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Long-Term Drought Dynamics and Multi-Index Evaluation in the Aleppo Region, Northern Syria (1984–2024)

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Abstract
Understanding long-term drought dynamics in semi-arid regions is essential for improving water-resource management and enhancing climate-resilience strategies. This study investigates drought variability in the Aleppo region of northern Syria over a 41-year period (1984–2024) using an integrated multi-index approach. Annual climatic and environmental variables—including precipitation, temperature, wind speed, soil moisture, runoff, solar radiation, potential evapotranspiration (PET), and NDVI—were extracted from TerraClimate and Landsat datasets. Four drought indicators were computed: the SPI to assess precipitation-driven drought, the SPEI to capture heat-amplified drought, a modified PDI incorporating NDVI to represent agricultural and eco-hydrological drought, and the composite CDI to integrate multiple drought dimensions. Trend analysis using the Mann–Kendall test revealed significant increases in temperature, PET, and NDVI, indicating intensifying evaporative demand and evolving land-surface conditions. Results show a clear climatic transition: drought was predominantly rainfall-driven before 2000, while post-2000 droughts were increasingly controlled by rising temperatures and atmospheric demand. PDI recorded the highest drought frequency, highlighting persistent soil-moisture and vegetation stress, whereas SPEI exhibited the longest drought durations, reflecting prolonged climatic drought episodes. NDVI strongly mirrored drought fluctuations, with marked declines during severe drought years (1999, 2008, 2010, 2017, 2021). Overall, the multi-index assessment demonstrates that Aleppo is experiencing more complex and persistent drought conditions driven by both climatic warming and environmental pressures. These findings underscore the need for adaptive agricultural strategies, improved water-resource planning, and enhanced early-warning systems to mitigate future drought impacts.

Keywords: Drought, Aleppo, Semi-Arid Regions, Climate Variability, Terra Climate, NDVI, SPI, SPEI, PDI, CDI, Mann–Kendall Test, Remote Sensing

Introduction
Drought is one of the most critical environmental hazards affecting dry and semi-arid regions worldwide, with profound impacts on water resources, agriculture, ecosystems, and socio-economic stability. In the Middle East, drought has intensified over recent decades due to rising temperatures, declining water availability, and increasing climatic variability. The Eastern Mediterranean, in particular, has been identified as a climate-change hotspot, experiencing accelerated warming and more frequent extreme events [1]. These climatic pressures have heightened the vulnerability of communities and ecosystems, especially in regions already facing water scarcity. Aleppo, located in northern Syria, represents one of the most drought-sensitive areas in the Levant. The region is characterized by a semi-arid Mediterranean climate, marked by highly variable rainfall, long dry seasons, and increasing exposure to heat extremes. Agriculture in Aleppo relies heavily on seasonal precipitation and shallow groundwater, making it particularly susceptible to rainfall deficits and rising evaporative demand. Over the past four decades, Aleppo has experienced recurrent drought episodes that have contributed to land degradation, reduced crop yields, and increased pressure on rural livelihoods. Assessing drought in such environments requires robust and multi-dimensional indicators capable of capturing the complex interactions between climate, soil, and vegetation. Traditional meteorological indicators such as the SPI quantify drought based solely on precipitation anomalies, while more advanced climatic indices like the SPEI incorporate temperature and potential evapotranspiration, allowing for the detection of heat-amplified drought. Agricultural and eco-hydrological

conditions, however, are better represented by indices such as the PDI, which integrates soil moisture, vegetation stress, and hydrological components. Composite indicators like the CDI provide a more holistic assessment by combining multiple drought dimensions into a single metric. Despite the importance of drought monitoring in Syria, few studies have conducted long-term, multi-index drought assessments for Aleppo using integrated climatic and environmental datasets. Existing research has often focused on broader regional patterns or short-term drought events, leaving a gap in understanding the temporal evolution, severity, and multi-dimensional nature of drought in this specific region. Addressing this gap is essential for improving drought preparedness, supporting agricultural planning, and informing sustainable water-resource management. This study aims to provide a comprehensive assessment of drought in Aleppo from 1984 to 2024 using a suite of meteorological, climatic, agricultural, and composite drought indicators. By analyzing long-term trends, drought characteristics, and vegetation responses, the study offers new insights into the shifting nature of drought in northern Syria and highlights the increasing influence of temperature-driven and agricultural drought processes. Accordingly, this study addresses the following research question: Has the dominant driver of drought in the Aleppo region shifted from precipitation deficits to temperature-induced evaporative demand over the past four decades (1984–2024)?

