

Supplement of:

Brief communication: Dose-dependent enhancement of snow mass loss by biomass-burning carbonaceous particles on a tropical Andean glacier

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Table S1. Manipulative experiments assessing snow responses to experimentally added carbonaceous particles.

Study	Experimental setting	Applied material	Loading / concentration	Measured response(s)	Direct snow melt or mass-loss quantification	Experimental replication
Conway et al. (1996)	Natural melting glacier snow; Blue Glacier, Washington, USA	Hydrophobic and hydrophilic soot	~3.3 and 33 g m ⁻² (hydrophobic); ~3.3 g m ⁻² (hydrophilic)	Albedo, particle redistribution, surface ablation	Yes. Direct surface ablation; no gravimetric mass measurement	No replicated multi-dose application
Brandt et al. (2011)	Artificial outdoor snowpacks; New York, USA	Commercial soot/BC surrogates	Main experiment: ~12 ppb BCeq control vs ~2.25–2.5 ppm soot	Spectral albedo; radiative-transfer model validation	No	Treatment snowpacks not independently replicated
SoS-2011 / Svensson et al. (2016)	Natural seasonal snow; southern Finland	Soot from wood and used-tire rubber combustion	Surface EC: ~20.9 µg g ⁻¹ vs ~0.08 µg g ⁻¹ reference	Albedo, snow properties, snow-depth melt rate	Yes. ~7 vs 3 cm d ⁻¹ melt rate; no gravimetry	One contaminated area vs one reference
SoS-2013 / Meinander et al. (2014); Peltoniemi et al. (2015); Svensson et al. (2016)	Natural seasonal snow; Sodankylä, Finland	Residential chimney soot, mainly wood-burning in the analyzed soot experiments	Surface EC: ~0.232–6.42 µg g ⁻¹ across spots	Albedo/BRF, density, metamorphism, surface soot retention	No	Equivalent replicate loadings were not achieved
Beres et al. (2020)	Natural alpine snow; Sierra Nevada, USA	BrC/OC aerosol from smoldering Alaskan peat	Two depositions; added surface-layer TOC ~4.4 and ~10.1 g m ⁻³ (0–2.5 cm)	Spectral albedo, TOC, optical properties, radiative forcing	No	Two separate depositions; not a replicated loading series
Lapuerta et al. (2022)	Natural seasonal mountain snow; Madrid, Spain	Diesel-engine soot	~3.3 → 9.3 mg kg ⁻¹ soot	Spectral/broadband albedo; model comparison	No	No replicated treatment series
González-Correa et al. (2022a)	Natural seasonal mountain snow; Sierra Nevada, Spain	Direct diesel-vehicle exhaust soot	0.65 → 9.00 mg kg ⁻¹ sequentially (spatial gradient); intermediate values interpolated	Spectral/broadband albedo; grain size and moisture	No quantified melt; hot exhaust caused melt as an artifact	No. Sequential dosing (soot gradient) on the same surface

Study	Experimental setting	Applied material	Loading / concentration	Measured response(s)	Direct snow melt or mass-loss quantification	Experimental replication
González-Correa et al. (2022b)	Natural seasonal mountain snow; Sierra Nevada, Spain	Diesel soot	~0.7–0.8 mg kg ⁻¹ artificial soot, plus background	Spectral and broadband albedo	No	No independent soot-loading replication
SoS-2018 / Svensson et al. (2024)	Natural seasonal snow; Sodankylä, Finland	Wood-burning and oil-burning soot	Actual/estimated soot BCeq: ~5.3–24 mg m ⁻² ; two nominal levels per source	Albedo, snow properties, melt-out date	Yes. melt-out date/snow-cover duration; no gravimetry	A/B spots served different measurement purposes, not replication
Present study	Natural glacier snow; Artesonraju Glacier, Cordillera Blanca, Peru	Biomass-burning-derived carbonaceous particles	0, 10.5, 52.6, 105.2, 526.1, and 1052.3 mg m ⁻² (0–10 mg per experimental unit)	Time-resolved gravimetric snow mass loss	Yes. Direct gravimetric snow mass loss	Yes. 3 independent units per loading and container type (36 units total)

