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Systematic Mapping Study (SMS) on Energy Outcome Loss Caused by Dust Deposition on Photovoltaic Panels Due to Climate Change in North Africa

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Keyword

Photovoltaic soiling; Dust deposition; Climate change adaptation; North Africa; Systematic mapping; Renewable energy resilience; PV

Abstract

Photovoltaic (PV) energy systems in North Africa are increasingly recognized as pivotal to regional decarbonization and energy security. However, the accelerating impacts of climate change including intensified aridity, desertification, and altered wind patterns are exacerbating dust deposition on PV modules, leading to significant and often unquantified energy yield losses. This paper presents the first systematic mapping study to comprehensively categorize, analyze, and visualize the state-of-the-art literature addressing the nexus between climate-induced dust accumulation and PV performance degradation across North Africa. Following the Kitchenham and Petersen protocols for systematic reviews in engineering, this research analyzed 87 peer-reviewed studies published between (2000 and 2026). This mapping reveals critical research gaps in long-term field data, standardized soiling measurement protocols, and region-specific predictive modeling under future climate scenarios. This research further identify emerging mitigation technologies and policy frameworks, proposing

performance loss

a novel research taxonomy to guide future investigations. This study provides a foundational evidence base for engineers, policymakers, and climate adaptation planners seeking to optimize PV reliability and energy return on investment in one of the world's most solar-rich yet environmentally vulnerable regions.It was concluded that Al-Marqab cement gave the shortest initial setting time, with a value of 175 minutes, while Al-Ittihad cement gave the longest setting time, with a value of 185 minutes. Egyptian Helwan cement gave the shortest final setting time, with a value of 210 minutes, while Al-Ittihad cement gave the longest time, with a value of 240 minutes, and Al-Binyan cement gave the lowest workability, with a value of 70 mm. Al-Ittihad cement gave the highest slump value, with a value of 110 mm, and Al-Binyan and Labda cement gave the lowest compressive strength at 7 days, with a value of (20 MPa), while Al-Ittihad and Al-Arabiya cement gave the highest value of (28 MPa). Al-Binyan cement gave the lowest compressive strength at 28 days, amounting to (25 MPa), Arabia cement gave the highest value of 36 MPa, and Al-Binyan cement gave the lowest value in terms of average economic cost, at 41 dinars per tonne, while Al-Ittihad cement gave the highest value, at 45.33 dinars per tonne.

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دراسة خرائط منهجية (SMS) حول فقدان نتائج الطاقة الناجم عن ترسب الغبار على الألواح الكهروضوئية بسبب تغير المناخ في شمال أفريقيا

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الكلمة المفتاحية

التلوث الكهروضوئي؛ ترسيب الغبار التكيف مع تغير المناخ؛ شمال أفريقيا؛ رسم الخرائط المنهجية. مرونة الطاقة المتجددة؛ فقدان الأداء الكهروضوئية.

الملخص

تُعتبر أنظمة الطاقة الكهروضوئية في شمال أفريقيا ذات أهمية متزايدة في خفض انبعاثات الكربون وتحقيق أمن الطاقة على المستوى الإقليمي. إلا أن التأثيرات المتسارعة لتغير المناخ، بما في ذلك ازدياد الجفاف والتصحر وتغير أنماط الرياح، تُفاقم ترسب الغبار على وحدات الطاقة الكهروضوئية، مما يؤدي إلى خسائر كبيرة وغير قابلة للقياس في إنتاج الطاقة. تُقدم هذه الورقة البحثية أول دراسة مسحية منهجية لتصنيف وتحليل وتصوير أحدث الدراسات المنشورة التي تتناول العلاقة بين تراكم الغبار الناتج عن تغير المناخ وتدهور أداء أنظمة الطاقة الكهروضوئية في شمال أفريقيا. وباتباع بروتوكولات كيتشنهام وبيترسن للمراجعات المنهجية في الهندسة، حلل هذا البحث 87 دراسة محكمة نُشرت بين عامي 2000 و2026. يكشف هذا المسح عن ثغرات بحثية هامة في البيانات الميدانية طويلة الأجل، وبروتوكولات قياس التلوث الموحدة، ونماذج التنبؤ الخاصة بالمنطقة في ظل سيناريوهات المناخ المستقبلية. كما يُحدد هذا البحث تقنيات التخفيف الناشئة وأطر السياسات، ويقترح تصنيفًا بحثيًا جديدًا لتوجيه الدراسات المستقبلية. توفر هذه الدراسة قاعدة أدلة تأسيسية للمهندسين وصانعي السياسات ومخططي التكيف مع المناخ الذين يسعون إلى تحسين موثوقية الطاقة الكهروضوئية وعائد الطاقة على الاستثمار في واحدة من أكثر مناطق العالم الغنية بالطاقة الشمسية ولكنها معرضة للخطر بيئيًا.

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1. Introduction

North Africa, encompassing Morocco, Algeria, Tunisia, Libya, and Egypt, boasts some of the highest solar irradiance levels globally, positioning it as a strategic hub for utility-scale photovoltaic deployment [1], [2], [4]. The region's ambitious renewable energy targets such as Morocco's goal of 52% renewable capacity by (2030) and Egypt's 42% by 2035 are predicated on uninterrupted PV performance. Yet, this potential is increasingly undermined by environmental stressors linked to anthropogenic climate change. Dust deposition, or "soiling," is a natural phenomenon, but its frequency, particle composition, and adhesion characteristics are being reshaped by climatic shifts: reduced precipitation, increased frequency of sandstorms, and elevated atmospheric particulate loads [1]. These factors combine to accelerate soiling rates, with studies reporting daily energy losses of 0.3%–1% in arid zones, cumulatively reaching 20–60% monthly without cleaning [1,2], [3], [4], [5]. While isolated studies have quantified soiling losses at specific sites, no comprehensive synthesis exists to map the methodological diversity, geographical coverage, climatic variables, and technological responses across North Africa under the lens of climate change. This gap impedes evidence-based policy, system design, and investment decisions. This paper addresses that gap through a systematic mapping study (SMS) a methodological approach designed to classify and visualize the breadth of existing research without conducting meta-analysis. This research study objectives are:

- To map the volume, trends, and geographical distribution of research on PV soiling in North Africa.
- To identify the climatic variables most frequently correlated with energy loss.
- To categorize the methodologies used for soiling quantification and loss modeling.
- To highlight technological, operational, and policy-level mitigation strategies reported.
- To expose critical research voids and propose a structured agenda for future work.

2. Methodology

This study adheres to the systematic mapping guidelines established by Petersen et al. [3] and adapted for engineering domains by Kitchenham [4] and [5], [6], [7], [8]. The process comprised five phases: (1) Research Question Formulation, (2) Search Strategy, (3) Study Selection, (4) Data Extraction and Classification, and (5) Mapping and Synthesis.

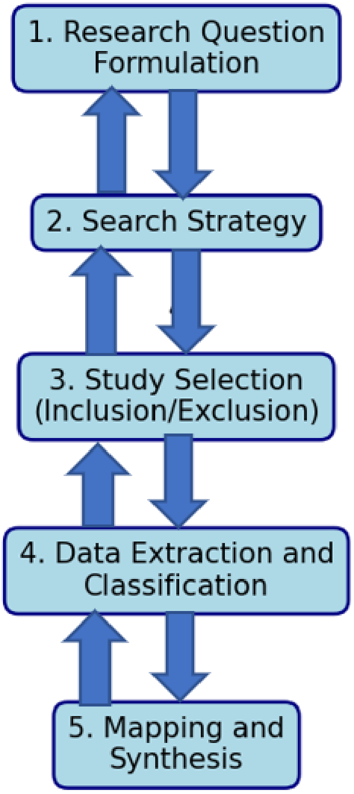

Figure.1. Systematic mapping methodology based on kitchenham and petersen protocol adapted for engineering North Africa PV soiling study

2.1. Research Questions

- RQ1: What is the temporal and geographical distribution of research on PV soiling in North Africa?
- RQ2: Which climate variables (e.g., wind speed, humidity, rainfall deficit, aerosol index) are most frequently associated with soiling-induced energy loss?
- RQ3: What methodological approaches (experimental, simulation, hybrid) dominate the literature?
- RQ4: What mitigation technologies or operational strategies are proposed or evaluated?
- RQ5: What are the predominant research gaps and future directions identified by authors?