Materials and Methods

Study Site and Data Collection

This study was carried out at the Aleppo meteorological station in northern Syria (36.20°N, 37.15°E), a semi-arid region characterized by hot, dry summers and cool winters. Climatic and environmental datasets were obtained from the Climate Engine platform. Annual variables—including precipitation, temperature, wind speed, soil moisture, runoff, solar radiation, and potential evapotranspiration (PET)—were extracted from the TerraClimate dataset for the period 1984–2024. Annual data were selected to reduce short-term climatic noise and ensure consistency with the temporal scale of the drought indices. Vegetation dynamics were evaluated using annual Normalized Difference Vegetation Index (NDVI) values derived from Landsat 5, 7, 8, and 9 imageries, processed using surface reflectance products to minimize atmospheric effects. All datasets were extracted at the exact coordinates of the Aleppo meteorological station to ensure spatial uniformity.

Climatic and Environmental Variables

A set of key climatic and environmental variables was selected to describe the hydro-climatic conditions of Aleppo. The annual variables included precipitation (mm), mean air temperature (°C), wind speed ($m\ s^{-1}$), soil moisture (mm), surface runoff (mm), solar radiation ($W\ m^{-2}$), NDVI, and PET ($mm\ year^{-1}$). PET was calculated using the Thornthwaite method, which provides reliable estimates of atmospheric evaporative demand—an essential driver of drought severity under warming conditions.

Drought Indices Calculation

Standardized Precipitation Index (SPI)

SPI is calculated by fitting a gamma distribution to the annual precipitation time series (1984–2024). The cumulative probability is then transformed to a standard normal distribution (mean = 0, standard deviation = 1)

$$SPI = \frac{X - \mu}{\sigma}$$

where X is annual precipitation, μ is the long-term mean, and σ is the standard deviation.

Standardized Precipitation–Evapotranspiration Index (SPEI)

SPEI incorporates both precipitation and atmospheric evaporative demand using the climatic water balance

$$D = P - PET$$

where P is annual precipitation and PET is annual potential evapotranspiration. The water-balance series is fitted to a log-logistic distribution, and SPEI is standardized similarly to SPI.

Palmer Drought Index (PDI)

A modified Palmer Drought Index (PDI) was developed to represent agricultural and eco-hydrological drought. It integrates soil moisture (SM), runoff (R) and satellite-derived NDVI by standardizing each variable separately.

$$SMstd = \frac{SM - \mu SM}{\sigma SM}$$

$$Rstd = \frac{R - \mu R}{\sigma R}$$

$$NDVIstd = \frac{NDVI - \mu NDVI}{\sigma NDVI}$$

Finally, the modified PDI was calculated as:

$$PDI = \frac{Z - \mu Z}{\sigma Z}$$

Composite Drought Index (CDI)

Composite Drought Index (CDI):

The Composite Drought Index (CDI) represents an integrated drought metric that combines the four previously computed indicators—meteorological (SPI), climatic (SPEI), agricultural and eco hydrological (PDI), —into a unified standardized measure. The CDI is designed to capture multi dimensional drought behavior by merging precipitation deficits, temperature driven evaporative demand, soil moisture stress, vegetation response, and hydrological conditions into a single composite signal. Each drought index is first standardized, then averaged to produce a combined drought score:

$$CDI = \frac{SPI + SPEI + PDI}{3}$$

Finally, the composite value is standardized using its long term mean and standard deviation:

$$CDI = \frac{Z - \mu_Z}{\sigma_Z}$$

where Z is the combined multi index value, μZ is the long term mean, and σZ is the standard deviation. This formulation ensures that CDI reflects the dominant drought processes in any given year while preserving the relative contribution of each drought dimension.

Drought Classification Criteria

Drought severity was classified using standard threshold values applied to all drought indices. Mild drought corresponds to values between 0 and −0.99, moderate drought between −1.0 and −1.49, severe drought between −1.5 and −1.99, and extreme drought at values ≤ −2.0.

