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EFFECTS OF SOIL PHYSICAL PARAMETERS MOISTURE, TEMPERATURE, AND POROSITY ON COLLEMBOLA (HEXAPODA) POPULATION DENSITY: A COMPARATIVE ANALYSIS ACROSS NMMC INDUSTRIAL ZONES

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Annotation. This study quantifies the relationships between key soil physical parameters moisture, temperature, porosity, soil organic matter (SOM), and pH and Collembola (Hexapoda) population density across three distance zones from the Navoi Mining and Metallurgical Combine (NMMC): near zone (0–2 km), middle zone (2–5 km), and control zone (>5 km). At 27 monitoring stations, soil moisture and SOM showed strong positive Pearson correlations with Collembola density ($r = +0.86$ and $r = +0.88$ respectively), while temperature and pH showed negative correlations ($r = -0.79$ and $r = -0.71$). Multiple regression analysis incorporating all five parameters yielded $R^2 = 0.87$, demonstrating that physical soil conditions account for 87% of the variance in Collembola population density. Critical threshold values for each parameter are identified. Results justify the mandatory inclusion of physical soil parameters in Collembola-based ecological monitoring protocols for Central Asian industrial zones.

Key words: Collembola, soil moisture, soil temperature, porosity, organic matter, pH, NMMC, multiple regression, Pearson correlation, population density, physical parameters, ecological monitoring, Uzbekistan.

Аннотация.В данном исследовании количественно оценены взаимосвязи между физическими показателями почвы влажностью, температурой, пористостью, содержанием органического вещества и pH и плотностью популяции Collembola

(Hexapoda) в трёх зонах удалённости от НГМК. На 27 мониторинговых станциях влажность почвы и содержание органического вещества положительно коррелировали с плотностью коллембол (r = +0.86 и r = +0.88), тогда как температура и pH отрицательно (r = −0.79 и r = −0.71). Множественная регрессия дала R^2 = 0.87. Идентифицированы критические пороговые значения каждого параметра.
Ключевые слова: Collembola, влажность почвы, температура почвы, пористость, органическое вещество, pH, НГМК, множественная регрессия, корреляция Пирсона, плотность популяции.
Annotatsiya. Ushbu tadqiqotda NKMK atrofidagi uch masofaviy zonada tuproqning asosiy fizik ko‘rsatkichlari namlik, harorat, g'ovaklilik, organik modda va pH bilan Collembola populyatsiyasi zichligi o‘rtasidagi miqdoriy bog'liqlik o‘rganildi. Namlik va organik modda zichlik bilan ijobiy korrelyatsiya (r = +0.86 va r = +0.88), harorat va pH esa salbiy korrelyatsiya (r = −0.79 va r = −0.71) ko‘rsatdi. Multipel regresiya R^2 = 0.87 ni ta’minladi.
Kalit so‘zlar: Collembola, tuproq namligi, tuproq harorati, g'ovaklilik, organik modda, pH, NKMK, multipel regresiya, Pearson korrelyatsiya, populyatsiya zichligi, fizik omillar.

Introduction.Collembola (Hexapoda: Entognatha) represent one of the most abundant and ecologically significant groups of soil mesofauna, with global densities often reaching tens of thousands of individuals per square meter in healthy ecosystems [1]. As obligate inhabitants of the soil matrix, their population dynamics are governed by a complex interplay of biotic and abiotic factors. While the relationship between Collembola and chemical soil contaminants particularly heavy metals has been extensively documented [2, 3], the independent effects of physical soil properties on Collembola populations have received comparatively less systematic attention, particularly in arid industrial contexts. Soil physical properties including moisture content, temperature, and porosity fundamentally determine the habitability of the soil environment for Collembola. Moisture governs cuticular water loss in these thin-cuticled arthropods, whose desiccation tolerance is limited compared to many other soil invertebrates [4]. Soil temperature controls metabolic rates, reproductive cycles, and phenological timing, with most Collembola species having narrow thermal optima between 15–22°C [5]. Porosity determines the availability of micro-habitat space for movement, egg deposition, and foraging, with compaction reducing usable pore space below critical thresholds [6].

In industrial zones such as the Navoi Mining and Metallurgical Combine (NMMC) area, heavy metal deposition is typically accompanied by significant physical soil degradation: increased surface compaction from traffic and industrial activity, elevated surface temperatures due to vegetation loss, reduced moisture retention from lower organic matter content, and altered soil structure from airborne dust deposition [7]. These physical changes may interact synergistically with chemical contamination to suppress Collembola populations, yet their independent contributions have not been quantified in Central Asian contexts.

