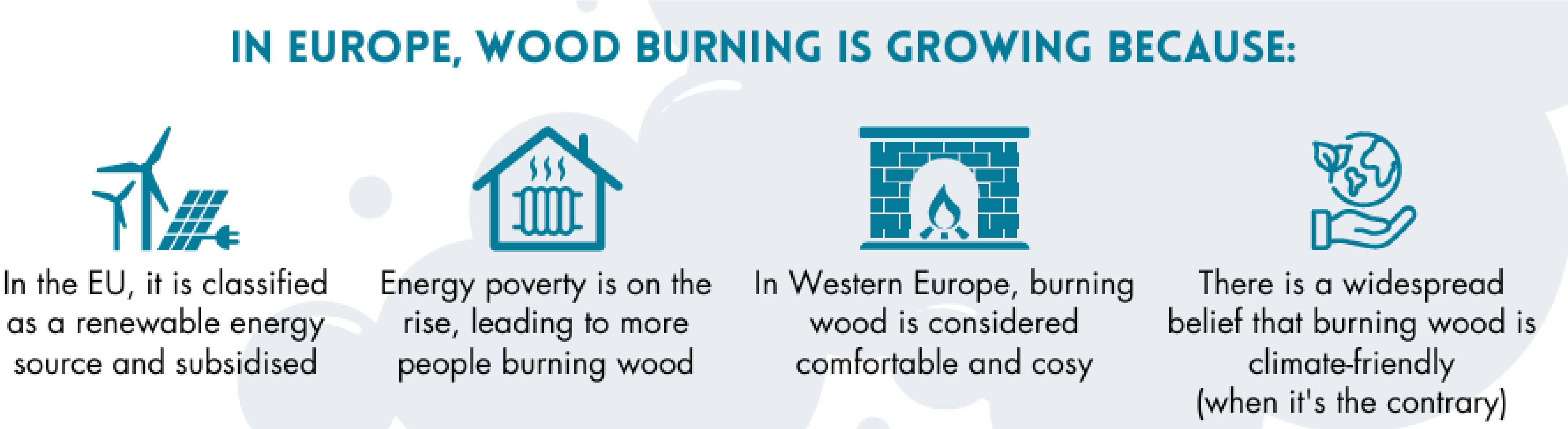
Residential wood combustion (RWC): a major aerosol source

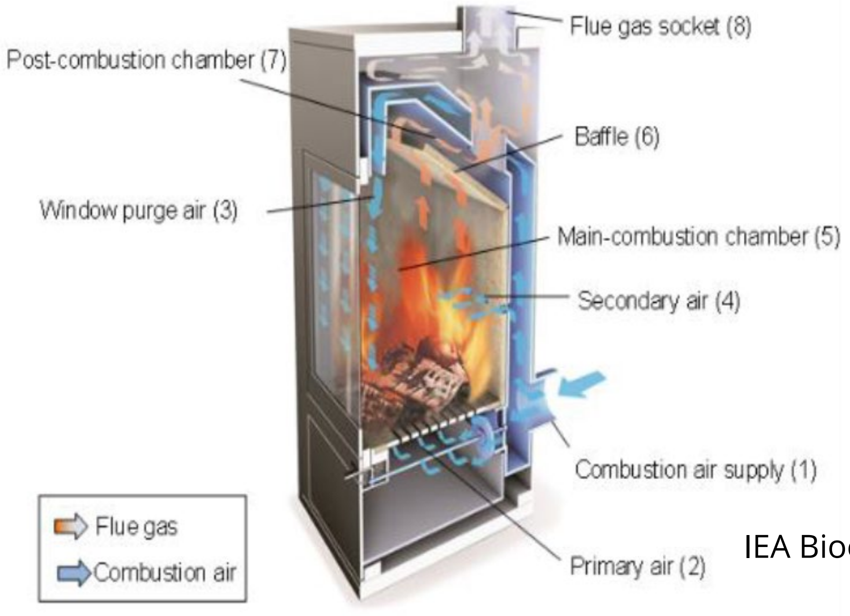
- **34%** Increase in EU residential wood use over the last decade
- **#1** Global anthropogenic source of black carbon (Bond et al. 2013)
- **BC** Modern stoves emit soot-rich exhaust— low OA/BC, unlike wildfires



What are ”modern” wood log stoves?

Heat resisting stove
(i.e. masonry heater)

Non-heat resisting stove
(i.e. chimney stove)



IEA Bioenergy, 2022

- Combustion air staging & optimized geometries to reach relatively good burnout of CO and organic gaseous compounds (OGC)
- Relatively air-tight and well insulated to reach high combustion temperatures
- Recent developments include also automatic control systems

Why this matters

BC-dominated emissions

Modern stoves with air-staging → low OA/BC ratios, closer to diesel than to wildfire smoke.

Atmos. Chem. Phys., 24, 3197–3215, 2024
https://doi.org/10.5194/acp-24-3197-2024

Atmospheric Chemistry and Physics
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Contribution of brown carbon to light absorption in emissions of European residential biomass combustion appliances