Notes. SoS-2013 is presented as one experimental campaign because Meinander et al. (2014), Peltoniemi et al. (2015), and Svensson et al. (2016) report complementary outcomes from the same campaign. “Direct melt or mass-loss endpoint” distinguishes physical melt/ablation endpoints from optical or radiative responses; “gravimetric” refers specifically to direct mass measurement. Loading/concentration values are reported using the metrics and units provided by the original studies and are therefore not directly interchangeable across experiments. The table is restricted to manipulative field experiments in which carbonaceous particles were experimentally added to snow. Modeling-only and observational studies, and laboratory experiments were excluded. **Abbreviations:** BC, black carbon; BCeq, black-carbon equivalent; BrC, brown carbon; EC, elemental carbon; BRF, bidirectional reflectance factor; TOC, total organic carbon.

Table S2. Experimental particle masses, exposed surface area, and corresponding surface loadings.

Applied particle mass per experimental unit (mg)	Exposed surface area (m ²)	Particle surface loading (mg m ⁻²)
0	0.009503	0
0.1	0.009503	10.5
0.5	0.009503	52.6
1	0.009503	105.2
5	0.009503	526.1
10	0.009503	1052.3

Note. Surface loadings were calculated by dividing the applied particle mass by the exposed surface area of each experimental unit (0.009503 m²; equivalent to approximately 95.0 cm²). Values are rounded to one decimal place.