Statistical analysis and trend detection

Statistical analyses were conducted to evaluate the temporal behavior, variability, and significance of climatic, environmental, and drought-related variables over the 1984–2024 period. Descriptive statistics—including mean, standard deviation, minimum, maximum, and quartiles—were computed to summarize the central tendency and dispersion of each variable. Long-term trends were assessed using the non-parametric Mann–Kendall (MK) test to detect monotonic increases or decreases in the time series, while Sen's slope estimator quantified the magnitude of these trends. All analyses were performed using annual time-series data to ensure consistency with the temporal resolution of the drought indices and to minimize short-term climatic fluctuations. This analytical framework enabled a robust evaluation of climatic variability and drought dynamics in the Aleppo region.

Drought frequency was calculated as the number of years with index values below −1.0 (drought conditions). Return period (RP) was calculated using the classical empirical formula

$$RP = \frac{N + 1}{nd + 1}$$

where N is the total number of years (41) and nd is the number of drought years (index value < -1.0). This formulation provides an unbiased estimate of the expected recurrence interval under the assumption of stationarity. For comparison, the simple frequency ratio (N / nd) is also reported All statistical analyses, trend detection procedures, and drought index computations were executed using Python-based libraries (including pandas, numpy, scipy, matplotlib, and seaborn) within a cloud-based computational environment to ensure reproducibility."

Results and Discussion

Climatic and Environmental Variability

The descriptive statistics (Table 1) reveal substantial interannual variability in precipitation, a hallmark of semi-arid Mediterranean climates where rainfall is highly episodic and driven by synoptic disturbances [2,3]. In contrast, temperature exhibits a narrower range, yet its long-term increase contributes significantly to rising atmospheric evaporative demand. This pattern is consistent with the Eastern Mediterranean being recognized as a climate-change hotspot [1].

Vegetation productivity (NDVI) shows moderate variability, reflecting its sensitivity to rainfall pulses and soil-moisture availability. Such behavior aligns with global dryland studies demonstrating that vegetation responds rapidly to rainfall anomalies [4,5].

Statistic	Precip	Temp	Wind	Soil Moisture	PET	Solar	NDVI	Runoff
Mean	308.39	18.45	2.34	13.33	1151.53	208.16	0.086	47.14
Std	78.88	0.81	0.12	3.62	83.97	3.21	0.022	44.67
Min	154	16.49	1.97	3.18	989.60	199.26	0.057	7
25%	250.25	17.94	2.28	11.23	1091.28	206.38	0.069	15
50%	305.50	18.42	2.34	13.80	1147.98	208.65	0.080	34
75%	342.25	18.94	2.41	15.24	1211.49	210.44	0.102	67
Max	501	19.89	2.61	20.38	1345.64	214.35	0.146	187

Table 1: Descriptive Statistics of Climatic and Environmental Variables (1984–2024)

Long-Term Trends and Drivers

Trend analysis using the Mann–Kendall test (Table 2) indicates statistically significant increases in temperature, wind speed, PET, and NDVI. The warming trend is consistent with the IPCC Sixth Assessment Report, which identifies the Eastern Mediterranean as one of the fastest-warming regions globally [6]. The increase in PET suggests intensifying evaporative stress, which can exacerbate drought even in years with near-normal rainfall [7]. Interestingly, NDVI also shows a significant upward trend despite increasing aridity. This pattern may be attributed to land-use changes, agricultural intensification, and expansion of irrigated areas—processes documented in northern Syria and neighboring regions [8,9].

Variable	Trend	p value	Tau	z value	Slope	Statistical Interpretation
Precipitation	No trend	1	−0.00116	0	0	Not significant
Temperature	Increasing	6.36×10^{-9}	0.63171	5.8069	0.053	Highly significant
Wind speed	Increasing	8.44×10^{-5}	0.42805	3.9314	0.00498	Significant
Solar radiation	No trend	0.64515	0.05122	0.4605	0.02183	Not significant
PET	Increasing	1.23×10^{-9}	0.66098	6.0765	5.71299	Highly significant
Soil moisture	No trend	0.14736	−0.15854	−1.4489	−0.07275	Not significant
NDVI	Increasing	3.02×10^{-7}	0.55732	5.1221	0.00141	Highly significant
Runoff	No trend	0.85728	0.02073	0.1798	0.05689	Not significant

Table 2: Mann–Kendall Trend Analysis for Climatic and Environmental Variables.