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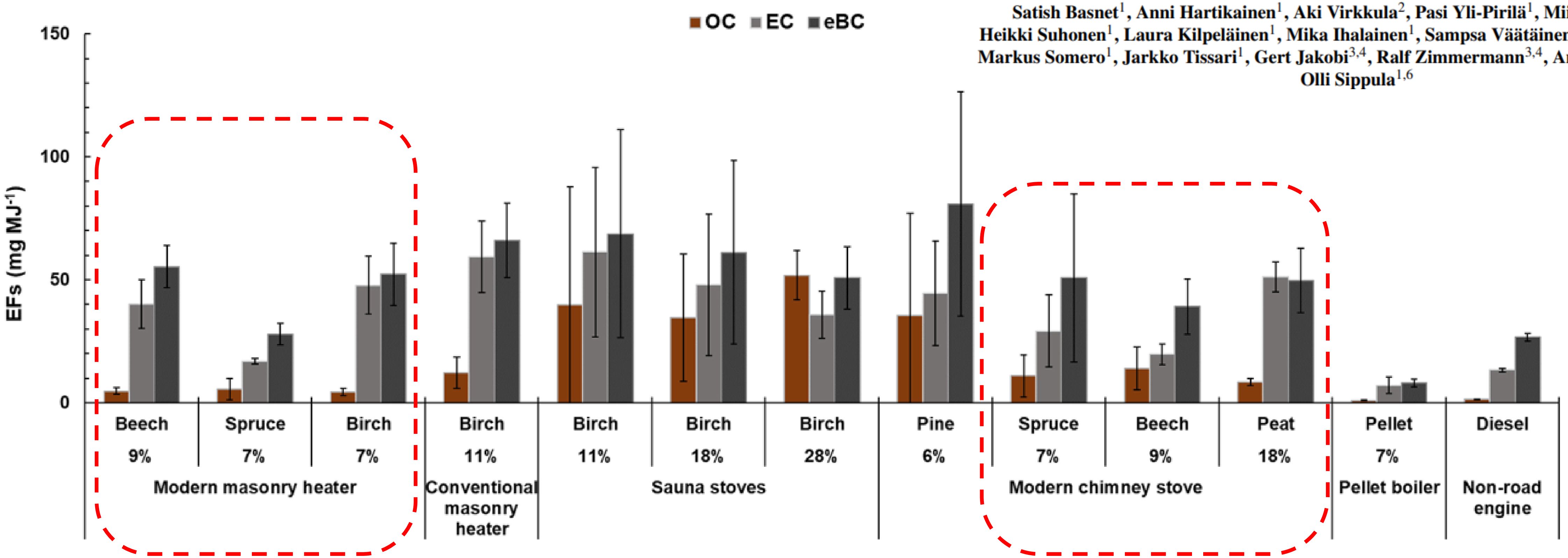
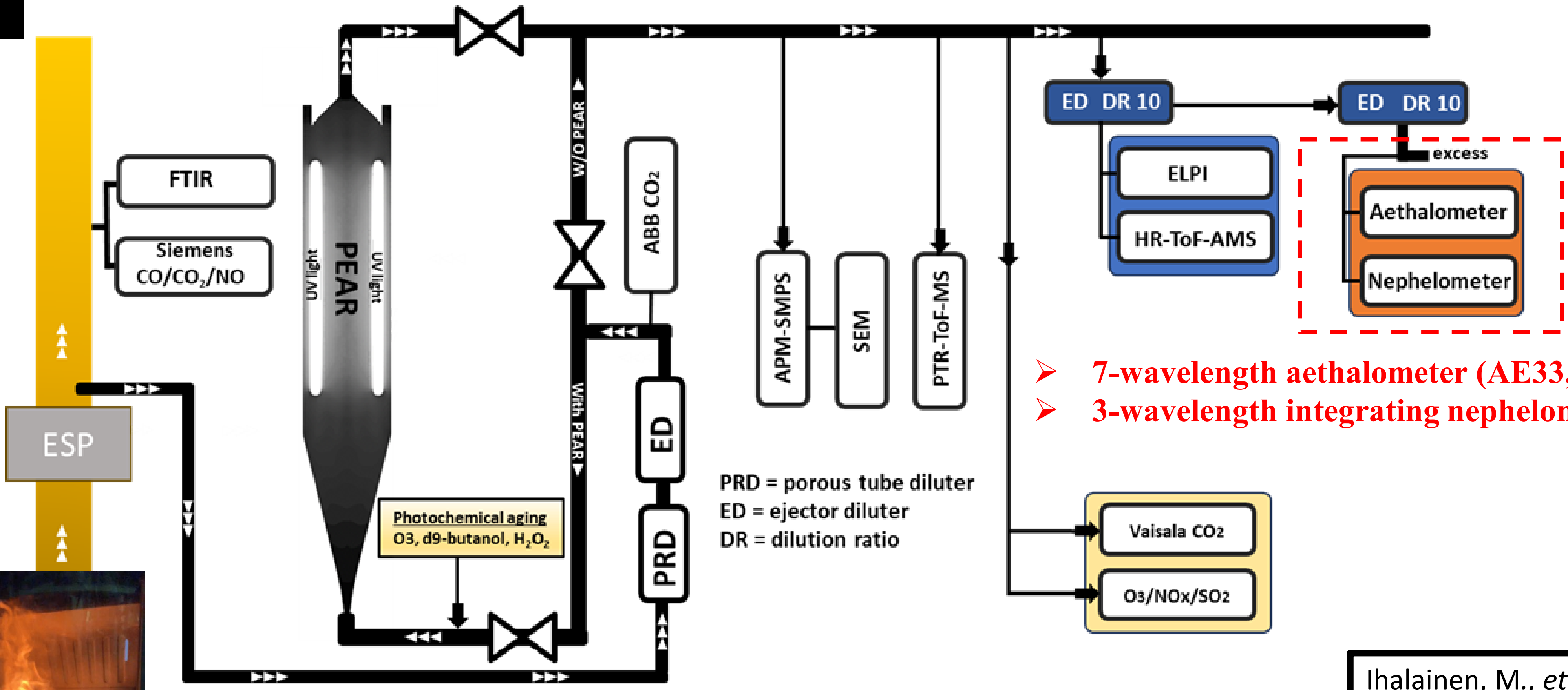


Experimental setup



- 7-wavelength aethalometer (AE33, Magee Scientific)
- 3-wavelength integrating nephelometer (Model 3563, TSI)

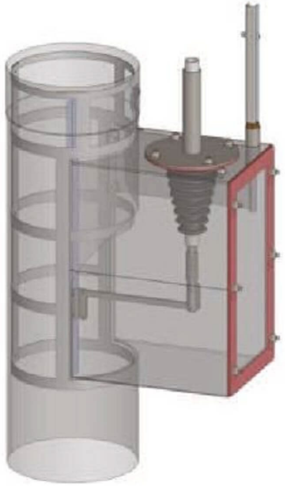
Two different aging setups:
short aging: 1.4 eqv. Days
Medium aging: 3.4 eqv. days

Ihalainen, M., *et al.: A novel high-volume Photochemical Emission Aging flow tubeReactor (PEAR). Aerosol Science and Technology. 2019. DOI:* ***10.1080/02786826.2018.1559918***