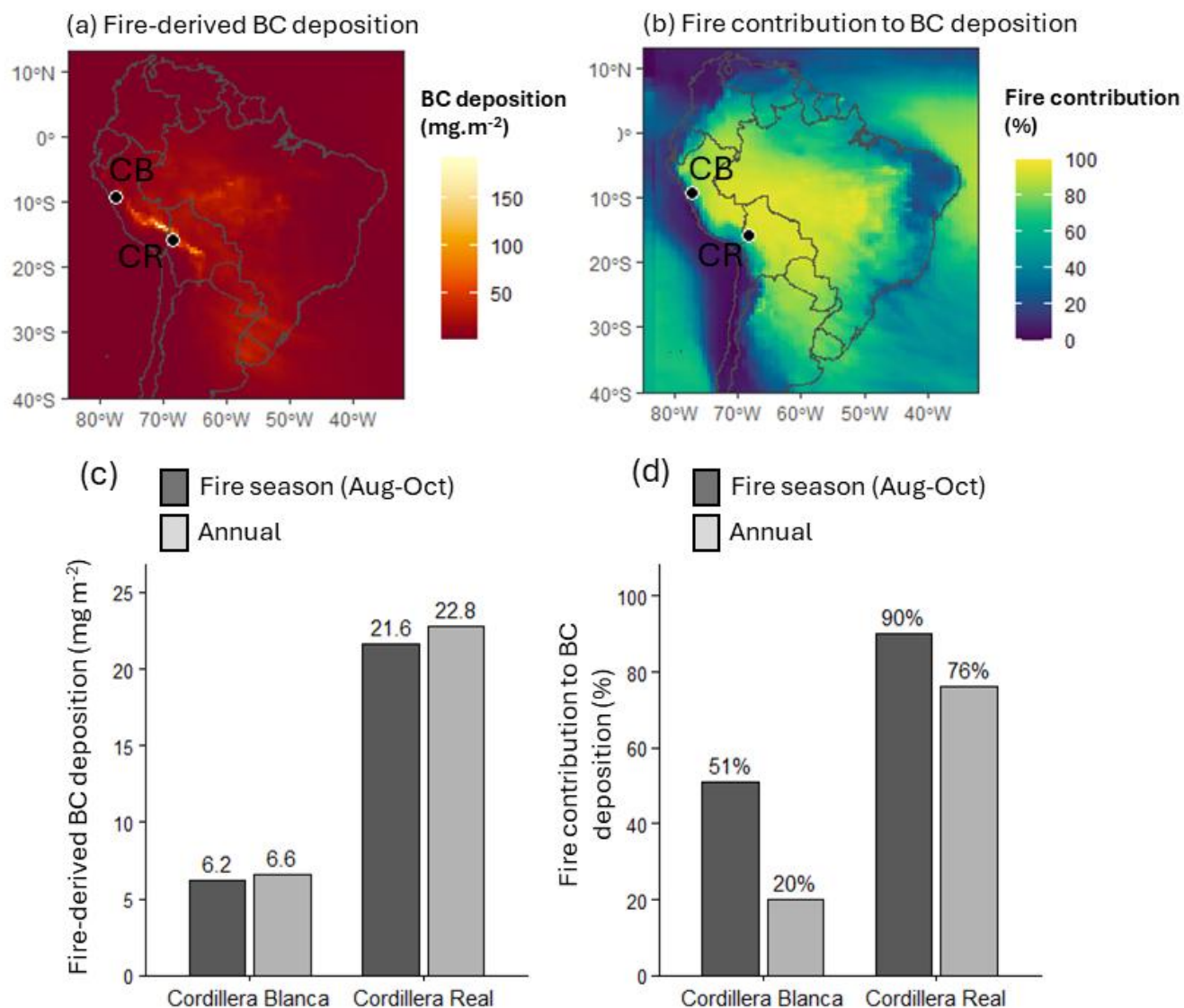


Figure S1. Environmental context of the experimental particle surface loadings in tropical Andean glacier regions. (a) Modeled fire-derived black carbon (BC) deposition over South America during August–October 2017. (b) Relative contribution of biomass burning to total BC deposition during the same period. CB and CR indicate the Cordillera Blanca, Peru, and Cordillera Real, Bolivia, respectively. (c) Fire-derived BC deposition during August–October 2017 and for the full year 2017 in the Cordillera Blanca and Cordillera Real. (d) Corresponding biomass-burning contribution to total BC deposition for the same periods.