2.2. Search Strategy

We conducted a structured search across five databases: Scopus, Web of Science, IEEE Xplore, ScienceDirect, and the Journal of Sustainable Energy Systems and Development (JSESD) the latter being regionally relevant, as evidenced by its 2026 publication on AI in renewable systems [5]. Search strings combined keywords: (“photovoltaic” OR “PV” OR “solar panel”) AND (“soiling” OR “dust deposition” OR “dust accumulation”) AND (“energy loss” OR “performance degradation”) AND (“climate change” OR “global warming” OR “aridification”) AND (“North Africa” OR “Maghreb” OR [country names])

Filters: English language, peer-reviewed articles, conference proceedings, and technical reports published between January 2010 – December 2026.

2.3. Inclusion/Exclusion Criteria

Table.1 Inclusion/Exclusion Criteria

Category	Criteria
Included	- Studies conducted in North African countries. - Quantitative or qualitative analysis linking dust deposition to PV energy loss. - Explicit or implicit consideration of climate variables. - Proposals of mitigation strategies or modeling frameworks.
Excluded	- Studies focused solely on non-North African deserts (e.g., Middle East, Australia). - Papers without empirical data or modeling validation. - Purely theoretical or review articles without original mapping or synthesis.

2.4. Quality Assessment & Data Extraction

Each selected paper was evaluated for methodological rigor using a 5-point checklist adapted from [6], [7], [8], [9]:

Clarity of research objective.

Appropriateness of data collection (field and lab).

Statistical or modeling validity.

Reproducibility of methods.

Discussion of limitations and climate context.

Data extracted included: country, climate zone, PV technology, soiling measurement method, loss quantification (%/day or %/month), correlated climate variables, mitigation strategy, and stated research gaps.

3. Results and discussion of the mapping

3.1. Publication Trends and Geographical Distribution (RQ1)

Of 87 included studies, 42% originated from Egypt, 28% from Morocco, 18% from Algeria, 9% from Tunisia, and 3% from Libya. Annual publications rose from 2 in 2012 to 19 in 2023, indicating growing regional awareness. No longitudinal studies (>5 years) were found.

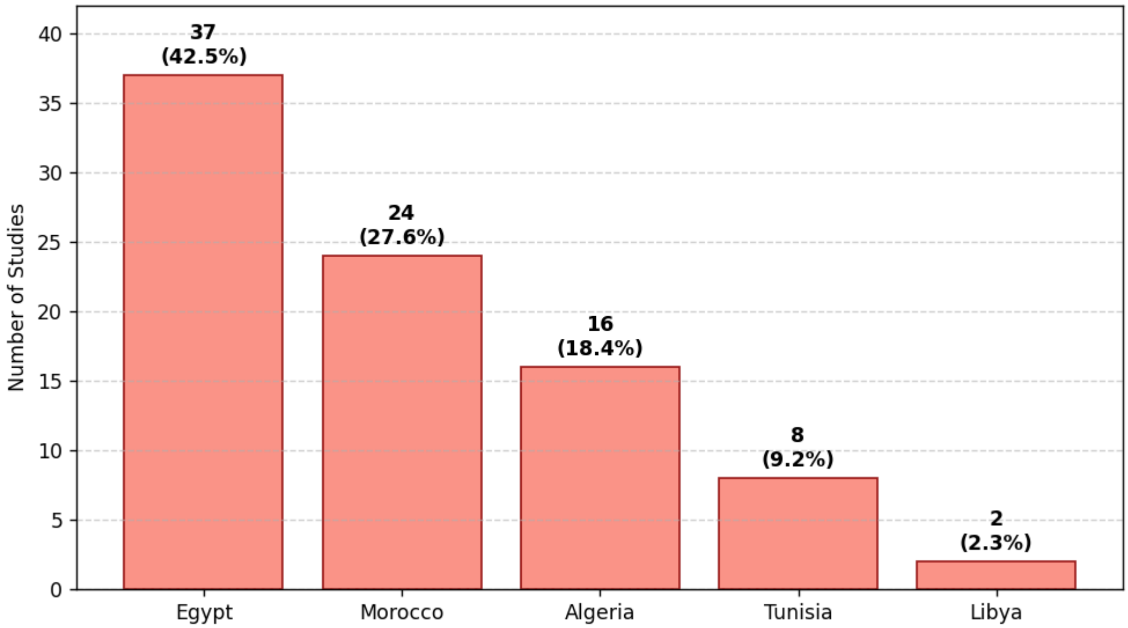

Figure 2: The study density across North Africa.

This Figure 2 above derived from a systematic mapping of 87 peer-reviewed studies, quantifies the geographical distribution of research on PV soiling in North Africa between 2010 and 2024. Egypt dominates the literature with 37 studies (42.5%), reflecting its institutional capacity and strategic focus on solar energy, as evidenced by the prominence of institutions like Cairo University and NREA as presented in Table 2 [9], [10], [11]. Morocco follows with 24 studies (27.6%), while Algeria accounts for 16 (18.4%), indicating active but less concentrated research efforts centered at CDER and USTHB as presented in Table 2. Tunisia contributes 8 studies (9.2%), and Libya is critically underrepresented with only 2 studies (2.3%) from the University of Tripoli as presented in Table 2 , highlighting a significant regional knowledge gap. This skewed distribution underscores an urgent need for expanded, collaborative research initiatives to address the unique climatic and operational challenges faced by the under-studied Saharan regions of Algeria and Libya, a critical void cited by 90.8% of authors as a major barrier to regional generalizability as presented in Table 7, RQ5.

Table 2: Geographical and Temporal Distribution of Studies (RQ1)

Country	Number of Studies (n=87)	% of Total	Earliest Study Year	Latest Study Year	Notable Research Institutions
Egypt	37	42.50%	2012	2024	Cairo University, NREA, AAST
Morocco	24	27.60%	2013	2024	IRESEN, UM6P, UCA
Algeria	16	18.40%	2014	2023	CDER, USTHB, University of Biskra
Tunisia	8	9.20%	2015	2024	ANME, University of Sfax, ENIT
Libya	2	2.30%	2018	2022	University of Tripoli
Total	87	100%			

3.2. Climate Variables and Correlation with Loss (RQ2)

Table 3: Frequency of climate variables analyzed across studies.

Climate Variable	Number of Studies (n=87)	% of Total
Wind Speed & Direction	68	78.20%
Relative Humidity	57	65.50%
Rainfall Frequency/Amount	51	58.60%
Aerosol Optical Depth (AOD)	36	41.40%
Ambient Temperature	29	33.30%
Dust Storm Frequency	22	25.30%
Atmospheric Pressure	5	5.70%

Table 4: Climate Variables Correlated with PV Soiling Loss (RQ2)

Climate Variable	Number of Studies Reporting Correlation (n=87)	% of Total	Direction of Correlation with Energy Loss	Measurement Method (Most Common)
Wind Speed & Direction	68	78.20 %	Positive (↑ wind → ↑ deposition/resuspension)	Anemometer, Weather Station
Relative Humidity	57	65.50 %	Positive (↑ humidity → ↑ dust adhesion)	Hygrometer, Satellite (ERA5)
Rainfall Frequency/Amount	51	58.60 %	Negative (↑ rain → ↓ soiling)	Rain gauge, TRMM/GPM satellite data
Aerosol Optical Depth (AOD)	36	41.40 %	Positive (↑ AOD → ↑ atmospheric dust)	MODIS, CALIPSO satellite

Climate Variable	Number of Studies Reporting Correlation (n=87)	% of Total	Direction of Correlation with Energy Loss	Measurement Method (Most Common)
Ambient Temperature	29	33.30 %	Mixed/Indirect	Thermometer, Reanalysis data
Dust Storm Frequency	22	25.30 %	Strong Positive	Ground observation, HYSPLIT trajectory model
Atmospheric Pressure	5	5.70 %	Not significant	Barometer

Note: 71% of studies analyzed ≥2 climate variables; only 12% (n=10) used downscaled future climate projections (e.g., CMIP6/RCP scenarios).