Experimental setup

Beech logs

Aduro 9.3
Wood stove

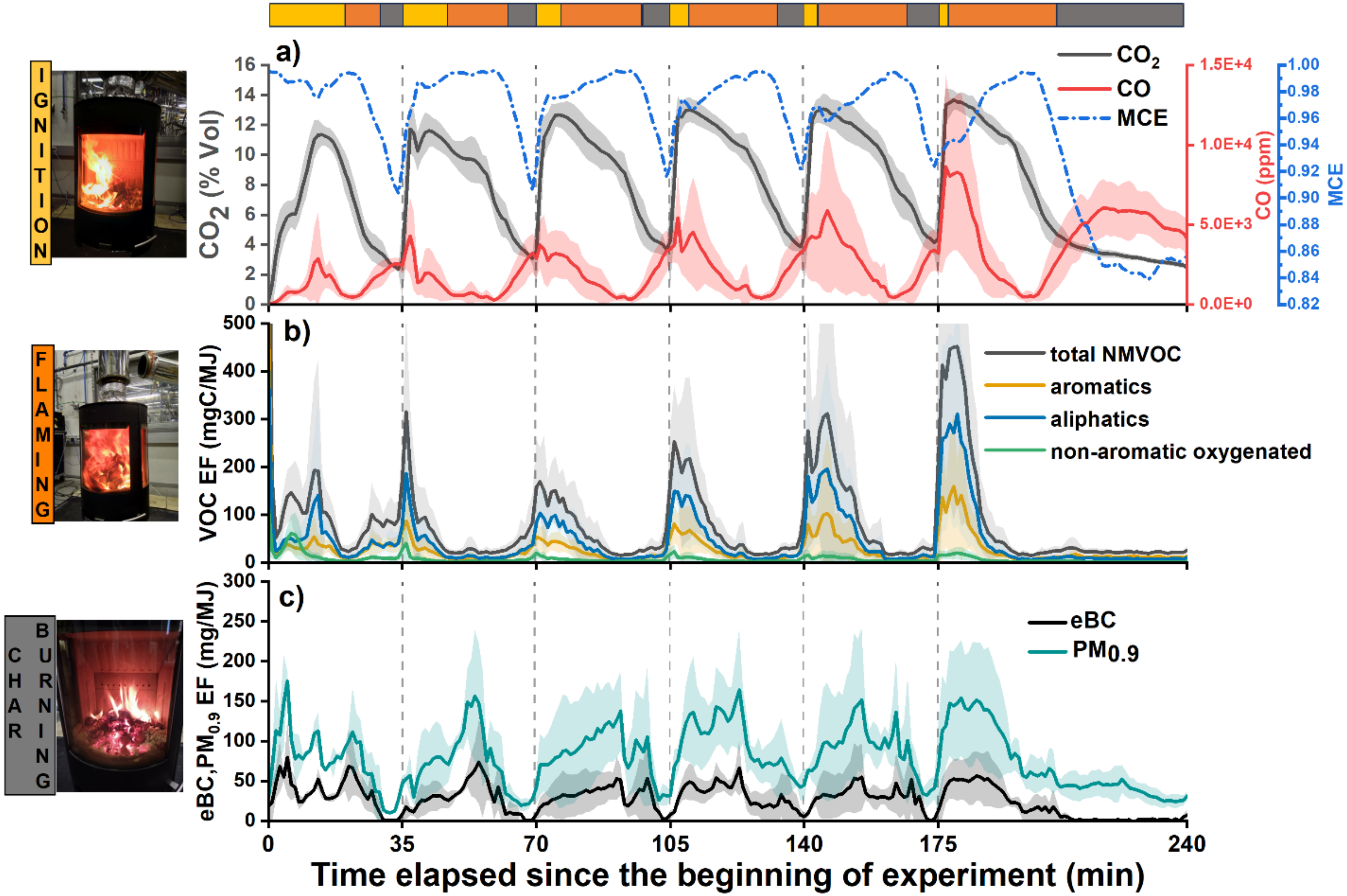


Oekotube,
inside model

Enjoying coffee after successful installation

Combustion procedure: gaseous & PM emissions without ESP

- 6 batches of 2 kg beech logs
- Each batch lasted 35 min
- At the end 30 min of residual char burning
- Three replicates of each experiment
- Combustion phases were defined based on CO2 and CO concentrations
- Mean fine particle mass emission (PM0.9) approx. 80 mg/MJ

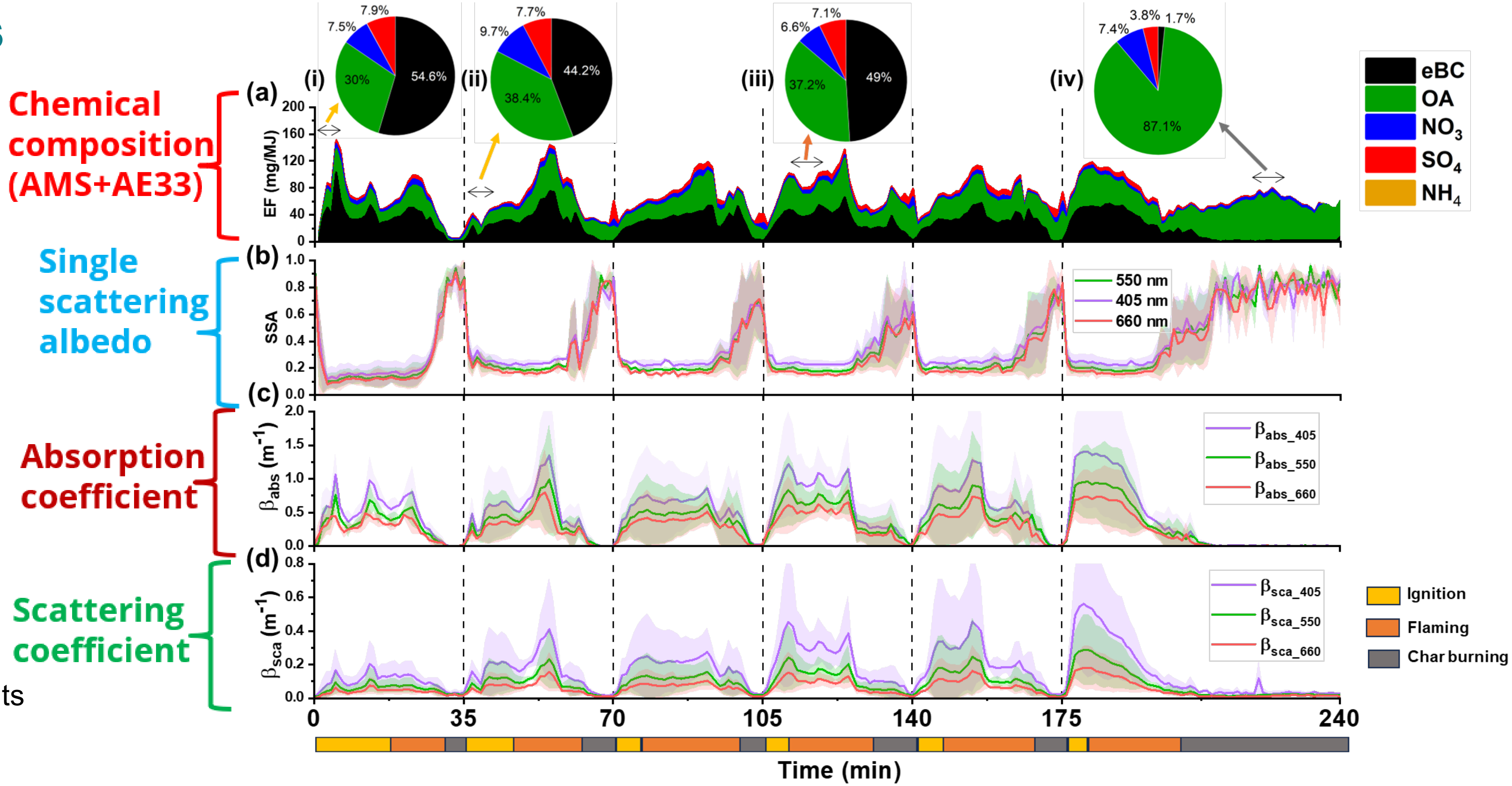


Mukherjee, A., *et al.: Black carbon and particle lung-deposited surface area in residential wood combustion emissions: Effects of an electrostatic precipitator and photochemical aging. Science of The Total Environment. 2024. DOI:* ***10.1016/j.scitotenv.2024.175840***