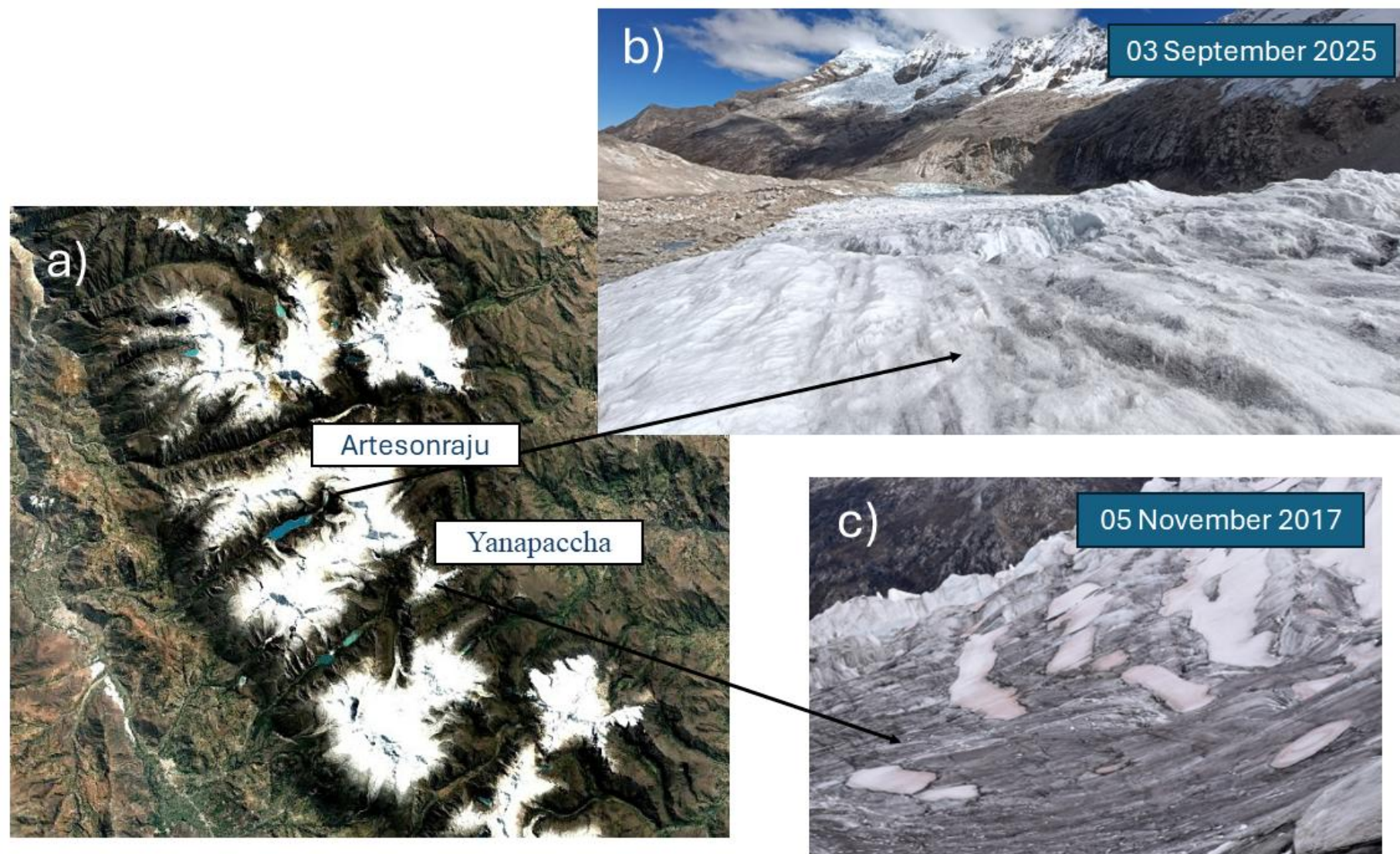


Figure S2. Examples of glacier-surface darkening in the Cordillera Blanca, Peru. (a) Location of Artesonraju and Yanapaccha glaciers, which are separated by approximately 6 km. Base image: Google Earth; imagery and map data © Google and respective imagery providers, as displayed in the original Google Earth view. (b) Artesonraju Glacier on 3 September 2025, during the regional fire season, showing pronounced surface darkening. (c) Yanapaccha Glacier on 5 November 2017, near the end of the fire season, showing extensive surface darkening. Photographs: Wilmer Sánchez.