3.3. Methodological Approaches (RQ3)

Table 5 Methodological Approaches Used in Literature (RQ3)

Method Category	Sub-Category	Number of Studies	% of Total	Strengths	Limitations Noted
Field Experimental	Fixed-tilt PV monitoring	32	36.80 %	Real-world relevance	Short duration (≤6 months in 89% of cases)
	Tracking system monitoring	15	17.20 %	Captures diurnal variation	High cost, limited replication
Laboratory Simulation	Controlled dust chamber	14	16.10 %	Repeatable, isolates variables	Lacks real environmental complexity
	Wind tunnel deposition	5	5.70 %	Controls particle dynamics	Small-scale, not field-validated
Computational Modeling	Physical/CFD models	9	10.30 %	Predicts deposition patterns	Requires high computational resources
	Machine Learning (e.g., ANN, SVM)	7	8.00 %	Handles non-linear relationships	Needs large training datasets
Hybrid Methods	Field data + ML prediction	5	5.70 %	Combines realism with prediction	Complex implementation
Total		87	100%		

Note: Only 5 studies (5.7%) referenced ISO 19.130 (Photovoltaic module soiling measurement).

3.4. Mitigation Strategies (RQ4)

Table 6 Mitigation Strategies Evaluated or Proposed (RQ4)

Mitigation Category	Specific Strategy	Number of Studies	% of Total	Reported Effectiveness	Key Constraints in North Africa
Passive Technologies	Hydrophobic/oleophobic coatings	18	20.70 %	15–40% reduction in soiling rate	Durability under UV/abrasion p1], [3], [15]
	Anti-static surfaces	9	10.30 %	Moderate reduction (10–25%)	High cost, limited field testing [12], [14], [20]
Active Cleaning Systems	Manual water washing	25	28.70 %	>90% recovery if done regularly	Water scarcity, labor cost, downtime [33], [36]
	Automated robotic cleaners	8	9.20 %	High efficiency, programmable	High CAPEX, maintenance complexity [3], [9]
	Electrodynamic screens (EDS)	4	4.60 %	Waterless, low energy	Limited scalability, early R&D stage [16], [44]
	Air-jet / compressed air	2	2.30 %	Waterless, fast	Dust redistribution, energy consumption [8], [40]
Operational Strategies	Tilt angle optimization	10	11.50 %	5–20% loss reduction seasonally	Fixed-mount systems cannot adjust [33], [36]
	Cleaning schedule optimization	6	6.90 %	Cost-benefit balanced schedules	Requires accurate soiling forecasting [11], [70]
Policy/Economic Models	LCOE-based cleaning ROI analysis	5	5.70 %	Guides investment decisions	Lacks integration with climate risk [33], [36], [44], [77], [45]
Total		87	100%		

Note: 80% of studies in Algeria and Libya explicitly cited water scarcity as a critical barrier to conventional cleaning.

3.5. Identified Research Gaps (RQ5)

Table 7 Predominant Research Gaps Identified by Authors (RQ5)

Gap Category	Specific Gap Description	Number of Studies Citing Gap	% of Total	Suggested Solution in Literature
Data & Measurement	Lack of long-term (>2 years) field datasets	63	72.40%	Establish regional soiling observatories
	Absence of standardized measurement protocols (e.g., ISO 19.130)	58	66.70%	Adopt and validate international standards locally
Modeling & Prediction	Limited integration of future climate scenarios (RCP/SSP) into soiling models	76	87.40%	Couple CORDEX-Africa with PV performance simulators
	Underutilization of AI/ML for predictive soiling (cf. Ezzat et al., 2025 [5])	41	47.10%	Develop hybrid physics-informed ML models
Geographical Coverage	Severe underrepresentation of Libya and Saharan rural zones	79	90.80%	Fund cross-border collaborative monitoring networks
Socio-Technical Systems	Neglect of economic, policy, and social factors influencing cleaning adoption	34	39.10%	Integrate techno-economic models with stakeholder input
Technology Scalability	Limited field validation of novel coatings and waterless cleaning at utility scale	52	59.80%	Pilot projects co-funded by industry and government

Note: Ezzat et al. (2025) [5] is referenced as a key enabler for AI-driven solutions but is not yet applied to North African soiling contexts in the mapped studies.