Fresh RWC emission characterization

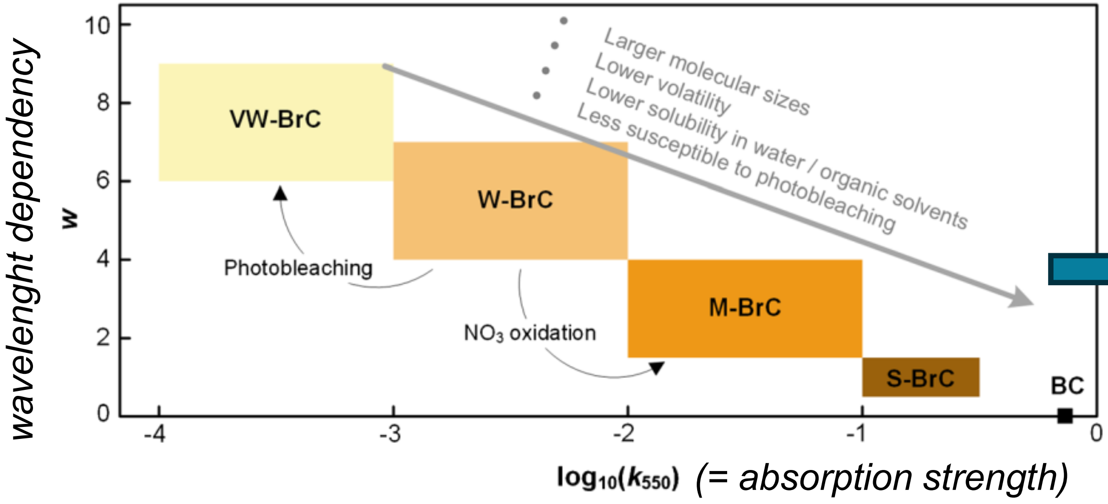
KEY OBSERVATIONS

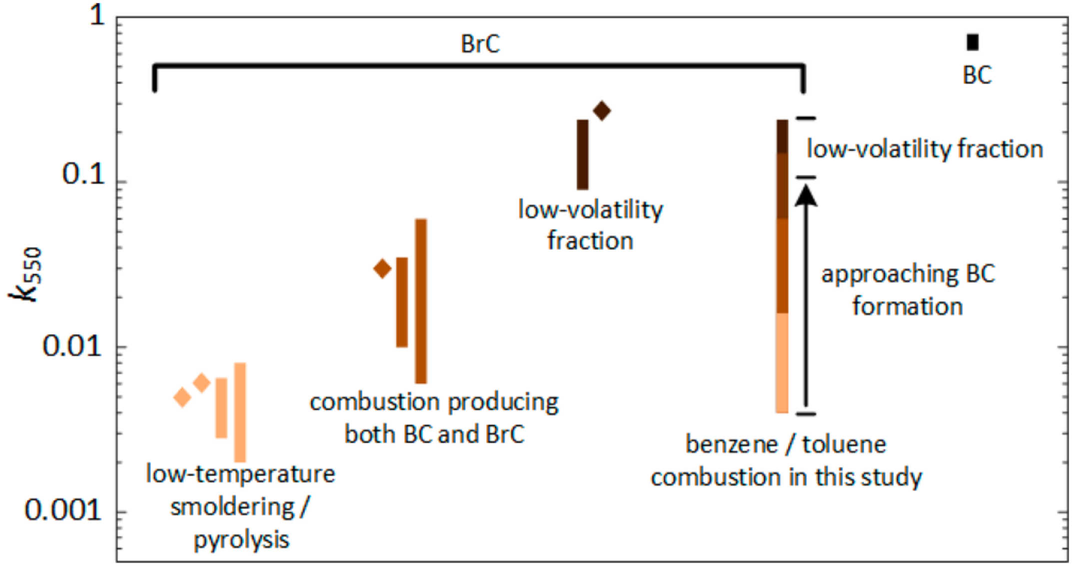
- Cold ignition & flaming → eBC-dominant (~45–55%)
- Char burning → OA-dominant (~87%); MCE drops below 0.9
- char burning lead to relatively scattering aerosol ; flaming phase emissions are strongly absorbing
- NO_3^- stable ~7–10% — alkali salts (KNO_3, $NaNO_3$)

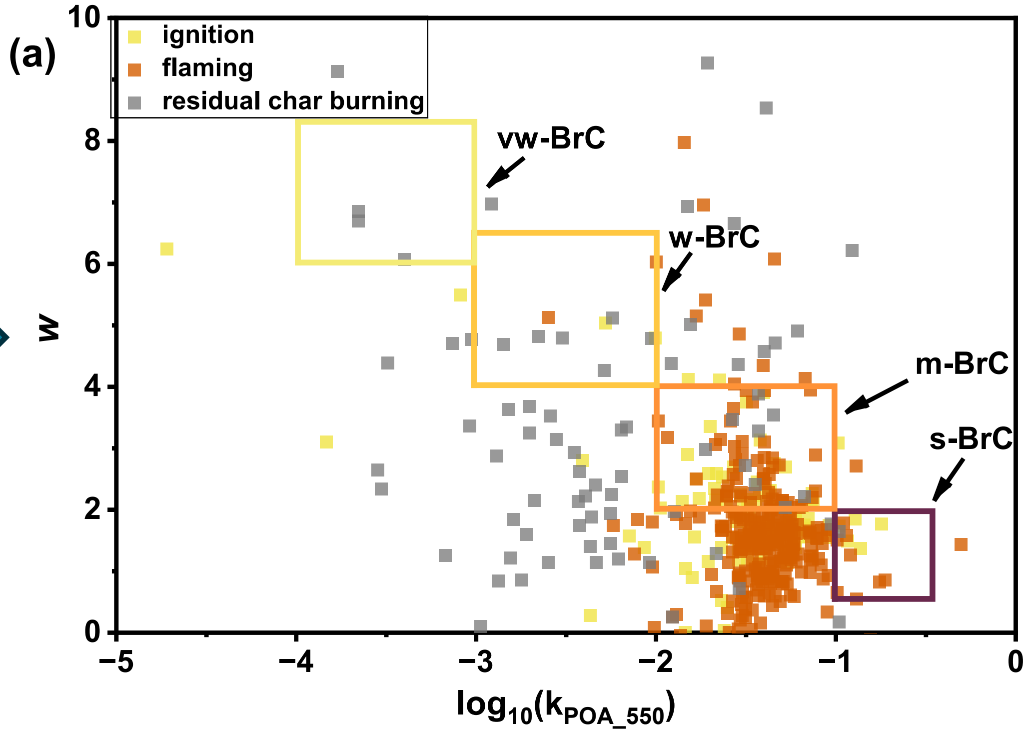


Brown carbon in fresh emissions

BrC classified in k550-w space (Saleh, 2020)







