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Investigations on soiling effects on solar energy systems in Morocco and abroad: insights on their modeling and prediction

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Investigations on soiling effects on solar energy systems in Morocco and abroad: insights on their modeling and prediction

Dedication

To my parents Zhor Mouhtarim and Larbi Laarabi

To my soulmate Youssef El houti

To my parents in law Rabiaa Fahim and Abdellah El houti (may his soul rest in peace)

To my grandmother Laaziza Baghdadi

To all members of my family Mouhtarim,

To all members of my family Laarabi

To all members of my family El houti

To my uncle in law Abdelkader Tatahaj (may his soul rest in peace)

To all my professors

To all my friends all over the world

Being so grateful for all your support, guidance and love <3

I dedicate you this work!

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قال الله تعالى:

- "هُوَ الَّذِي جَعَلَ الشَّمْسَ ضِيَاءً وَالْقَمَرَ نُورًا وَقَدَّرَهُ مَنَازِلَ لِتَعْلَمُوا عَدَدَ السِّنِينَ وَالْحِسَابَ. مَا خَلَقَ اللَّهُ ذَلِكَ إِلَّا بِالْحَقِّ، يُفَصِّلُ الْآيَاتِ لِقَوْمٍ يَعْلَمُون" *يونس: 5*

Allah said:

- “It was He that made the sun a brightness and the moon a light, and determined it in phases so that you might know the number of years and the reckoning. Allah did not create them except in truth, and distinguishes the verses to a nation who know.” Yunus: 5

- *"Science [...] is composed of errors that it is right to make, for they lead step by step to the truth"*

Jules Verne

- *"Anyone starting out to research for a doctorate degree should remember that hours of self-centered work has the ability to be the spark for others to progress. All research is potentially useful to open doors or show others that door does not lead anywhere useful. Advancements happen by building on others research."*

Ian R. McAndrew

Abstract

This thesis investigates the effects of soiling on solar energy systems in Morocco and abroad (India), and presents various and important insights on their modeling and prediction. The investigation on soiling effect has shown this phenomenon is a much-localized. The exploration of the effect of the factors that influence soiling has revealed that their effect is very complex and highly depend on their each other effect, the amount of data used as well as on the location. This makes it highly difficult to predict soiling losses based on the variables that affect it. By correlating the mass density and the transmittance loss, the best generalized model which has the highest R^2 and the smallest RMSE and MAE is the exponential model (New model 3 (EXP)). Regarding the physical characterization of dust particles, the majority of dust particles have a regular shape and the shape factor is affected by the magnification. Particles size distribution was concentrated in the range (3-4) µm in the capital region of Morocco and in the range of (0-1) µm in Tamil Nadu State of India. It is affected by the magnification, the inclination, and the number of images captured on the sample. Furthermore, capturing three images on the surface of the sample is more representative of the distribution of soiling on it. The transmittance loss and the fractional coverage area found to be correlated and this latter can be used to estimate the transmittance loss. On the subject of the chemical characterization of dust particles, soiling samples have almost the same chemical and mineralogical composition but with different percentages in the components.

Key words: Solar energy; PV modules; Soiling; Morocco; India; Transmittance; Mass density; Modeling; Prediction; Shape Factor; Chemical-physical analyses.

Résumé

Cette thèse étudie les effets de l'encrassement sur les systèmes d'énergie solaire au Maroc et à l'étranger (Inde), et présente un aperçu et de diverses réflexions importantes sur leur modélisation et leur prédiction. L'évaluation de l’effet de l’encrassement a montré que ce phénomène est très localisé. L'exploration de l'effet des facteurs qui influencent l'encrassement a révélé que leur effet est très complexe et dépend fortement de leur effet réciproque, de la quantité de données utilisées ainsi que l’emplacement. Il est donc très difficile de prédire les pertes les effets de l’encrassement à partir des variables qui les affectent. En corrélant la masse du dépôt et la perte en transmittance, le meilleur modèle généralisé qui a le R^2 le plus élevé et les RMSE et MAE les plus faibles est le modèle exponentiel (Nouveau modèle 3 (EXP)). En ce qui concerne la caractérisation physique des particules des salissures, la majorité des particules ont une forme régulière et le facteur de forme est affecté par le grossissement. La distribution granulométrique des particules était concentrée dans la gamme (3-4) µm dans la région capitale du Maroc et dans la gamme de (0-1) µm dans l'État du Tamil Nadu en Inde. Elle est affectée par le grossissement, l'inclinaison et le nombre d'images capturées sur l'échantillon. De plus, la capture de trois images à la surface de l'échantillon est plus représentative de la répartition des salissures sur celui-ci. La perte en transmittance et le pourcentage de surface couverte sont corrélées et cette dernière peut être utilisée pour estimer la perte en transmittance. En ce qui concerne la caractérisation chimique des particules de salissures, les échantillons de salissures ont presque la même composition chimique et minéralogique mais avec des pourcentages différents.

Mots-clés: Énergie solaire ; modules photovoltaïques ; Encrassement ; Maroc ; Inde ; Transmittance; Densité de masse ; Modélisation ; Prédiction ; Facteur de forme ; Analyses physiques-chimiques.