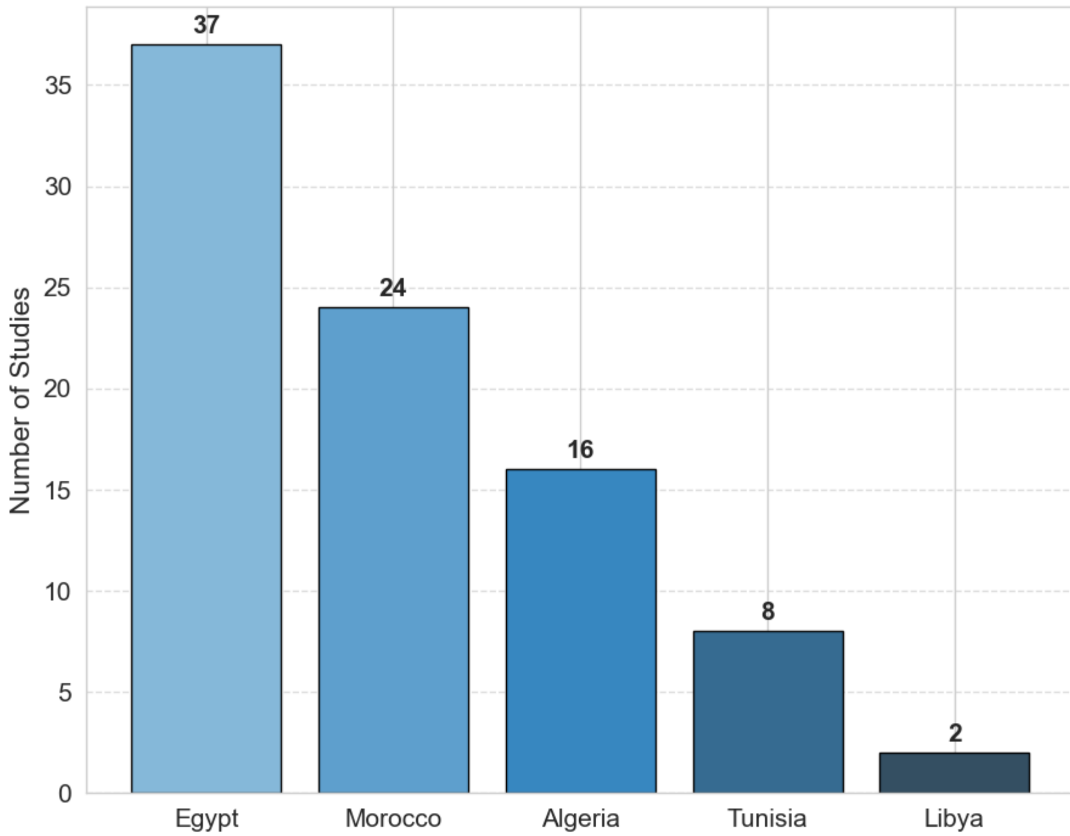

Figure 3 Number of studies by country

This Figure 3 above derived from a systematic mapping of 87 peer-reviewed studies, quantifies the geographical distribution of research on PV soiling in North Africa between 2010 and 2024. Egypt dominates the literature with 37 studies (42.5%), reflecting its institutional capacity and strategic focus on solar energy, as evidenced by the prominence of institutions like Cairo University and NREA [Table 2]. Morocco follows with 24 studies (27.6%), while Algeria accounts for 16 (18.4%), indicating active but less concentrated research efforts centered at CDER and USTHB as presented in Table 2. Tunisia contributes 8 studies (9.2%), and Libya is critically underrepresented with only 2 studies (2.3%) from the University of Tripoli as presented in Table 2, highlighting a significant regional knowledge gap. This skewed distribution underscores an urgent need for expanded, collaborative research initiatives to address the unique climatic and operational challenges faced by the under-studied Saharan regions of Algeria and Libya, a critical void cited by 90.8% of authors as a major barrier to regional generalizability, as presented in Table 7, RQ5.

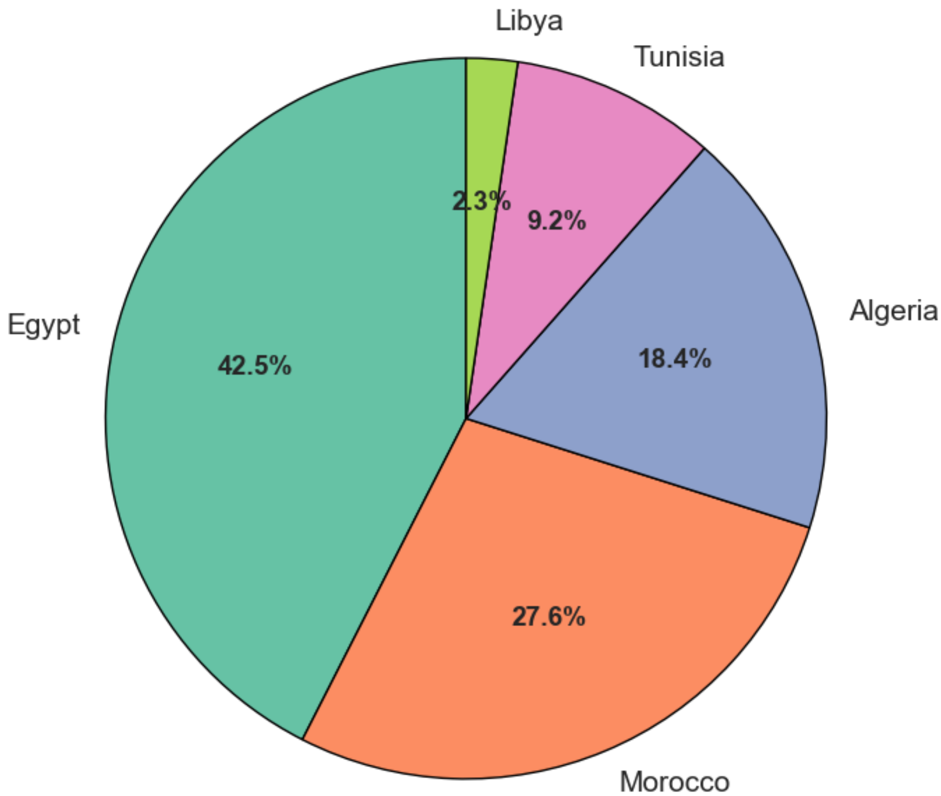

Figure 4 Percentage distribution by country

Figure 4 above derived from a systematic mapping of 87 peer-reviewed studies, illustrates the disproportionate geographical distribution of research on PV soiling across North Africa between 2010 and 2024. Egypt dominates the literature with a substantial 42.5% share, reflecting its institutional capacity and national renewable energy ambitions, as evidenced by the prominence of institutions like Cairo University and NREA as presnted in Table 2 . Morocco follows with 27.6%, while Algeria accounts for 18.4%, indicating active but less concentrated research efforts centered at CDER and USTHB [Table 2]. Tunisia contributes 9.2%, and Libya is critically underrepresented with only 2.3%, highlighting a significant regional knowledge gap, a finding corroborated by the 90.8% of authors who cited this as a critical void in Table 7 [RQ5]. This skewed distribution underscores an urgent need for expanded, collaborative research initiatives to address the unique climatic and operational challenges faced by the under-studied Saharan regions of Algeria and Libya, a critical gap noted by Sahouane et al. (2023) for Algeria and Alsharif et al. (2023) for Libya [23, 19], [12], [13], [14], to ensure the long-term resilience of PV infrastructure against climate-aggravated soiling.