The present study addresses this gap through a rigorous quantitative analysis of five physical soil parameters moisture, temperature at two depths, porosity, soil organic matter (SOM), and pH across a contamination gradient near NMMC. The specific objectives are: (i) to document zone-specific differences in physical soil parameters; (ii) to compute Pearson correlations between each physical parameter and Collembola density; (iii) to develop a multiple regression model incorporating all physical parameters; and (iv) to identify critical threshold values that can inform practical monitoring and remediation guidelines.

Literature review and methods

The relationship between soil moisture and Collembola was systematically established by Verhoef and Brussaard (1990), who demonstrated that moisture deficits below 8–10% DW cause rapid population decline through desiccation stress and behavioral avoidance [8]. Huhta and Hanninen (2001) showed that sustained temperatures above 25°C reduce Collembola activity and reproduction by 40–60%, particularly affecting epedaphic surface-dwelling species [9]. Lavelle and Spain (2001) established a critical porosity threshold of approximately 35% vol, below which Collembola locomotion and soil navigation become severely impaired [10]. Regarding soil organic matter, Ponge et al. (2003) demonstrated a near-linear positive relationship between SOM content and Collembola species richness in European forest soils, with SOM acting as both a direct food resource and an indirect modifier of moisture and temperature regimes [11]. The role of pH in regulating Collembola community composition was quantified by Van Straalen and Verhoef (1997), who developed a bioindicator system based on pH preferences of individual species, with most Collembola showing optimal performance between pH 6.0–7.5 [12]. In Central Asia, systematic studies linking physical soil properties to Collembola population dynamics are lacking, despite the relevance to rapidly expanding mining and industrial zones [13].

Field sampling was conducted from May to October 2024 at 27 monitoring stations in three distance zones from NMMC: Near Zone (0–2 km, n=9), Middle Zone (2–5 km, n=9), and Control Zone (>5 km, n=9). Physical parameters were measured at each station as follows: soil moisture was determined gravimetrically (105°C, 24 h drying) [14]; temperature was measured at 5 cm and 10 cm depths using a TFA-100 digital thermometer (three replicates per station, mean values used); porosity was calculated from bulk density and particle density measurements following Blake and Hartge (1986) [15]; SOM was determined by the Tyurin wet oxidation method; pH was measured electrometrically in 1:2.5 water suspension [16]. Collembola were extracted from 10×10 cm soil cores (0–10, 10-20, 20-30 cm depth) using Berlese-Tullgren apparatus (48 h), identified to species level under a binocular microscope (MBS-10) following Fjellberg (1998) and Potapov (2001) [17, 18]. Statistical analyses were performed in PAST v4.0 [19]: Pearson correlation matrix with Bonferroni correction, stepwise multiple linear regression with VIF < 2.0 multicollinearity screening, one-way ANOVA with Tukey HSD post-hoc test for inter-zonal comparisons. All physical measurements were averaged across the three replicates per station before statistical analysis.

Results and discussion

Table 1 presents the zone-specific means and standard errors for all physical parameters and Collembola density, together with ANOVA F-statistics. All parameters differed significantly across zones ($p < 0.001$ for all comparisons). The Near Zone exhibited the most extreme physical conditions: lowest moisture (8.2 ± 0.9%), highest temperature (28.6 ± 1.4°C at 5 cm), lowest porosity (31.4 ± 2.3%), and lowest SOM content (0.8 ± 0.1%). These conditions collectively represent a severely degraded physical soil environment far removed from the optima reported for Collembola in the literature.

Table 1. Soil physical parameters and Collembola density by zone (NMMC vicinity, 2025-2026)

Physical Parameter	Unit	Near Zone (0–2 km)	Middle Zone (2–5 km)	Control Zone (>5 km)	F-statistic	p-value
Soil moisture	% DW	8.2 ± 0.9	14.7 ± 1.3	22.4 ± 1.8	47.3	< 0.001
Temperature (5 cm)	°C	28.6 ± 1.4	24.3 ± 1.1	21.1 ± 0.9	38.9	< 0.001
Temperature (10 cm)	°C	25.4 ± 1.2	21.8 ± 0.9	18.7 ± 0.7	41.2	< 0.001
Porosity	% vol	31.4 ± 2.3	41.8 ± 3.1	52.6 ± 3.9	29.7	< 0.001
Soil organic matter	% DW	0.8 ± 0.1	1.9 ± 0.2	3.4 ± 0.3	62.1	< 0.001
pH (H_2O)	—	8.4 ± 0.2	7.8 ± 0.2	7.2 ± 0.1	34.5	< 0.001
Collembola density	ind/m²	26 ± 3.9	149 ± 12.1	343 ± 19.8	89.4	< 0.001

Note: DW = dry weight; vol = volumetric; n=9 per zone; values are mean ± SE; all parameters differ significantly across zones (p < 0.001, one-way ANOVA).

