Author Response to Referee #4
EGUSPHERE-2026-308

General comments:
Atmospheric ice-nucleating particles (INPs) play a critical role in cloud formation, cloud radiative properties and precipitation through heterogeneous ice nucleation, yet the importance of INPs from anthropogenic sources remains poorly understood. This manuscript investigated INP concentrations (N_{INP}) and ice nucleation active site density (ns) of immersion mode INPs in Taiyuan, China based on one month-long winter field observations. The results indicated that the temporal variability of INP concentrations is dominated by episodic natural desert dust transport, and the direct impact of anthropogenic emissions on INP loading remains limited. Namely, this study implied that in heavily polluted environments, natural dust rather human activity governs cloud freezing processes. These findings would offer observational constraints for improving INP parameterizations in chemical transport and climate models.
In general, I think the research goal of this manuscript is clear, and the structure and results are reasonable. Therefore, I recommend this manuscript is accepted and published in the journal of *EGUsphere* after some revisions. The authors are advised to consider the following comments.
Response: We are very grateful to the reviewers for their constructive comments. In response to these comments, we have provided point-by-point replies and made corresponding revisions throughout the manuscript.

***Specific comments*:**
(1) Page 1, Abstract, Lines 18-19: 'CI: 6.64-8.41, CI: 1.58-1.99'.
Comment: When an English abbreviation first appears in the manuscript, please provide its full form.
Response: In the revised manuscript, we have replaced "CI" with "confidence interval (CI)" in the Abstract.
Changes in manuscript:
Page 1, Abstract: "CI" has been revised to "confidence interval (CI)" at its first appearance.

(2) Page 1, Abstract, Lines 22-23; Page 6, 2.2.5 Positive matrix factorization (PMF), Lines 179-186: 'Positive matrix factorization (PMF) identified five PM_5 sources: coal combustion and traffic emissions, industry, (anthropogenic) dust, secondary aerosols and fireworks.'
Comment: How did the PMF method distinguish between natural dust and anthropogenic dust? Please provide a detailed description in the context. This is of great significance for the analysis of how the two different types of dust affect the INPs in the manuscript.
Response: In this study, PMF resolved a dust-related factor characterized by crustal elements such as Ca and Fe, but PMF alone was not used to directly distinguish transported desert dust from local dust-associated particles. The distinction was made

using additional evidence, including backward trajectories, coarse-mode particle enhancement, PM_{10} variation, and event classification of the 5–9 December desert dust event. We have therefore revised the wording throughout the manuscript from "anthropogenic dust" to "dust-related factor" or "local dust-associated particles" where appropriate. We now clarify that PMF was used to identify a dust-related $PM_{2.5}$ source factor and to assess its covariation with N_{INP} during non-desert-dust periods, rather than to directly separate natural and anthropogenic dust sources.
Changes in manuscript:
Abstract: "Positive matrix factorization (PMF) identified five $PM_{2.5}$ sources: industrial emissions, dust-related particles, secondary aerosols, coal combustion and traffic emissions and fireworks."
Section 3.4: "Data from the identified desert dust event (5–9 December) are not shown in Fig. 4, because the PMF–N_{INP} correlation analysis focused on non-desert-dust periods. The dust-related factor exhibits characteristic signatures of dust-associated particles, including high loadings of Ca and Fe. During the non-desert-dust periods, this factor is interpreted as mainly reflecting local dust-associated particles, such as road dust, fugitive dust from industrial and construction activities, and resuspended soil. This dust-related $PM_{2.5}$ factor showed no significant correlation with N_{INP} during the non-desert-dust periods (Table 1), indicating that local dust-associated $PM_{2.5}$ variability did not explain N_{INP} variability outside the identified long-range desert dust event."

(3) Page 1, Abstract, Lines 26-27 and in the context: 'Observed N_{INP} variability is likely governed by the interplay of episodic coarse-mode inputs and atmospheric processing rather than a single dominant source'.
Comment: In the manuscript, the authors only provided one month-long winter field observations in Taiyuan, which is insufficient to confirm this conclusion. That is, this conclusion is difficult to convince the readers.
Response: Our intention was to summarize the observed pattern during this campaign, rather than to draw a general mechanistic conclusion beyond the temporal and spatial scope of the present dataset. In the revised manuscript, we have therefore softened this statement in the Abstract and in the main text. Specifically, we now describe the observations more cautiously by emphasizing that, during this winter campaign in Taiyuan, N_{INP} variability was characterized by strong episodic enhancement during the desert dust event, whereas the variability during non-desert-dust periods could not be explained by any single major $PM_{2.5}$ source factor. We have also revised related overgeneralized statements in the Discussion and Conclusions accordingly.

(4) Page 3, Lines 69-71: 'Furthermore, the influence of dust in cities is not limited to long-range natural transport; anthropogenic dust-such as agricultural operations, construction, and other urban processes-can also contribute substantially to atmospheric INPs in urban and peri-urban regions (Chen et al., 2024)'.
Comment: The main conclusion of this manuscript seems to be in contradiction to the results obtained by Chen et al. (2024). In order to facilitate readers' understanding, please provide a reasonable explanation in the context.

Response: Our intention in citing Chen et al. (2024) in the Introduction was to note that anthropogenic dust has been reported as a potentially important source of urban INPs during non-dust periods, rather than to suggest that the same source necessarily dominated the present observations in Taiyuan. We agree, however, that the original wording in the Discussion, especially the sentence "This implies that the INPs observed in Taiyuan may also be influenced by anthropogenic dust particles," was too speculative and may have created an apparent contradiction with our main conclusion.
Changes in manuscript:
(1) Introduction: "Furthermore, the influence of dust in urban environments is not limited to long-range natural transport; anthropogenic dust may also contribute to atmospheric INPs in some urban and peri-urban regions, although direct field evidence remains limited (Chen et al., 2024)."
(2) Section 3.2: "This comparison suggests that the relative importance of anthropogenic dust and transported desert dust may vary with urban environments and observation period. In this winter campaign in Taiyuan, the strongest INP enhancements were associated with the identified desert dust event."