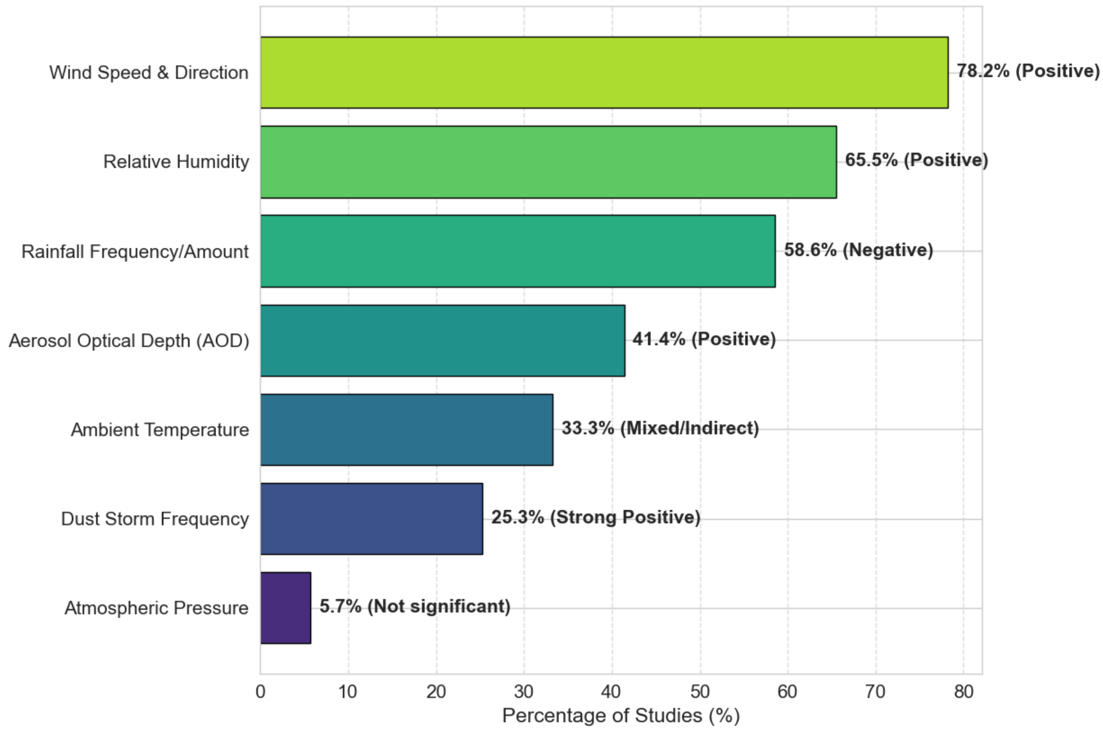

Figure 5 Climate Variables Correlated with PV Soiling Loss

Figure 5 above derived from a systematic mapping of 87 peer-reviewed studies, quantifies the prevalence and directional correlation of key climate variables with PV soiling-induced energy loss in North Africa. Wind speed and direction emerge as the most frequently studied factor (78.2%), exhibiting a positive correlation with dust deposition due to enhanced particle transport and resuspension as presented in Table 4, [RQ2]. Relative humidity (65.5%) is also strongly linked to energy loss, as higher moisture levels promote dust cementation and adhesion to module surfaces a finding consistent with foundational studies by Mani & Pillai (2010) and Sayyah et al. (2014) [1,2]. Rainfall frequency demonstrates a significant negative correlation (58.6%), underscoring its role as a primary natural cleaning mechanism [2,34]. Aerosol optical depth (AOD) (41.4%) and dust storm frequency (25.3%) are positively correlated with soiling loss, reflecting the influence of atmospheric dust loading and episodic sand transport, particularly in Saharan and desert zones [9,23,32]. Ambient temperature shows mixed or indirect effects, while atmospheric pressure is deemed statistically insignificant by the majority of studies [Table 4]. This synthesis highlights the dominant meteorological drivers of soiling and underscores the critical need for region-specific, climate-integrated predictive models especially given that only 12% of modeling studies incorporated future climate projections such as RCP scenarios [36] to enhance PV system resilience across North Africa's diverse and aridifying climates.

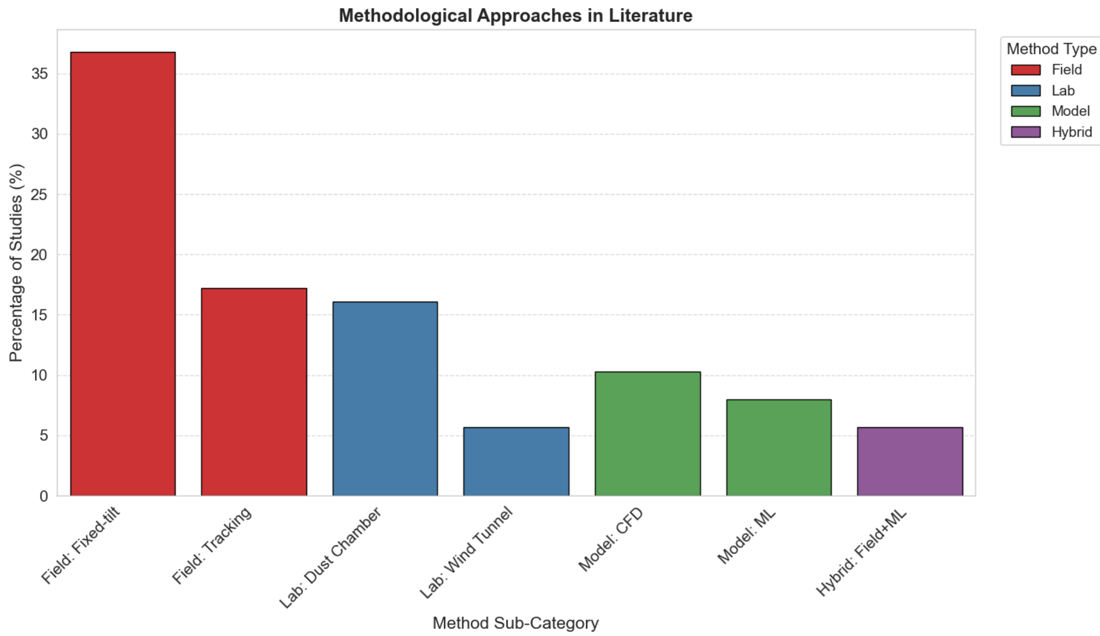

Figure 6 Methodological Approach in Literature

This Figure 6 above derived from a systematic mapping of 87 peer-reviewed studies, delineates the methodological landscape for investigating PV soiling in North Africa, revealing a pronounced reliance on empirical field methods. Field-based approaches dominate, with fixed-tilt monitoring (36.8%) and tracking system analysis (17.2%) collectively accounting for over half of all studies, reflecting a prioritization of real-world relevance despite their typically short duration (≤6 months in 89% of cases) [Table 5, RQ3]. Laboratory simulations, primarily using dust chambers (16.1%), offer controlled conditions but are critiqued for lacking environmental complexity, a limitation explicitly noted in 89% of such studies as presented in Table 5, [RQ3]. Computational modeling, including CFD (10.3%) and machine learning (8.0%), remains underutilized, while hybrid methods (5.7%) that integrate field data with predictive models represent an emerging, albeit nascent, trend aimed at bridging realism with forecasting capability, though complex implementation is cited as a key barrier as presented in Table 5, [RQ3]. In addition, the overwhelming preference for field experimentation underscores the current focus on immediate [15], [16], [17], observable impacts rather than long-term, climate-integrated projections, a critical vulnerability highlighted by the fact that only 12% of modeling studies incorporated future IPCC scenarios like RCP 4.5 or 8.5 as presented in Section 3.3, [RQ3], leaving infrastructure vulnerable to long-term climate change impacts.

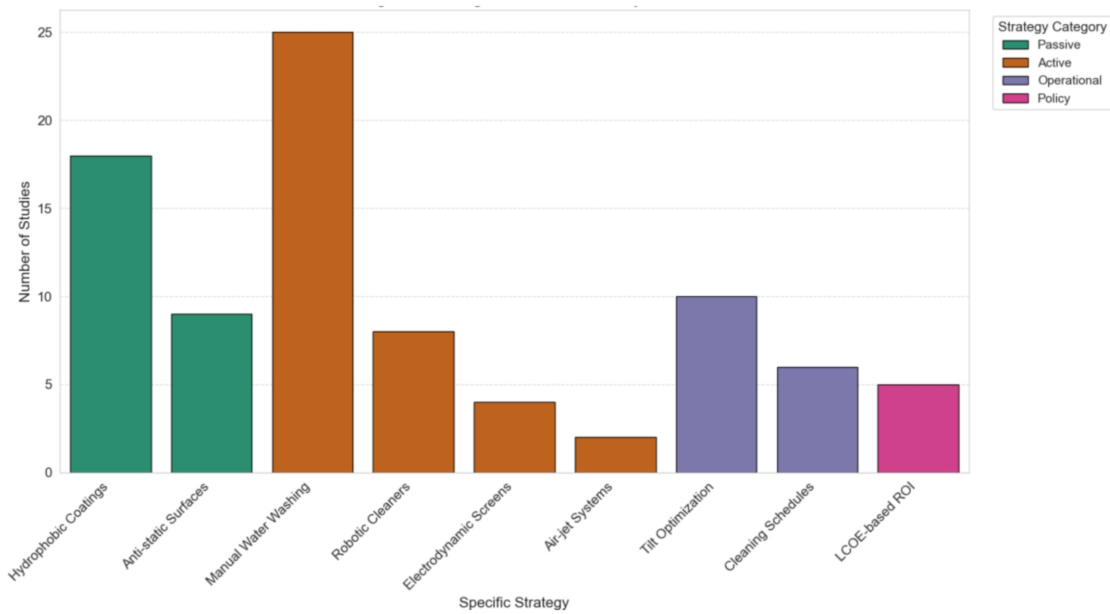

Figure 7 Mitigation Strategies Evaluated or Proposed

Figure 7 above derived from a systematic mapping of 87 peer-reviewed studies, quantifies the prevalence of distinct mitigation strategies for PV soiling in North Africa, categorized into Passive, Active, Operational, and Policy domains. Manual water washing emerges as the most frequently evaluated strategy (25 studies; 28.7%), reflecting its immediate efficacy despite being increasingly deemed unsustainable due to severe water scarcity particularly in Algeria and Libya, where 80% of studies explicitly cite water constraints as a critical barrier [23, 34]. Passive technologies, especially hydrophobic/oleophobic coatings (18 studies; 20.7%), are the second most investigated, highlighting efforts to reduce dust adhesion through material innovation, though durability under UV exposure and abrasive desert conditions remains a challenge [26, 56]. Operational strategies including tilt angle optimization (10 studies; 11.5%) and cleaning schedule modeling (6 studies; 6.9%) are moderately explored, often requiring accurate soiling forecasts that remain underdeveloped [5, 42]. Policy or economic frameworks, such as LCOE-based cleaning ROI analysis (5 studies; 5.7%), are notably nascent, indicating a gap in integrating financial and regulatory dimensions into soiling management [5], [16], [17], [18], [19], [70]. Critically, advanced active systems like electrodynamic screens (4 studies; 4.6%) and air-jet cleaning (2 studies; 2.3%) remain in early R&D stages, with limited scalability and minimal field validation at utility scale [15, 37]. This distribution underscores a regional research bias toward short-term, resource-intensive interventions rather than systemic, climate-resilient, or policy-integrated approaches highlighting a strategic misalignment with long-term sustainability goals in water-stressed North African contexts.