Temporal Dynamics of Drought Indices

Fig 1 illustrates the temporal evolution of SPI, SPEI, PDI, and CDI from 1984 to 2024.The indices show synchronized drought and wet periods, but with distinct sensitivities: SPI responds solely to precipitation deficits. SPEI integrates temperature and PET, capturing heat-amplified drought ([7]. PDI reflects agricultural and hydrological drought by incorporating soil moisture, vegetation stress, and runoff.

CDI provides a composite view of multi-dimensional drought [10]. These differences highlight the importance of using multiple indices to capture the full spectrum of drought processes in semi-arid environments.

Drought Classification

The drought-classification results (Table 3) show that "normal" conditions dominate the record, followed by mild drought. Moderate and severe droughts occur intermittently, consistent with the episodic nature of drought in the Levant [11].

SPI and SPEI detect more mild and moderate drought years, while PDI identifies more frequent agricultural drought due to its sensitivity to soil-moisture fluctuations. CDI provides a more integrated classification, capturing both meteorological and eco-hydrological stress.

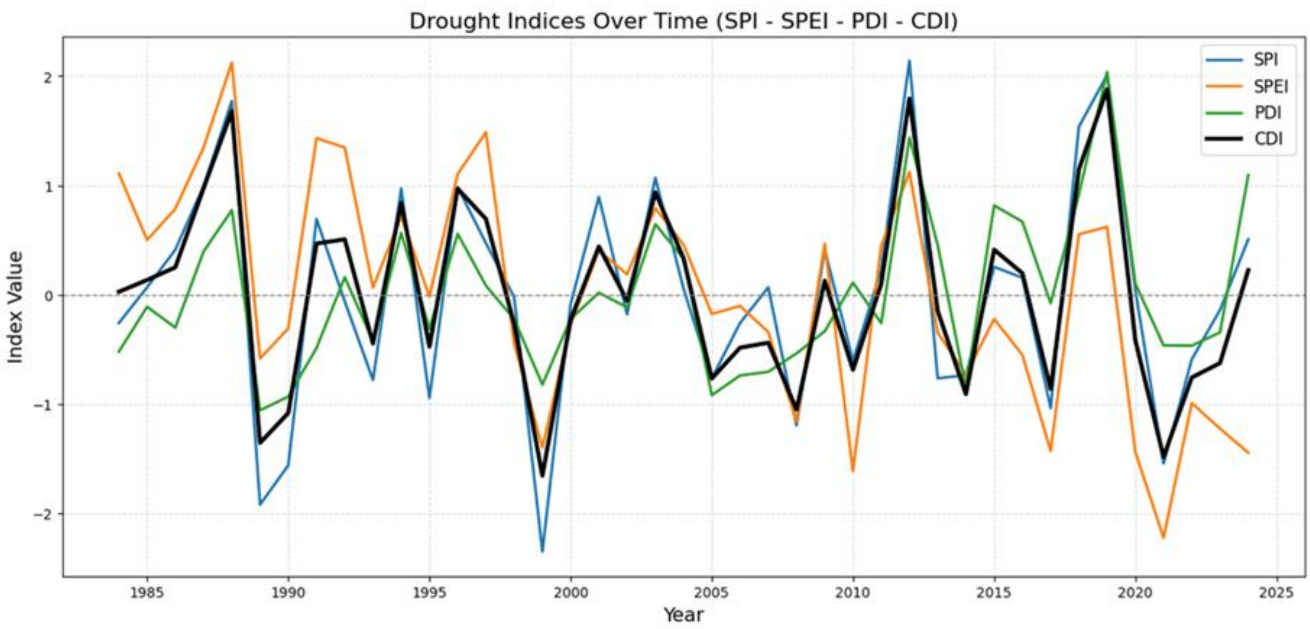

Figure 1: Temporal Evolution of SPI, SPEI, PDI, and CDI in Aleppo, Northern Syria (1984–2024)

	SPI	SPEI	PDI	CDI
extreme	1	1	-	-
mild	14	13	22	15
severe	3	1	-	1
moderate	2	6	1	4