- Brown carbon contribution to absorption was estimated from aethalometer data assuming that AAE of pure black carbon = 1.12 (Wang et al., 2021 & Basnet et al., 2024)
- <u>Flaming emitted BrC falls in s-BrC regime</u>

k_OA (at 550 nm)

up to 0.49

flaming phase

ESP reduces emission; but modifies optical properties of the particles

−70%
β_abs at 550 nm

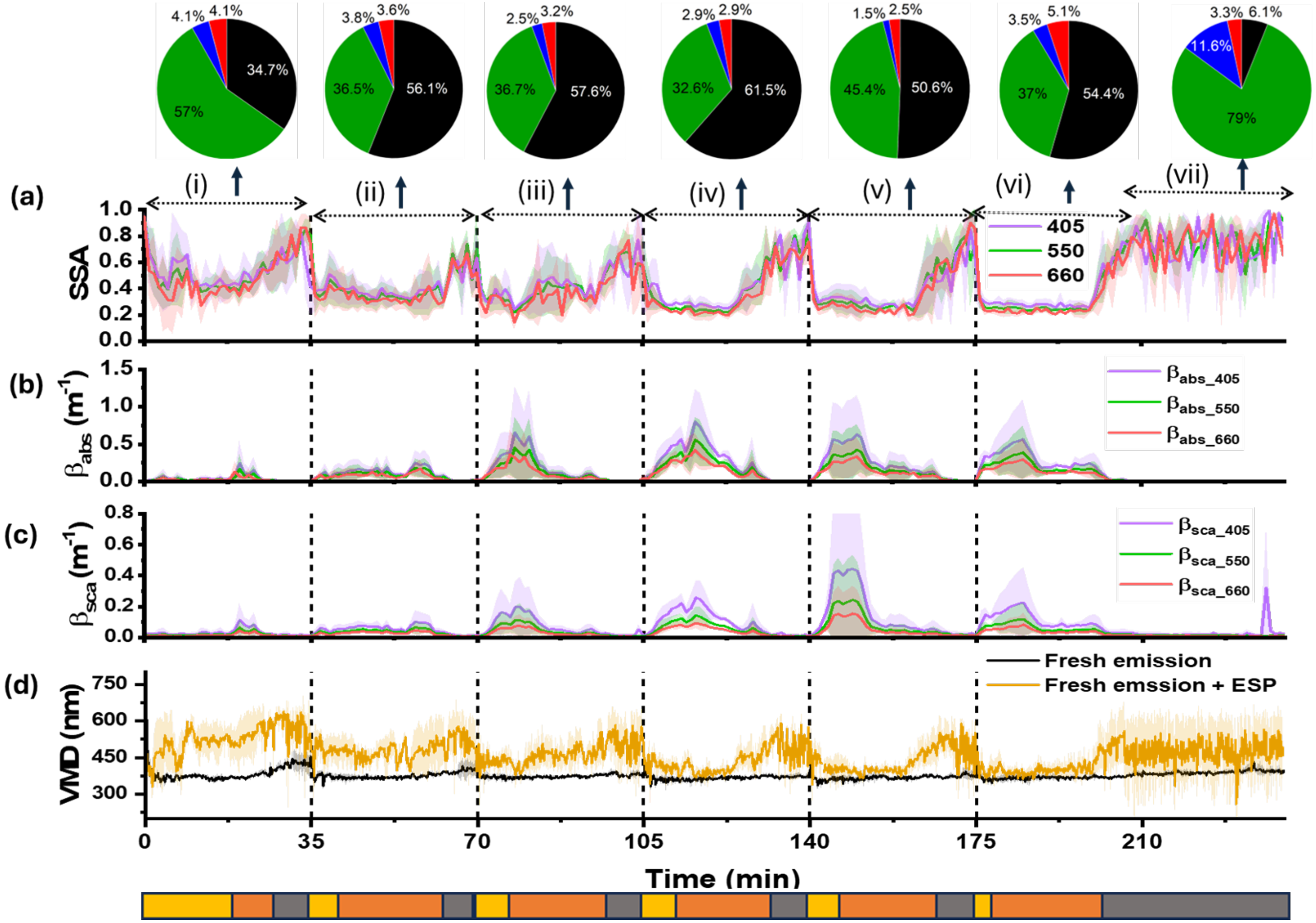
−52%
β_scat at 550 nm

+27%
SSA at 550 nm

+23%
Vol. mean diameter
(375 → 463 nm)

+40%
MSC at 550 nm

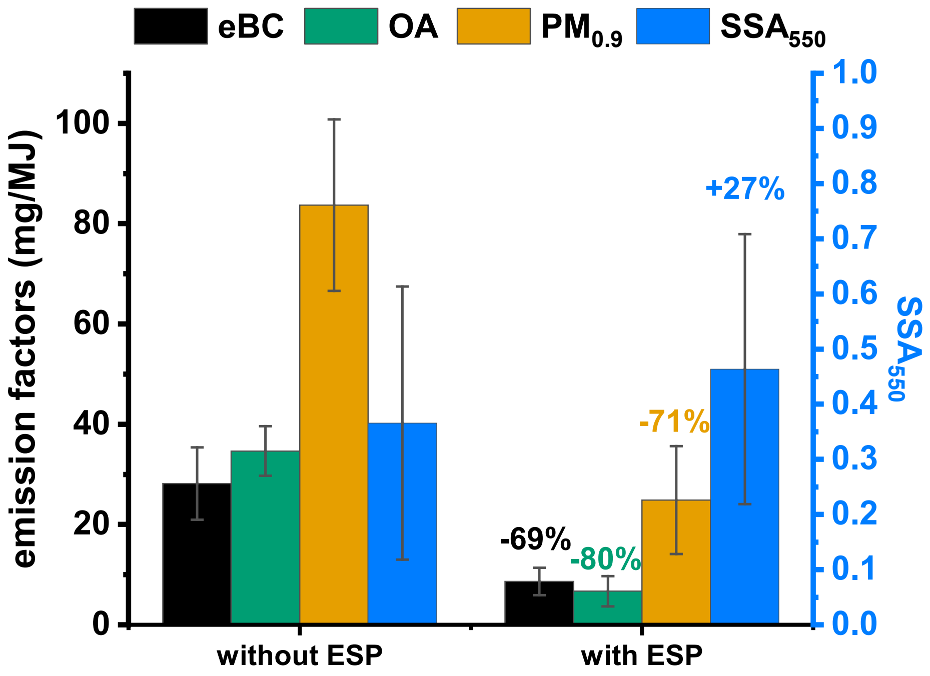
- Reduction in both absorption and scattering of aerosols
- Increase in particle volume size
- OA more efficiently removed than in eBC
- Increase in SSA