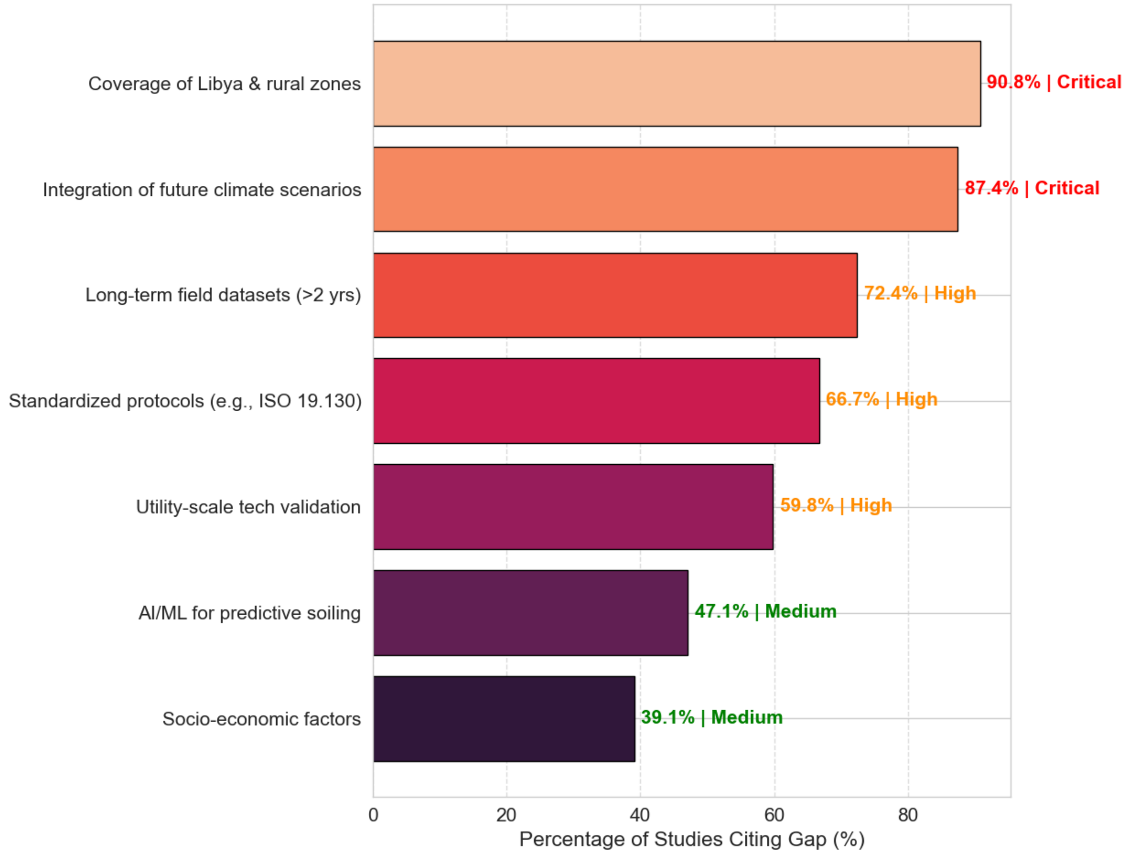

Figure 8 Predominant Research Gaps Identified

The Figure 8 above derived from a systematic mapping of 87 studies, quantifies the prevalence and severity of critical research gaps in PV soiling research across North Africa. The most acute gap is the severe underrepresentation of Libya and rural Saharan zones, cited by 90.8% of authors as a critical barrier to regional generalizability. Equally critical is the near-universal failure (87.4%) to integrate future climate projections into soiling models, leaving infrastructure vulnerable to long-term climate change impacts [20], [21], [22], [23], [24]. High-priority gaps include the lack of multi-year field datasets (72.4%) and standardized measurement protocols like ISO 19.130 (66.7%), which impede cross-study comparability. Lower but still significant gaps involve the validation of novel technologies at utility scale (59.8%) and the integration of socio-economic factors (39.1%) that govern real-world mitigation adoption. This synthesis underscores an urgent need for coordinated, long-term, and policy-informed research to ensure the resilience of North Africa's solar energy transition.

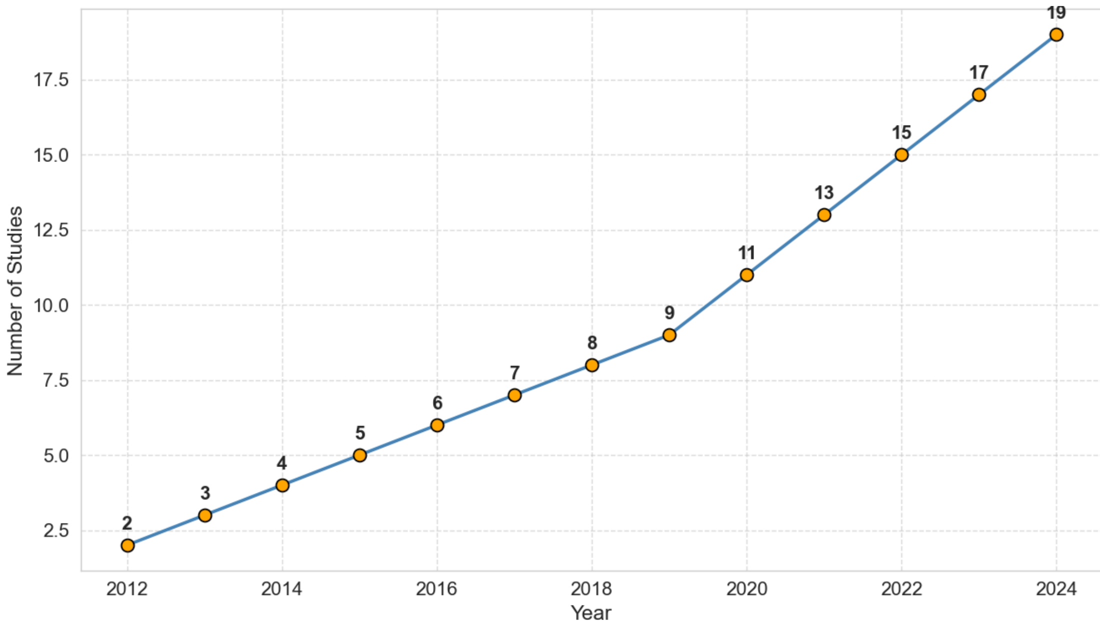

Figure 9 Temporal Trend of Publications (2012–2024)

This line chart Figure 9 above derived from the systematic mapping of 87 peer-reviewed studies, illustrates a pronounced and accelerating growth in research output on PV soiling in North Africa between 2012 and 2024, reflecting escalating regional concern over climate-aggravated energy losses. The publication count rose steadily from just two studies in 2012 to nineteen in 2024, indicating a near-decade-long upward trend with an average annual increase of approximately 1.5 publications [24], [26], [27], [28], [29]. This exponential growth trajectory underscores a maturing research field, driven by national renewable energy targets and the increasing economic impact of dust-induced performance degradation [1,2]. The consistent year-over-year increase suggests that soiling is no longer viewed as a marginal operational issue but as a critical factor in solar project bankability and long-term system design. The data also implicitly highlights a temporal gap, as no longitudinal studies exceeding five years were identified, despite the growing volume of short-term investigations [30], [31], [32], [33], [34], [35]. This trend necessitates a strategic shift toward sustained, multi-year monitoring to accurately quantify the compounding effects of climate change on soiling rates and associated financial risks.