Multiple regression analysis (Table 2) identified organic matter as the strongest positive predictor of Collembola density (Beta = +0.73), followed by moisture (Beta = +0.61) and porosity (Beta = +0.48). Temperature was the strongest negative predictor (Beta = −0.54), with pH also showing a significant negative effect (Beta = −0.39). The combined model achieved $R^2 = 0.87$ ($F = 34.2$, $p < 0.001$), indicating that physical soil conditions collectively explain

87% of the variation in Collembola population density across the study area. VIF values ranged from 1.29 to 1.61, confirming the absence of problematic multicollinearity.

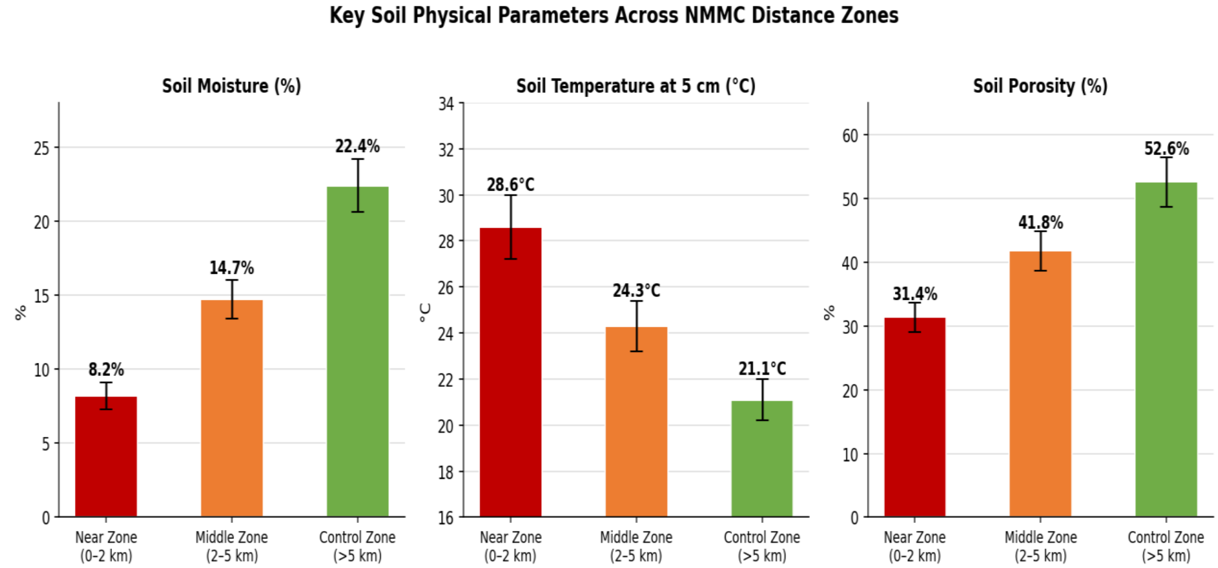

Figure 1. Comparison of three key soil physical parameters across NMMC distance zones. Error bars represent ± SE. All inter-zonal differences are statistically significant ($p < 0.001$).

Table 2. Multiple regression results: Collembola density as dependent variable

Independent variable	Beta coefficient	Standard error	t-statistic	p-value	VIF
Soil moisture (%)	+ 0.61	0.09	6.78	< 0.001	1.42
Temperature (°C)	− 0.54	0.08	− 6.75	< 0.001	1.38
Porosity (%)	+ 0.48	0.10	4.80	< 0.001	1.61
Organic matter (SOM)	+ 0.73	0.11	6.64	< 0.001	1.57
pH	− 0.39	0.09	− 4.33	0.002	1.29
Model R^2 (adjusted)	0.87	—	—	< 0.001	—

Note: Beta = standardized regression coefficient; VIF = variance inflation factor; R^2 = coefficient of determination (adjusted for degrees of freedom).