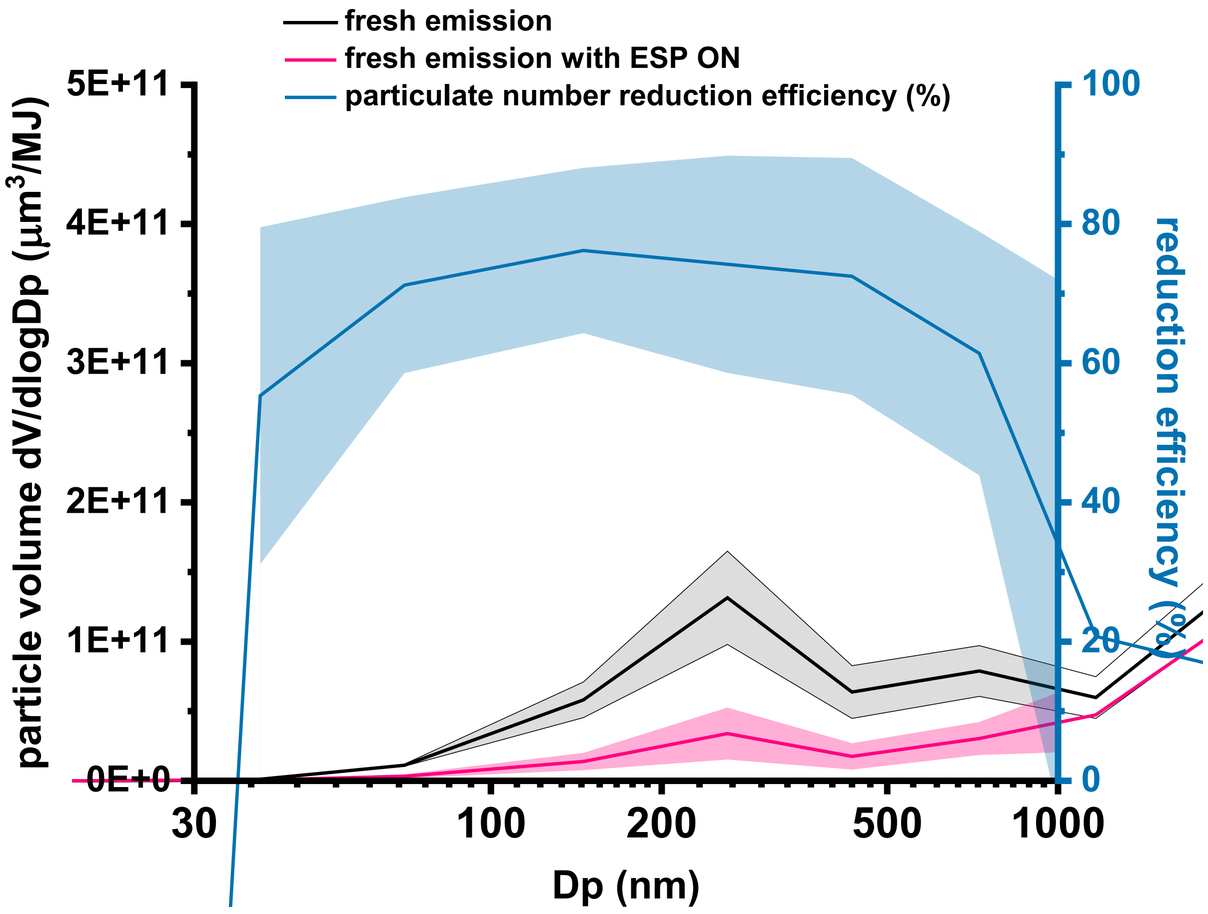


Effects of ESP (continued)

WHY THE OPTICS SHIFT

- Diffusion charging more efficient for d < 200 nm
- Surviving particles are larger ⇒ scatter more strongly
- MSC ↑, SSA ↑ while MAC ≈ unchanged
- Sub-50 nm nanoparticles form downstream of the ESP



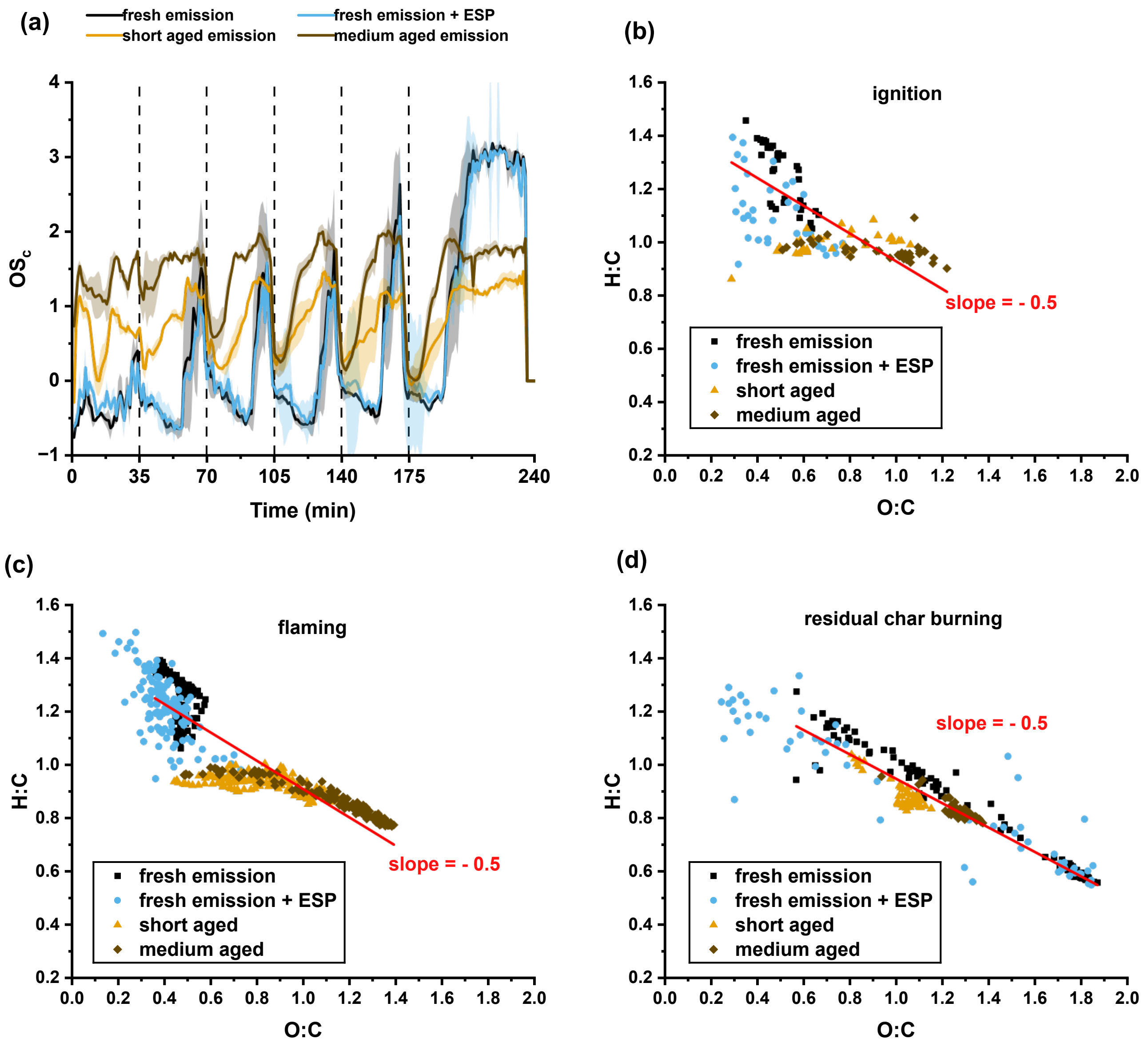


Effect of photochemical aging in PEAR

AGING CHEMISTRY

- OH + O_3 → POA oxidation
- SOA condenses on BC ⇒ lensing effect
- BrC photobleaches (m-BrC ⇒ w-BrC)
- Van-Krevelen slope ≈ −0.5