Table 3: Drought Classification Based on SPI, SPEI, PDI, and CDI

Dominant Drought Driver Per Year

The "Most Dry Index" analysis (Table 4) reveals a clear temporal shift in drought drivers: Before 2000 → SPI dominates → drought was primarily rainfall-driven. After 2000 → SPEI dominates → drought became temperature-driven. This transition reflects the increasing role of warming and evaporative demand in shaping drought severity. Similar transitions have been reported in global drylands experiencing accelerated warming [12,13].

year	SPI	SPEI	PDI	CDI	Most _Dry_ Index
1989	-1.91678	-0.58142	-1.05496	-1.35276	SPI
1990	-1.55831	-0.30655	-0.92995	-1.0801	SPI
1999	-2.34641	-1.39619	-0.82088	-1.65248	SPI
2008	-1.19264	-1.15917	-0.53488	-1.04812	SPI
2010	-0.60308	-1.61128	0.111576	-0.68426	SPEI
2017	-1.03492	-1.42616	-0.07634	-0.85894	SPEI
2020	0.043522	-1.43546	0.10404	-0.4138	SPEI
2021	-1.54108	-2.21986	-0.46152	-1.48188	SPEI
2023	-0.13746	-1.22271	-0.34289	-0.62311	SPEI
2024	0.508103	-1.44222	1.094895	0.226383	SPEI

Table 4: Most Dry Index Per Drought Year (1989–2024)

Drought Characteristics: Severity, Duration, Frequency, Return Period

The drought-characteristics summary (Table 5) provides deeper insight: PDI records the highest number of drought years (23), reflecting persistent agricultural stress. SPEI shows the highest average severity, confirming the intensification of heat-driven drought. Return periods are shortest for PDI (1.78 years), indicating frequent soil-moisture stress. Durations are longest for SPEI (up to 5 years), highlighting prolonged climatic drought episodes. These patterns demonstrate that meteorological droughts are intermittent, while agricultural and climatic droughts can be more persistent—consistent with findings by [14].

Indicator	Drought Years	Avg_Severity	Return Period (years)	Max Duration (years)	Mean Duration (years)
SPI	20	-0.79	2.05	3	1.6
SPEI	21	-0.81	1.95	5	2.9
PDI	23	-0.49	1.78	5	1.9
CDI	20	-0.71	2.05	4	2

Table 5: Drought Characteristics (Severity, Duration, Frequency, Return Period)

Comparative Performance of Drought Indices

A comparative assessment (Table 6) show: SPI is optimal for detecting rainfall-driven drought. SPEI is superior for capturing heat-amplified drought. PDI excels in identifying agricultural and hydrological drought. CDI provides the most holistic assessment of multi-dimensional drought. This multi-index approach aligns with recommendations by Mishra and Singh (2010), who emphasize the need for integrated drought assessment frameworks in complex environments [15].

Drought Index	Meteorological	Climatic	Agricultural	Hydrological	Overall
SPI	Very high	Not sensitive	Low	Very low	Best for rainfall drought
SPEI	High	Very high	Moderate	Low	Best for heat driven drought
PDI	Moderate	Low	Very high	High	Best for agricultural drought
CDI	High	High	High	High	Best integrated indicator

Table 6: Comparative Performance of Drought Indices Across Drought Dimensions

Linking Drought to Vegetation and Soil Moisture

NDVI responds strongly to drought conditions, particularly those captured by PDI and CDI. Years with severe drought (1999, 2008, 2010, 2017, 2021) show clear declines in vegetation productivity. Conversely, NDVI increases in years with above-average rainfall (1988, 1996, 2003, 2012, 2018, 2019), confirming that vegetation in semi-arid regions is primarily rainfall-controlled [4,5].

Integrated Environmental–Climatic Interpretation

The combined results indicate that the region is undergoing a climatic transition: From rainfall-driven drought in earlier decades to heat-driven drought in recent years This transition is accompanied by: Increased evaporative demand More persistent agricultural drought Greater vegetation sensitivity. Land-use changes that partially offset climatic stress
Overall, the findings reinforce the classification of the Eastern Mediterranean as a climate-change hotspot experiencing intensifying drought conditions [1,6].