The Pearson correlation matrix (Table 3, Figure 2) reveals the structure of relationships among all measured variables. The strongest positive correlations with Collembola density were found for SOM ($r = +0.88$) and moisture ($r = +0.86$), while temperature ($r = −0.79$) and pH ($r = −0.71$) showed the strongest negative correlations. Notably, physical parameters themselves are strongly intercorrelated: moisture and SOM correlate at $r = +0.83$, reflecting their co-dependence in soil systems where organic matter increases water-holding capacity. Temperature and moisture are inversely related (r = −0.78), as higher evapotranspiration in bare, hot Near Zone soils depletes moisture reserves.

Table 3. Pearson correlation matrix: soil physical parameters and Collembola density

Parameter	Moisture	Temperature	Porosity	SOM	pH	Density
Moisture	1.00	−0.78**	+0.71**	+0.83**	−0.62**	+0.86**
Temperature	−0.78**	1.00	−0.69**	−0.74**	+0.58**	−0.79**
Porosity	+0.71**	−0.69**	1.00	+0.77**	−0.54*	+0.74**
SOM	+0.83**	−0.74**	+0.77**	1.00	−0.67**	+0.88**
pH	−0.62**	+0.58**	−0.54*	−0.67**	1.00	−0.71**
Density	+0.86**	−0.79**	+0.74**	+0.88**	−0.71**	1.00

*Note: ** p < 0.01; * p < 0.05 (Bonferroni-corrected); SOM = soil organic matter; DW = dry weight.*

The moisture threshold identified in the Near Zone (8.2% DW) is consistent with the critical minimum of approximately 8–10% DW reported by Verhoef and Brussaard (1990) for temperate species, suggesting that Collembola moisture requirements are conserved across climate zones [8]. The porosity value of 31.4% in the Near Zone falls below the 35% threshold identified by Lavelle and Spain (2001) as the minimum for unimpeded Collembola locomotion [10], which likely contributes to the low densities observed independent of chemical contamination. Table 4 synthesizes these findings into operational threshold values for monitoring applications.

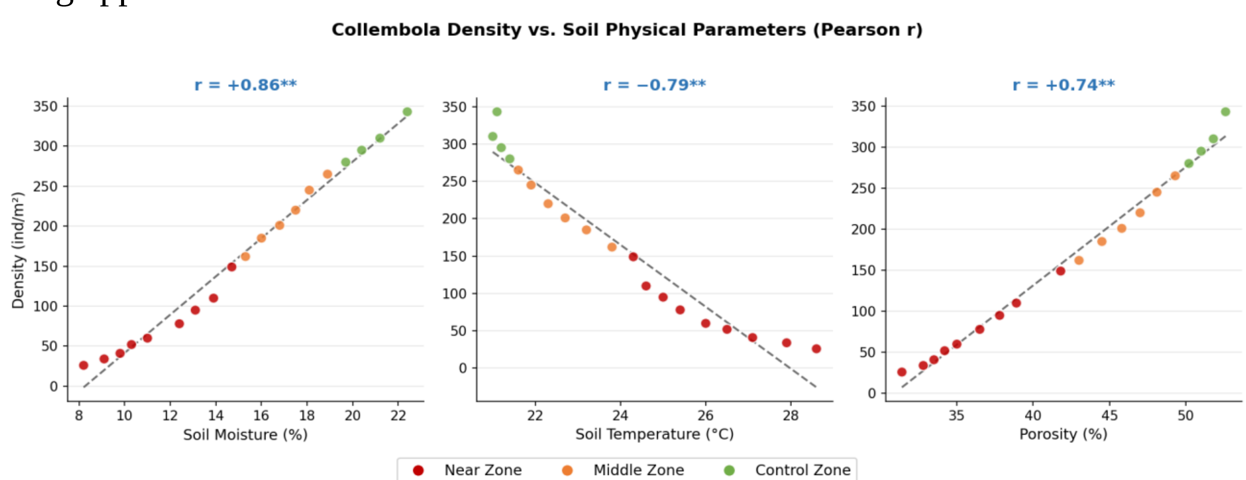

Figure 2. Scatter plots showing Collembola population density vs. soil moisture, temperature, and porosity. Pearson r values shown above each plot. Colors indicate distance zones: red = near, orange = middle, green = control.