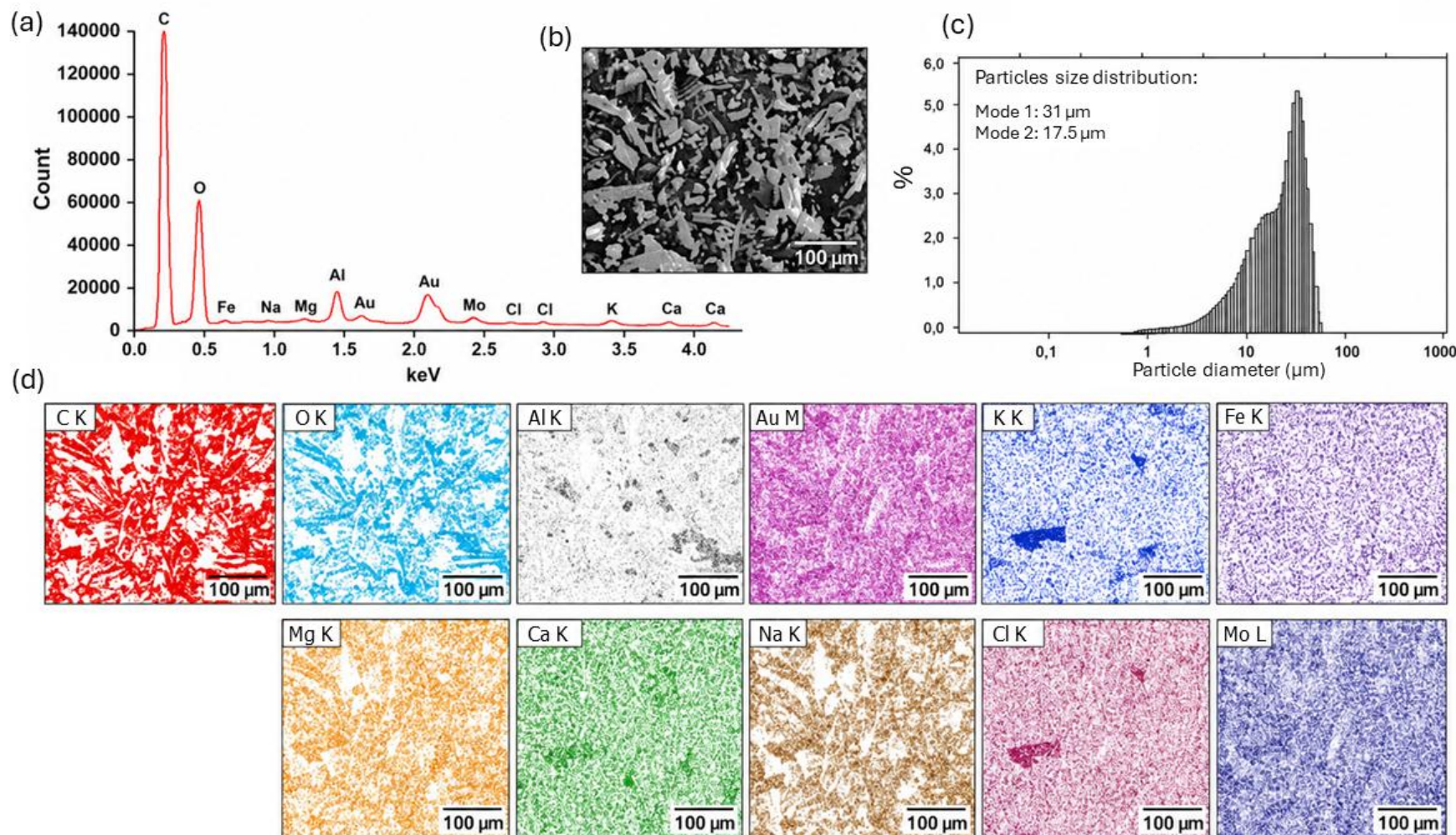


Figure S3. Morphological, elemental, and size characterization of the biomass-burning-derived carbonaceous particles used in the field experiment.

(a) Energy-dispersive X-ray spectroscopy (EDS) spectrum of the material, showing a dominant carbon signal together with O and minor signals from Fe, Na, Mg, Al, Au, Mo, Cl, K, and Ca. The Au signal originates from the gold coating applied during sample preparation for SEM analysis, while part of the Al signal may reflect contamination introduced by the aluminum foil used during particle production. (b) Representative scanning electron microscopy (SEM) image showing the irregular morphology and heterogeneous shape of the particles; scale bar: 100 µm. (c) Particle-size distribution determined by laser diffraction using a CILAS 1064 particle-size analyzer, showing a broad distribution with modal particle sizes of approximately 17.5 and 31 µm. (d) EDS elemental maps showing the spatial distribution of C, O, Al, Au, K, Fe, Mg, Ca, Na, Cl, and Mo across the analyzed material. The predominance and spatial distribution of the C signal support the characterization of the experimental material as predominantly carbonaceous.