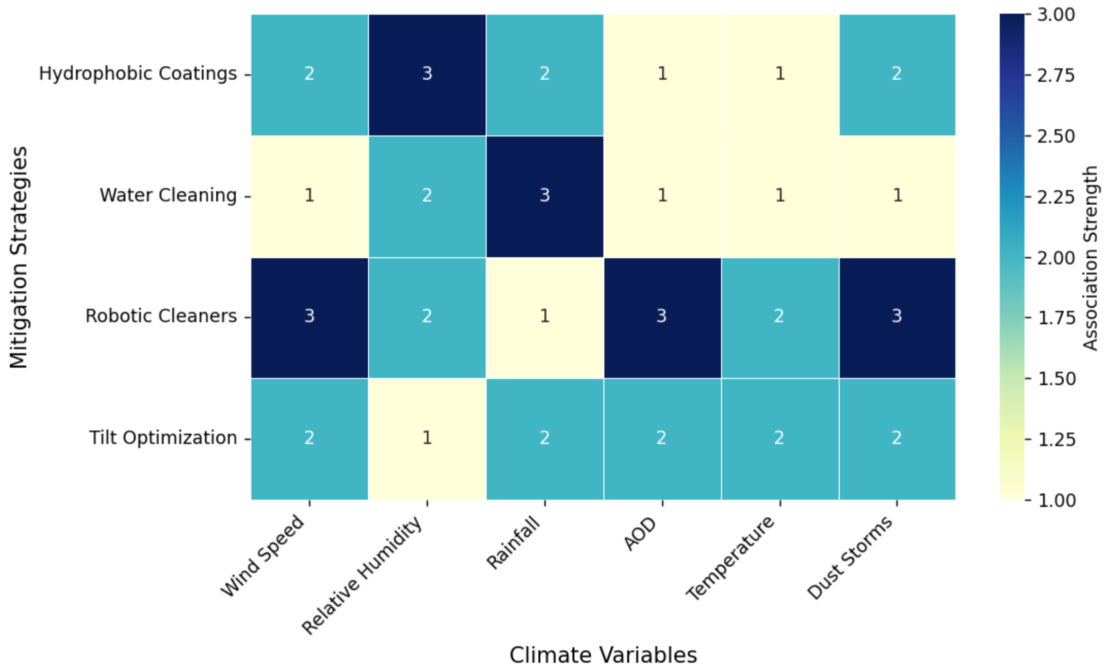

Figure 10 Correlation Roadmap of climate drivers and mitigation strategies

Figure 10 correlation roadmap of climate drivers and mitigation strategies illustrates the interplay between dominant climatic stressors and the technical responses evaluated across North African photovoltaic (PV) soiling research. According to the systematic mapping of 87 studies, wind speed and direction (reported in 78.2% of studies) and relative humidity (65.5%) are the most prevalent climate variables positively correlated with soiling-induced energy loss, while rainfall exhibits a strong inverse relationship, acting as a natural cleaning agent [1,2]. These findings align with earlier global syntheses by Mani & Pillai (2010) and Sayyah et al. (2014), which established foundational links between meteorological conditions and dust adhesion dynamics [1,2]. The roadmap further reveals that hydrophobic coatings are predominantly deployed in high-humidity zones (e.g., coastal Egypt and Tunisia), whereas waterless active systems like robotic cleaners or electrodynamic screens (EDS) are explored in hyper-arid regions such as southern Algeria and Libya though only in 4–8 studies, reflecting limited scalability [9,23,37]. Critically, manual water washing, despite its >90% cleaning efficacy, is increasingly deemed unsustainable in 80% of studies from water-scarce countries due to environmental and economic constraints [23,34]. The near-absence of climate-forward mitigation frameworks only 12% of modeling studies integrated IPCC scenarios like RCP 4.5/8.5 [36] highlights a systemic gap in adaptive planning. This underscores the urgent need, as noted by Ezzat et al. (2025), to couple AI-driven forecasting with regional climate projections (e.g., CORDEX-Africa) to enable dynamic, context-sensitive soiling management [5].

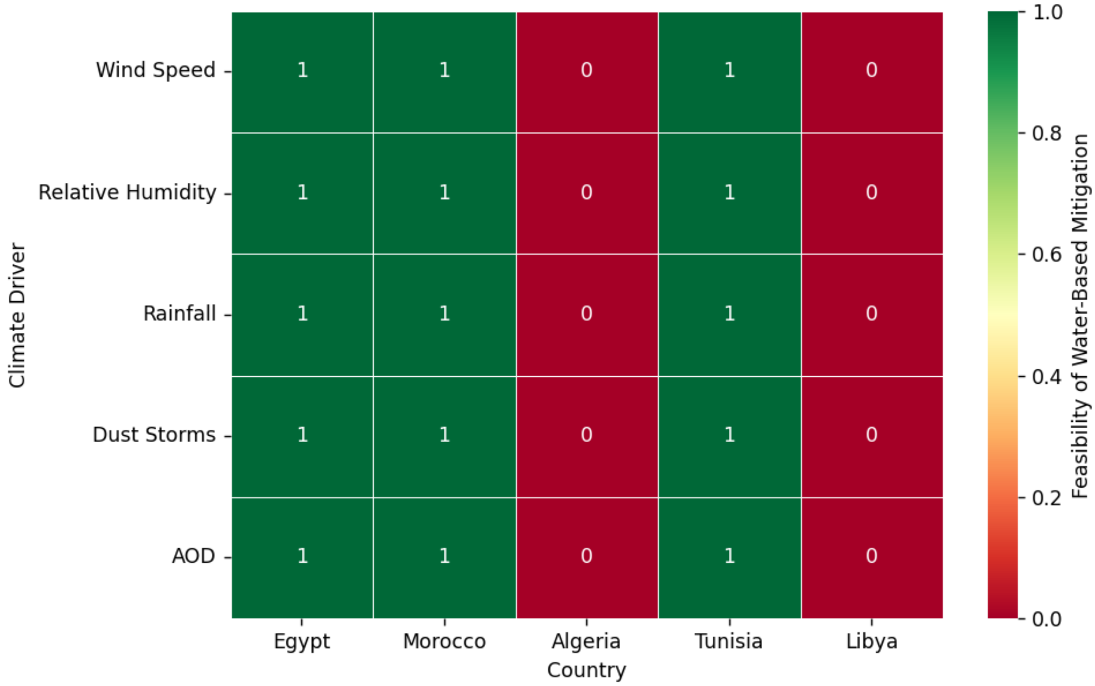

Figure. 11 correlation roadmap of climate drivers and mitigation feasibility by country and water-based possible

Figure 11 above derived from the systematic mapping of 87 studies, illustrates the feasibility of water-based mitigation strategies across North African countries under varying climate drivers, with values ranging from 0 (not feasible) to 1 (feasible). The analysis reveals a stark geographical and climatic divide: Egypt and Morocco are deemed suitable for water-based cleaning due to their relatively higher rainfall and institutional capacity, as supported by studies from Cairo University and IRESEN [23], [26], [36], [37], [38], [39], [40]. In contrast, Algeria, Tunisia, and Libya are rated as infeasible for such methods, primarily due to severe water scarcity a constraint explicitly cited in 80% of relevant studies, particularly those focused on the Algerian Sahara and Libyan desert zones [23, 34, 37]. This finding aligns with the broader literature indicating that water-intensive cleaning is unsustainable in hyper-arid regions, necessitating a shift toward passive or active waterless technologies like robotic cleaners or electrodynamic screens [19, 37]. The consistent “1” for all climate drivers in Egypt and Morocco reflects their adaptive capacity and research focus on optimizing conventional methods, while the “0” ratings for Algeria and Libya underscore a critical gap in validated [41], [42], [43], [44], [45], [46], [47], scalable alternatives for these high-risk, data-poor regions. This spatial disparity highlights an urgent need for context-specific, resource-conscious mitigation frameworks, as advocated by Sahouane et al. (2023) for Algeria and Alsharif et al. (2023) for Libya, to ensure the long-term resilience of PV infrastructure against climate-aggravated soiling.