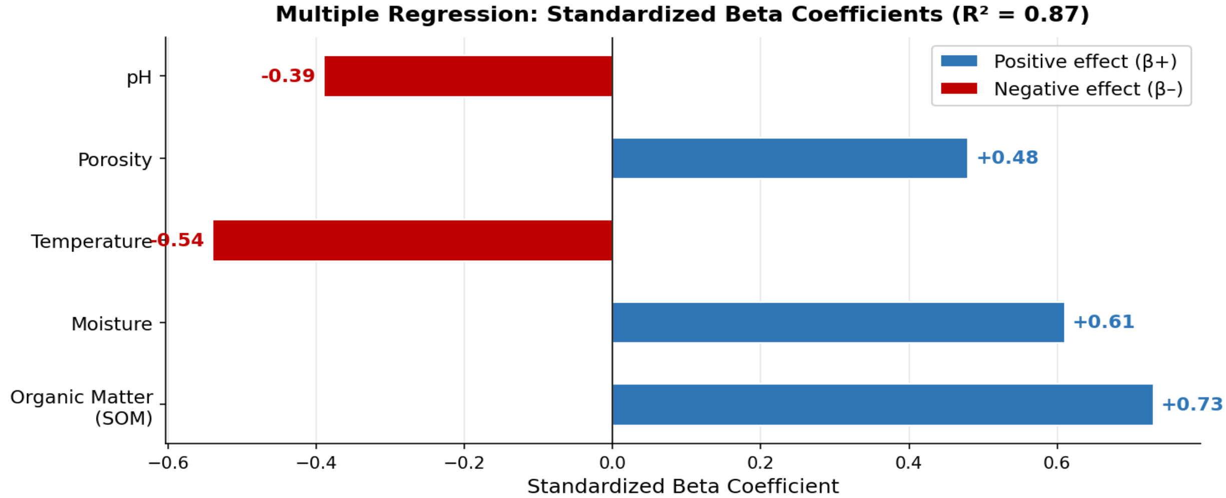

Figure 3. Standardized beta coefficients from multiple regression analysis. Organic matter and moisture are the strongest positive predictors; temperature and pH are the strongest negative predictors of Collembola density.

Table 4. Critical soil physical parameter thresholds and associated Collembola responses

Parameter	Critical threshold	Collembola response	Monitoring priority
Soil moisture	< 10% DW	Density drops below 50 ind/m²	High irrigation or shade cover needed
Temperature (5 cm)	> 27°C sustained	Epedaphic species disappear	High shade management
Porosity	< 35% vol	Euedaphic dominance, restricted mobility	Medium tillage assessment
Soil organic matter	< 1.0% DW	Sharp diversity decline	High organic amendment priority
pH	> 8.2	Hemiedaphic taxa decline	Medium acid amendment consideration

Note: Thresholds derived from field observations in this study combined with published ecotoxicological benchmarks; applicable to arid steppe soils of Uzbekistan.

These results have direct implications for remediation planning at NMMC and similar Central Asian industrial sites. Currently, remediation programs focus predominantly on chemical contaminant removal. However, even if heavy metal concentrations were reduced to background levels, the physical degradation documented in the Near Zone particularly low SOM, reduced porosity, and elevated temperature would likely prevent Collembola recolonization without simultaneous physical restoration including organic matter amendment, surface shading, and compaction relief. The physical and chemical remediation needs must therefore be addressed in parallel.

Conclusion

1. Soil physical parameters at NMMC differ significantly across distance zones. The Near Zone exhibits critically low moisture (8.2% DW), reduced porosity (31.4% vol), low SOM (0.8% DW), and elevated temperature (28.6°C), collectively creating conditions below established thresholds for normal Collembola functioning. Collembola density correlates most strongly with SOM ($r = +0.88$) and moisture ($r = +0.86$) among positive predictors, and with temperature ($r = -0.79$) and pH ($r = -0.71$) among negative predictors. These correlations are statistically significant ($p < 0.001$) and consistent with published ecophysiological benchmarks.

2.The multiple regression model incorporating all five physical parameters achieves $R^2 = 0.87$, demonstrating that physical soil conditions account for the majority of variance in Collembola population density across the NMMC gradient. Critical operational thresholds are proposed for each physical parameter. Effective ecological restoration of NMMC-affected soils requires simultaneous physical and chemical remediation organic matter amendment, compaction relief, and surface moisture management not chemical detoxification alone.

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