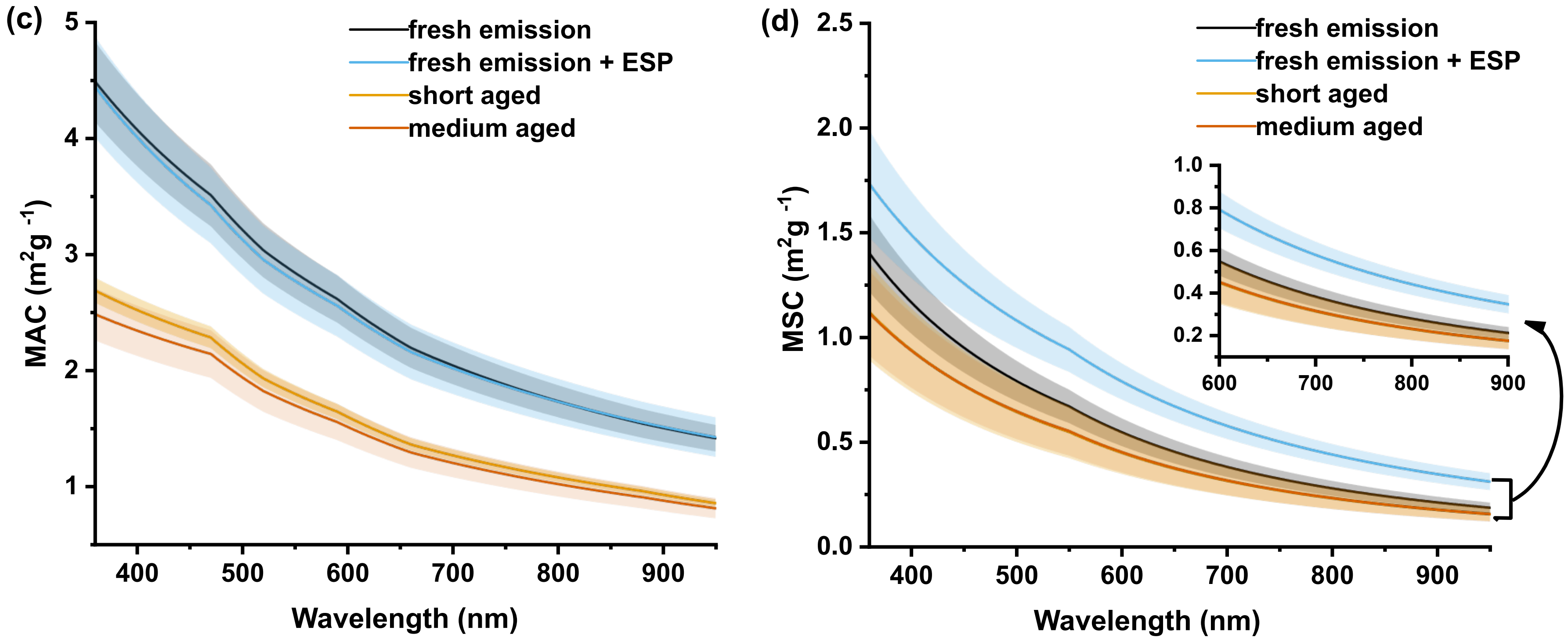
(fragmentation + carboxylic group addition)



Effects of photochemical aging (continued)

- increase in OA mass
- OA enhancement of 4.5
- Increase in scattering SSA

Net effect:
MAC ↓ ~40%,
SSA ↑ ~26%,
MSC ≈ unchanged

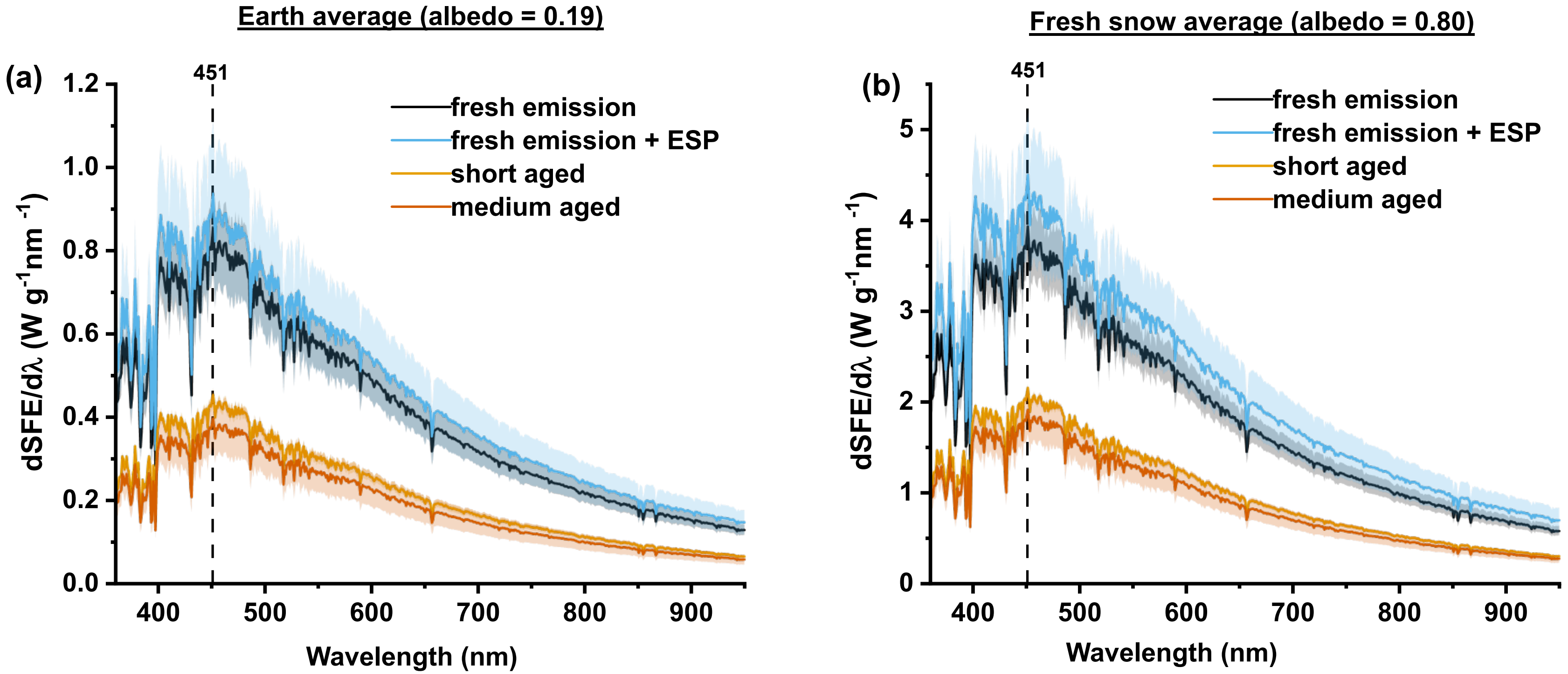


Simple forcing efficiency (SFE)