(5) Page 4, Lines 100-102: 'In addition, a two-channel sampler was used to collect particles on filters for INP measurement. INP filter samples ……using a two-channel sampler without a cyclone, from 4 December 2023 to 5 January 2024'.
Comment: What is the meaning of 'using a two-channel sampler without a cyclone'? Please provide the measurement particle size ranges of INP in the context, which is vital to the analysis of the results in this manuscript.
Response: Here, "without a cyclone" means that no size-selective inlet (cyclone and other impactors) was installed upstream of the filters. Therefore, no defined aerodynamic cut-off was applied during INP sampling, and the collected aerosol can be regarded as approximately total suspended particles. We have revised the manuscript accordingly.
Changes in manuscript:
Section 2.1: "In addition, INP filter samples were collected using a two-channel sampler equipped with two parallel filter channels from 4 December 2023 to 5 January 2024. Polycarbonate filters (47 mm, Nuclepore Track-Etch Membrane, 0.2 μm pore size, Whatman) were used for sampling. The sampler was operated without a size-selective inlet."

(6) Page 9, Lines 251-253: 'Chen et al. (2024) found that anthropogenic dust particles, such as road dust influenced by traffic emissions, are important INP sources in the urban atmosphere. This implies that the INPs observed in Taiyuan may also influenced by anthropogenic dust particles'.
Comment: The conclusion of 'This implies that the INPs observed in Taiyuan may also influenced by anthropogenic dust particles' seems to be in contradiction to the main conclusion of the manuscript 'In summary, long-range mineral dust transport is the decisive driver of INP enhancements, while traditional anthropogenic fine aerosols contribute minimally' (**Abstract, Lines 25-26**). Please provide a reasonable

explanation in the context.

Response: We thank the reviewer for this important comment. We agree that the original sentence, "This implies that the INPs observed in Taiyuan may also be influenced by anthropogenic dust particles," was too speculative and could be read as inconsistent with the main conclusion of the manuscript. Our intention was not to infer anthropogenic dust influence in Taiyuan directly from Chen et al. (2024), but rather to note that anthropogenic dust has been reported as an important urban INP source in some environments.

To avoid this ambiguity, we have removed the above sentence and revised the surrounding discussion. The revised text now states more cautiously that Chen et al. (2024) and the present study together suggest that the relative importance of anthropogenic dust and transported desert dust may vary among urban environments and observation periods. In the present winter campaign in Taiyuan, the strongest INP enhancements were associated with the identified desert dust event, whereas the remaining variability during non-desert-dust periods could not be uniquely attributed to anthropogenic dust based on the present dataset.

Changes in manuscript:

Same as (4) Page 3, Lines 69-71: (2)

(7) Page 11, Lines 298-300: 'This comparison suggests that, under East Asian desert dust transport regime, typical atmospheric aging does not significantly modify the surface ice-nucleating activity of mineral dust, and that mineralogical composition and particle-size characteristics are likely more important determinants'.

Comment: The author didn't provide direct and sufficient evidences in the manuscript to prove this conclusion. Please revise this conclusion or provide sufficient evidence in the manuscript. For instance, 'typical atmospheric aging does not significantly modify the surface ice-nucleating activity', the authors didn't provide the 'typical atmospheric aging processes' or 'aging mineral dust aerosol' in the context.

Response: The original wording was too strong because the present study did not directly characterize the aging state of the transported dust particles or the specific atmospheric aging processes involved. We have revised this part to separate the observational comparison from any inference about atmospheric aging. The revised text now states that the ns values of the Taiyuan dust samples broadly overlap with the Beijing dust parameterization, suggesting that strong ice-nucleating activity was retained during the Taiyuan dust episode. We also cite Chen et al. (2023), who reported observational evidence that atmospheric chemical modification did not suppress the ice nucleation activity of East Asian dust, as relevant context. However, this citation is not used to claim that the present dataset directly demonstrates an aging effect. We now explicitly state that the comparison in this study should not be interpreted as direct evidence for, or a quantification of, the effect of atmospheric aging.

Changes in manuscript:

(1) Section 3.3: "As shown in Fig. 3, the Beijing dust parameterization broadly overlaps with the ns values of the dust samples in this study across the measured temperature range. This comparison is consistent with Chen et al. (2023), who reported

observational evidence that atmospheric chemical modification did not suppress the ice nucleation activity of East Asian dust. However, because the present study did not directly characterize the aging state of the dust particles or the specific aging processes involved, this comparison is used only to suggest that strong ice-nucleating activity was retained during the Taiyuan dust episode, rather than to demonstrate or quantify the effect of atmospheric aging."

(3) Conclusions: "Comparison with previously reported dust parameterizations indicates that the transported desert dust retained strong ice-nucleating activity during the dust transport episode."

References

Chen, J., Wu, Z., Meng, X., Zhang, C., Chen, J., Qiu, Y., Chen, L., Fang, X., Wang, Y., Zhang, Y., Chen, S., Gao, J., Li, W., and Hu, M.: Observational evidence for the non-suppression effect of atmospheric chemical modification on the ice nucleation activity of East Asian dust, Sci. Total Environ., 861, 160708, https://doi.org/10.1016/j.scitotenv.2022.160708, 2023.