The Greening Paradox: Increasing NDVI Under Drying Conditions

A notable finding of this study is the statistically significant increasing trend in NDVI ($p < 3.02 \times 10^{-7}$, Table 2), despite concurrent increases in temperature, PET, and drought frequency. This apparent paradox requires careful interpretation, particularly when examined through the lens of the four drought indices used in this study. Relationship with drought indices: Visual comparison of NDVI trajectories with the four drought indices (Fig 1) reveals that NDVI declines are most pronounced during years when PDI and CDI indicate severe agricultural drought. The severe drought years (1999, 2008, 2010, 2017, 2021) identified in Table 4 correspond with marked negative NDVI anomalies, confirming that vegetation responds strongly to soil moisture deficits captured by PDI. In contrast, SPI-only drought events (e.g., 1989, 1990) showed weaker vegetation responses, suggesting that meteorological drought without accompanying soil moisture stress does not necessarily reduce NDVI. Explaining the paradox: Several non-climatic factors may explain the increasing NDVI trend despite more frequent drought detected by all four indices. First, agricultural intensification and expansion of irrigated areas in the Aleppo region during wetter periods (e.g., 1990s and early 2000s) may have increased baseline vegetation cover, which persisted even during subsequent dry years [8]. Second, shifts in cropping patterns toward more drought-tolerant or deeper-rooted species could maintain greenness under water stress. Third, CO_2 fertilization effects—well documented in global drylands—can enhance water-use efficiency and promote vegetation growth even under reduced rainfall [16,17]. Important caveat: The NDVI increase does not indicate improved ecosystem health. The strong negative anomalies during severe drought years (1999, 2008, 2010, 2017, 2021) demonstrate that vegetation remains highly vulnerable to climatic extremes. The long-term positive trend may partly reflect land-use changes rather than genuine ecological recovery. This distinction is critical for policymakers: a "greener" landscape observed from remote sensing does not necessarily imply greater drought resilience, especially when PDI continues to show frequent agricultural drought (23 years, return period 1.78 years; Table 5).

Conclusion

This study provides a comprehensive, multi-dimensional assessment of drought conditions in Aleppo over the period 1984–2024 using a suite of meteorological, climatic, agricultural, and composite drought indicators. The results reveal a clear climatic transition in the region: drought was predominantly rainfall-driven in earlier decades, as captured by the SPI, but has increasingly become temperature-driven in recent years, as indicated by the stronger and more persistent signals in the SPEI. This shift reflects the intensifying influence of warming and rising evaporative demand on drought severity in semi-arid Mediterranean environments. Agricultural and eco-hydrological droughts, represented by the PDI, were found to be more frequent and persistent than meteorological droughts, highlighting the vulnerability of soil moisture and vegetation to prolonged dry conditions. The composite CDI further demonstrated the interconnected nature of drought processes by integrating climatic, hydrological, and ecological stressors into a unified signal. Together, these indicators show that Aleppo is experiencing increasingly complex drought dynamics driven by both climatic warming and environmental degradation. Vegetation responses, assessed through NDVI, confirmed the strong coupling between rainfall variability and ecosystem productivity. Years of severe drought corresponded to marked declines in vegetation health, while wet years produced rapid recovery—underscoring the sensitivity of Aleppo's agro-ecosystems to climatic fluctuations. These findings emphasize the need for adaptive agricultural strategies, improved water-resource management, and long-term monitoring systems capable of capturing multi-dimensional drought behavior. Overall, the study highlights the growing importance of integrating multiple drought indices to fully understand drought evolution in dryland regions. By documenting long-term trends, identifying dominant drought drivers, and linking climatic stress to vegetation response, this research provides essential insights for policymakers, land-use planners, and environmental managers working to enhance drought resilience in northern Syria. Strengthening early-warning systems, promoting sustainable land management, and improving irrigation efficiency will be critical for mitigating the impacts of future droughts in Aleppo's increasingly fragile climate.

Declarations

Ethics Approval and Consent to Participate: Not applicable. This study does not involve human participants, animals, or sensitive data.

Consent for Publication: Not applicable.

Availability of Data and Materials: The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request. TerraClimate and Landsat datasets are publicly accessible.

Competing Interests: The author declares that there are no competing interests.

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Author's Contributions: Conceptualization, data collection, methodology, analysis, visualization, writing – original draft, and writing – review & editing.

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