- SFE estimates the impact of unit mass of emitted particles on the Earth's radiative balance for a clear sky

dS(λ)/dλ: solar irradiance
τ_{atm}: atmospheric transmission (0.79)
a_s: surface albedo (0.19 and 0.8)
Fc: cloud fraction (0.6)

b: backscattering fraction
MAC: mass absorption cross section
MSC: Mass scattering cross section



Chen and Bond (2010)

$$\frac{dSFE}{d\lambda} = -\frac{1}{4}\frac{dS(\lambda)}{d\lambda}\tau_{atm}^2(1-Fc)[2(1-a_s)^2 \times b(\lambda) \times MSC(\lambda) - 4a_s \times MAC_{aerosol}(\lambda)]$$

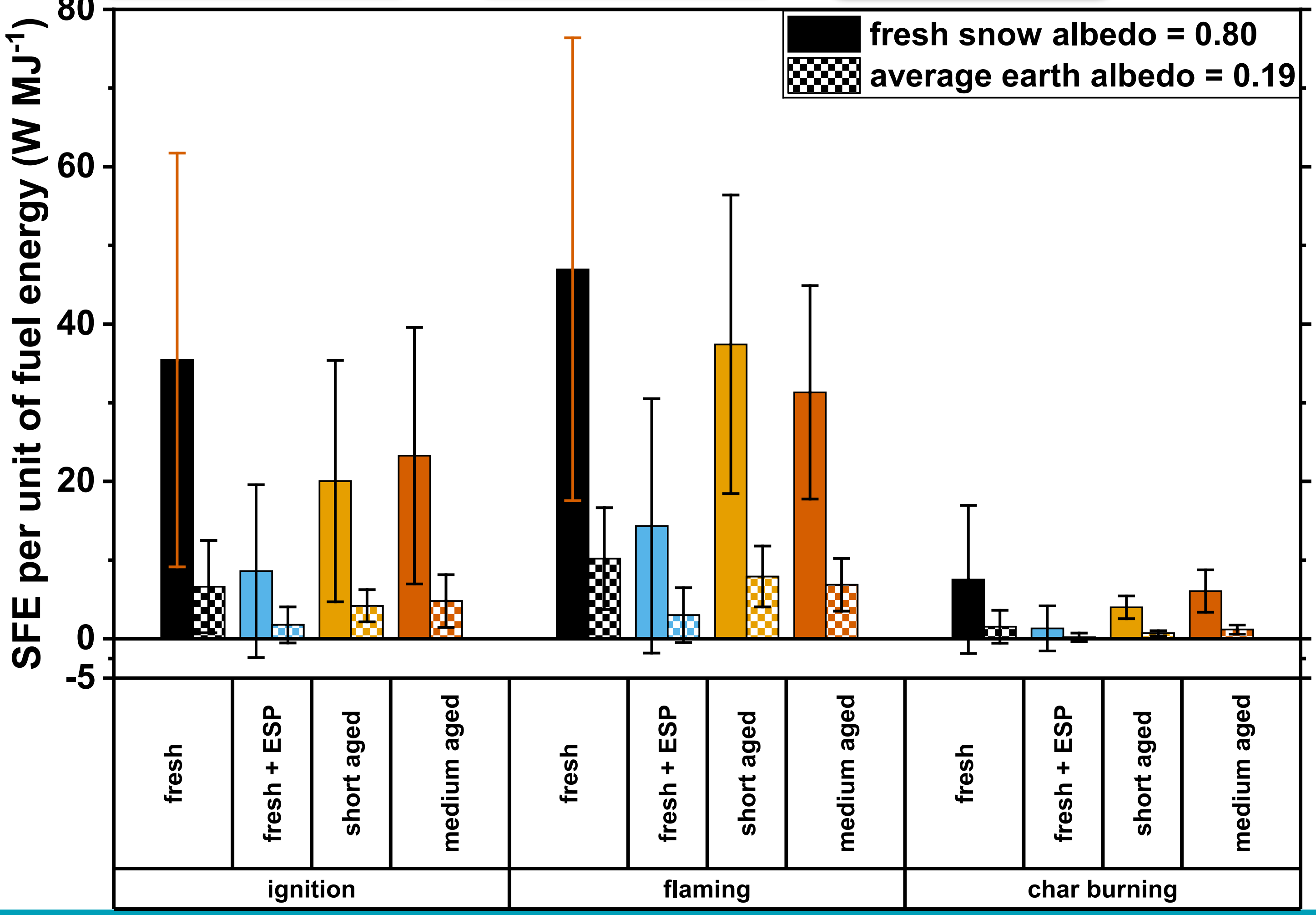
SFE per fuel energy: higher than literature

35.3 W / MJ
fresh, fresh-snow albedo

7.7 W / MJ
fresh, Earth-mean albedo

−71%
with ESP

−26 to −34%
with aging *1.4 / 3.4 eqv. days*



vs PREVIOUS LITERATURE

This work (fresh emission)
180-560 (mean. 435 W/g)

Estimated from Saliba et al., 2016 (snow albedo)
≈ 150-200 W/g (Soot rich cookstove emission)

Elser et al., 2019 (snow albedo)
≈ 1800 W/g (Aircraft soot)

Chen & Bond 2010, (snow albedo)
~23 W/g (wood pyrolysis)

Cuesta-Mosquera et al., 2024 (snow albedo)
≈ 44-61 W/g (ambient RWC)

Take-home messages

1 RWC in modern chimney stove ≠ wildfire

Soot-rich, low OA/BC; closer to diesel / cookstove than wildfire smoke. SFE estimated from wood pyrolysis and smouldering emissions reported ~10× lower values

2 Flaming-phase BrC in fresh RWC emission is strongly absorbing

$k_{OA,550}$ up to 0.49. Approaches the s-BrC regime of Saleh et al. 2020

3 Photochemical aging causes photobleaching of OA and reduces warming potential

OH/O_3 exposure equivalent to 1–3 days reduces SFE per fuel energy by 26–34%. Photobleaching of BrC dominates over SOA-driven lensing.

4 ESPs help — but modifies aerosol properties

−71% SFE per MJ. Surviving particles are larger, more scattering, with higher SSA. Net climate benefit, but the optical population shifts.

Thank you!

Acknowledgements:

- **Research Council of Finland (BbrCAC-project)**
- **AeroHEALTH-consortium**

Andreas Paul
(Aarhus Univ.)

Mika Ihalainen
(UEF)

Related work :

Anni Hartikainen: *Transient formation of organic gaseous emissions in residential wood combustion with and without an electrostatic precipitator*

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