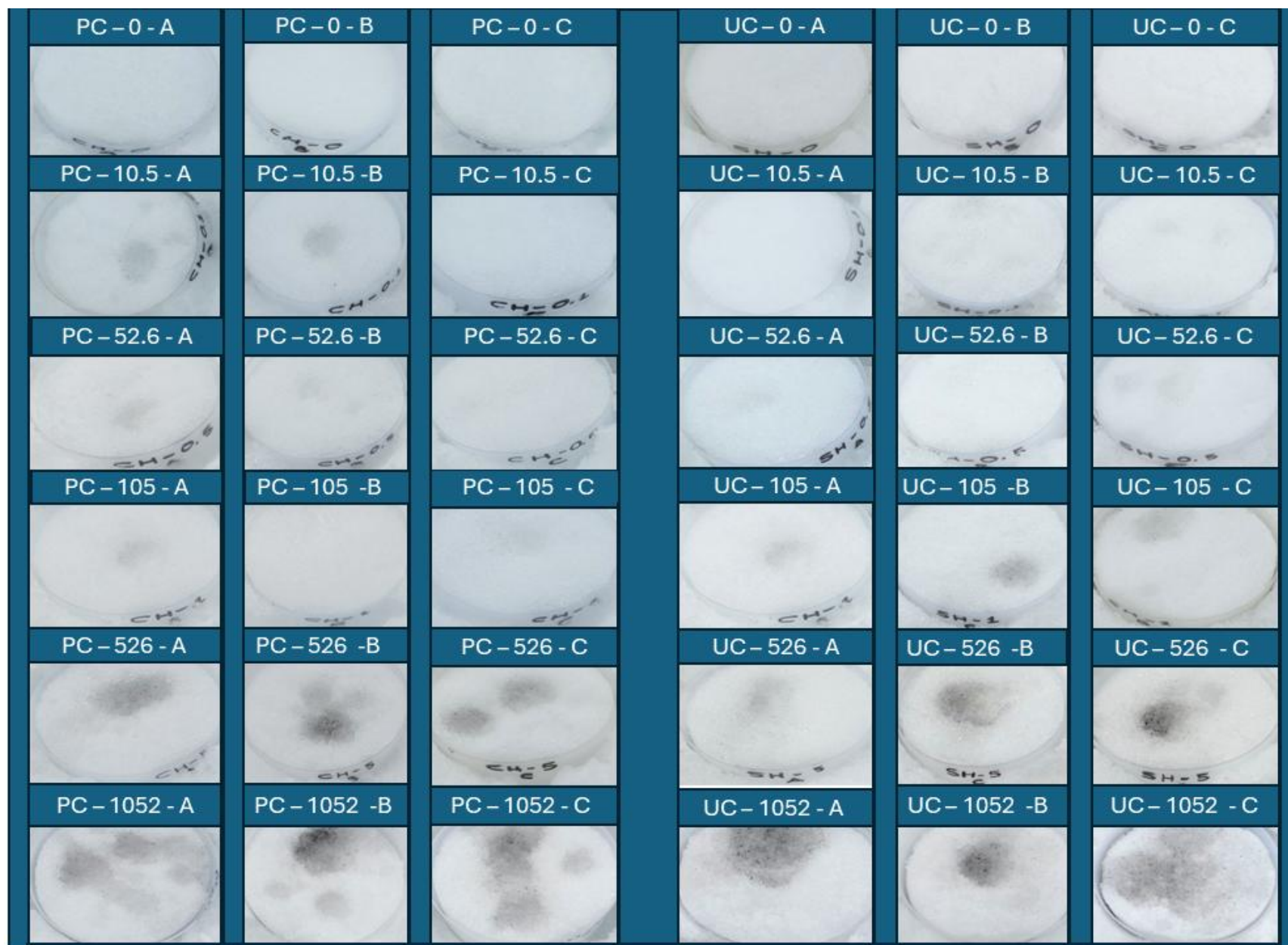


Figure S4. Initial condition of the experimental units at the beginning of the field experiment (09:00 local time) on Artesonraju Glacier. Photographs show the three independent replicates (A–C) for each particle surface loading in perforated containers (PC) and unperforated containers (UC). Labels indicate container type (PC or UC), nominal particle surface loading (mg m^{-2}), and replicate (A, B or C).