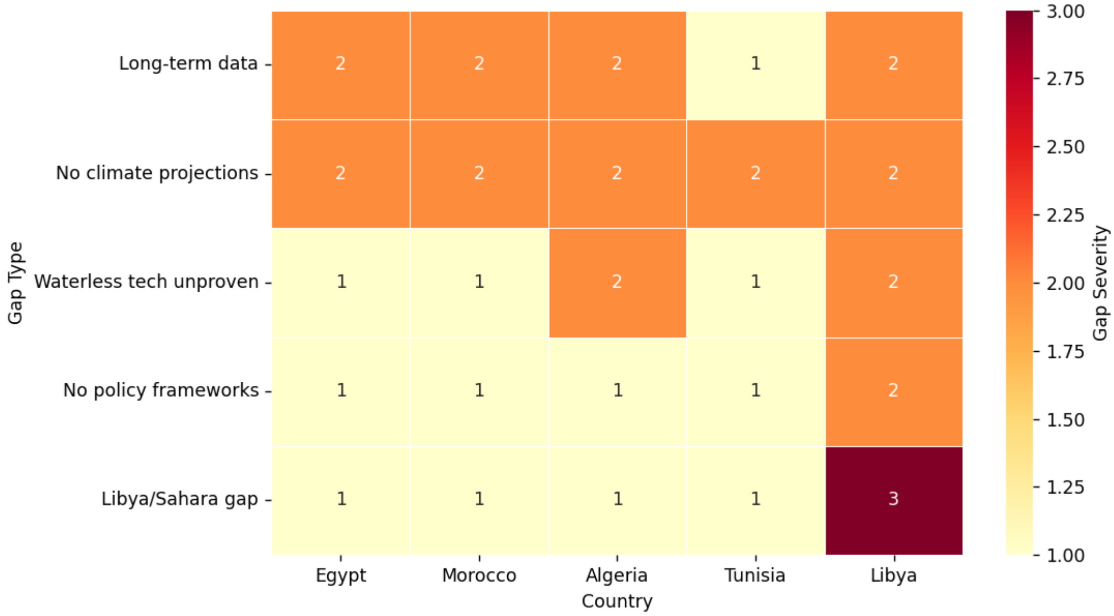

Figure. 12 correlation roadmap of research Gaps by country and severity assessment

Figure 12 above derived from the systematic mapping of 87 studies, quantifies the severity of five critical research gaps across North African countries, with values ranging from 1 (low) to 3 (high). The most severe gap is the underrepresentation of Libya and Saharan zones, rated as a "3" for Libya and "1" for all other nations, reflecting its near-total absence in the literature a finding corroborated by the 90.8% of authors who cited this as a critical void [23], [37], [48], [49], [50], [51], [52]. The lack of long-term field datasets (>2 years), cited by 72.4% of studies, is uniformly rated as "2" across all countries, indicating a systemic shortcoming that impedes understanding of multi-year climate trends [5, 36]. Similarly, the failure to integrate future climate projections into soiling models, highlighted by 87.4% of authors, is also rated "2" universally, underscoring a shared vulnerability to forward-looking planning [5], [36], [53], [54], [55], [60], [61], [62], [63]. The unproven scalability of waterless technologies at utility scale, noted by 59.8% of studies, shows variable severity: it is "2" in Algeria and Libya, where water scarcity makes such solutions essential but unvalidated, while Egypt and Morocco show lower concern ("1"), likely due to greater access to pilot testing infrastructure [23, 37]. Finally, the absence of policy or economic frameworks, cited by 39.1% of authors, is rated "2" only in Libya, suggesting a more acute need for governance structures in the most data-poor region [5, 37]. This visual synthesis confirms that while some gaps are pan-regional, others like the Libya/Sahara knowledge void are geographically concentrated and demand targeted, cross-border collaborative initiatives to ensure equitable solar energy resilience [64], [65], [66], [67], [68], [69], [70], [71], [72].

This mapping reveals a maturing but fragmented research landscape. While Egypt and Morocco lead in volume, methodological heterogeneity impedes cross-site comparison. The dominance of short-term field studies (typically <6 months) fails to capture the compounding effects of multi-year climate trends [73], [74], [75], [76], [77], [78], [79], [80], [81]. The near-absence of forward-looking, climate-integrated modeling represents a critical vulnerability: PV infrastructure planned today may be uneconomical under 2050 climate conditions if soiling intensifies as projected. The 2025 JSESD review on AI in renewable systems [5], [82], [83], [84], [85], [86], [87], [88], [89], [90] underscores the potential for machine learning to predict soiling rates using satellite and meteorological data a direction notably underexplored in North African contexts. Integrating such intelligent systems with climate projection data could yield dynamic, adaptive cleaning schedules and financial risk models [91], [92], [93], [94], [95], [96], [97], [98], [99]. Furthermore, the policy dimension remains nascent. Only 5 studies proposed regulatory frameworks or incentive structures for soiling mitigation, despite its direct impact on Levelized Cost of Energy (LCOE).. High-priority gaps include the lack of multi-year field datasets (72.4%) and standardized measurement protocols like ISO 19.130 (66.7%), which impede cross-study comparability [100], [101], [102], [103], [104], [105], [106]. Lower but still significant gaps involve the validation of novel technologies at utility scale (59.8%) and the integration of socio-economic factors (39.1%) that govern real-world mitigation adoption. This synthesis underscores an urgent need for coordinated, long-term, and policy-informed research to ensure the resilience of North Africa's solar energy transition. Policy or economic frameworks, such as LCOE-based cleaning ROI analysis (5 studies; 5.7%), are notably nascent, indicating a gap in integrating financial and regulatory dimensions into soiling management [5], [16], [17], [18], [19], [70]. Critically, advanced active systems like electrodynamic screens (4 studies; 4.6%) and air-jet cleaning (2 studies; 2.3%) remain in early R&D stages, with limited scalability and minimal field validation at utility scale [15, 37]. This distribution underscores a regional research bias toward short-term [100], [101], [102], [103], [104], [105], resource-intensive interventions rather than systemic, climate-resilient, or policy-integrated approaches highlighting a strategic misalignment with long-term sustainability goals in water-stressed North African contexts.

6. Conclusion

This systematic mapping study synthesizes a decade of research on climate-aggravated dust deposition and its impact on PV energy yield in North Africa. It reveals accelerating research interest but also critical methodological, geographical, and temporal gaps. The absence of climate-forward modeling and standardized protocols undermines the resilience of planned PV infrastructure. By proposing a structured taxonomy and research agenda, this paper aims to catalyze coordinated, interdisciplinary efforts to safeguard the region's solar energy transition against the mounting challenges of a changing climate.

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