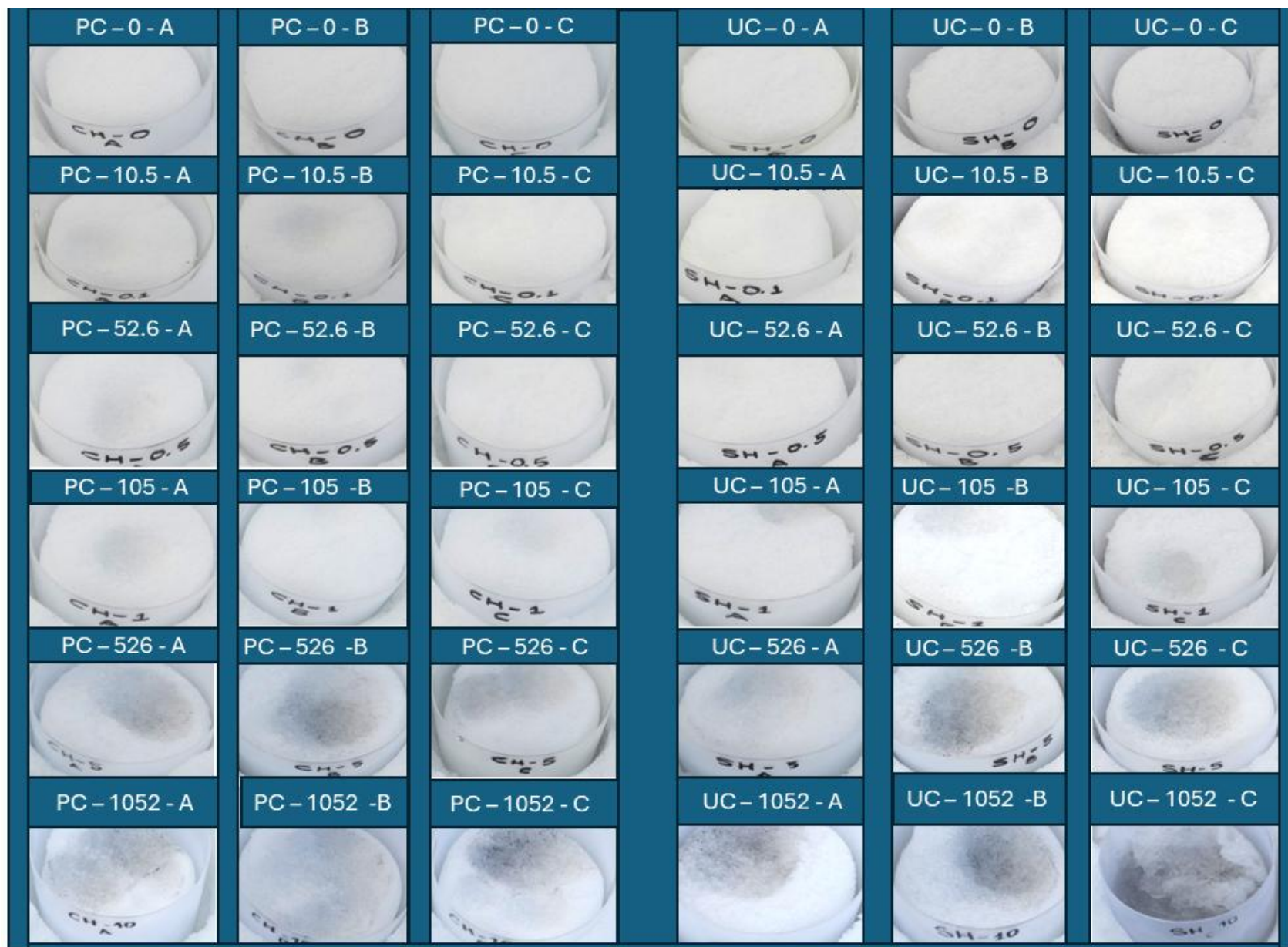


Figure S5. Final condition of the experimental units at the end of the 9 h field experiment (18:00 local time) on Artesonraju Glacier. Photographs show the three independent replicates (A–C) for each particle surface loading in perforated containers (PC) and unperforated containers (UC). Labels indicate container type (PC or UC), nominal particle surface loading (mg m^{-2}), and replicate (A, B or C).

Table S3. Summary of the final experimental results after the 9 h field experiment on Artesonraju Glacier.

Particle surface loading (mg m ⁻²)	Final total snow mass loss (mm w.e.)	Additional snow mass loss relative to control (mm w.e.)	Drainage-related enhancement (%)	Atmospheric enhancement (%)
0.0	6.90	0.00		
10.5	7.24	0.34	1.2 ± 0.9	0.2 ± 0.7
52.6	7.38	0.48	1.6 ± 0.4	0.4 ± 0.1
105.2	8.18	1.28	3.3 ± 2.4	2.4 ± 1.4
526.1	11.42	4.52	6.3 ± 2.0	3.7 ± 1.0
1052.3	16.49	9.59	14.7 ± 6.0	4.2 ± 1.7