Résumé développé

S'orienter vers l'utilisation de l'énergie solaire ou des énergies renouvelables en général a été initié afin de contribuer à la diminution de l'effet de serre résultant principalement de la pollution. Néanmoins, cette pollution elle-même affecte l'efficacité des systèmes d'énergie solaire en raison de dépôt des salissures sur les modules solaires photovoltaïques (PV). Ceci, réduit l'éclairement énergétique reçu par le module, diminue considérablement leurs performances et conduit à des pertes économiques importantes. La présente thèse étudie les effets de l'encrassement sur les systèmes d'énergie solaire au Maroc et en Inde, et présente un aperçu et de diverses réflexions importantes sur leur modélisation et leur prédiction.

L'évaluation de l'effet de salissure a montré que ce phénomène est très localisé. Les densités de dépôt dans la région capitale du Maroc ont été observées dans la gamme de 0,37 g/m²/mois et 2,86 g/m²/mois et la perte en transmittance a montré une réduction de 1,05% par mois à 10,04 % par mois. Ces quantités dépendent du site d'exposition, de l'inclinaison et de la durée d'exposition. Le site d'Alkarya (S2_M) a connu la plus forte densité de masse et perte en transmittance par rapport aux autres sites. Les densités de masse dans l'État du Tamil Nadu en Inde vont de 0,03 à 1,42 g/m²/mois, tandis que les pertes en transmission se situent entre 0,35 et 7,42 %/mois et les épaisseurs entre 0 et 9,21 µm/mois. La ville d'Erode (S2_In et S3_In) a connu un effet de salissure élevé par rapport à Vellore (S1_In et S5_In) et Namakkal (S4_In).

L'exploration de l'effet des facteurs qui influencent la salissure a révélé que leur effet est très complexe et dépend fortement de leur effet mutuel, de la quantité de données utilisées ainsi que de l'emplacement. Cela rend très difficile la prévision des pertes de salissures en fonction des variables qui l'affectent. Pour des densités de masse inférieures à 3g/m², une corrélation positive et linéaire entre la densité de masse et la perte en transmittance a été observée. Cependant, cela dépend de la période et du lieu de l'exposition. En corrélant la densité de masse et la perte en transmittance, trois nouveaux modèles généralisés ont été développés et qui peuvent prédire la perte en transmittance en fonction de la densité de masse avec plus de précision car ils couvrent de nombreux sites, différents angles d'inclinaison et orientations, et diverses périodes. Cependant, le meilleur qui a le facteur de détermination R^2 le plus élevé et les plus petits RMSE et MAE est le modèle exponentiel (Nouveau modèle 3 (EXP)).

Concernant la caractérisation physique des particules de poussière, bien que certaines particules aient des formes irrégulières, la majorité des particules de poussière ont une forme régulière. Cependant, des formes régulières ont été observées plus dans les surfaces inclinées que dans les horizontales. De plus, le facteur de forme est affecté par le grossissement, plus le grossissement augmente, plus des formes régulières sont détectées. La distribution de la taille des particules était concentrée dans la plage (3-4) µm dans la région capitale du Maroc et dans la plage (0-1) µm dans l'État du Tamil Nadu en Inde. Il est affecté par le grossissement, l'inclinaison et le nombre d'images capturées sur l'échantillon. Un grossissement plus élevé conduit à une détection plus élevée des petites particules. De plus, une homogénéité en termes de granulométrie est observée sur les surfaces horizontales que sur les surfaces inclinées. De plus, la capture de trois images à la surface de l'échantillon est plus représentative de la répartition des salissures sur celui-ci. La perte en transmittance et le pourcentage de surface couverte sont liés et cette dernière peut être utilisée pour estimer la perte en transmittance. Cependant, cette estimation est plus précise lorsque trois images sur l'échantillon sont prises.

A propos de la caractérisation chimique des particules de poussière. Les échantillons de salissures ont presque la même composition chimique et minéralogique mais avec des pourcentages différents des composants. Les constituants abondants dans les échantillons collectés dans la région capitale du Maroc sont principalement le quartz, la calcite et la kaolinite. L'échantillon de salissures de Rabat, plus sombre et riche en carbone, a montré le pire effet de détérioration par rapport à ceux d'Agadir ou d'Errachidia qui sont les plus blancs et les plus riches en oxyde de calcium. Néanmoins, le phénomène de salissure est plus prononcé à Errachidia qu'à Rabat. Les résultats obtenus confirment également l'effet de la composition chimique sur la corrélation entre la densité de masse et la transmittance. Dans l'État indien du Tamil Nadu, les principaux constituants trouvés sont Si, Na, Ca et Mg.

Mots-clés: Énergie solaire ; modules photovoltaïques ; Encrassement ; Maroc ; Inde ; Transmittance; Densité de masse ; Modélisation ; Prédiction ; Facteur de forme ; Analyses physiques-chimiques.

ملخص

تم البدء في التوجه نحو استخدام الطاقة الشمسية أو الطاقات المتجددة بشكل عام من أجل المساعدة في تقليل تأثير الاحتباس الحراري الناتج بشكل أساسي عن التلوث. ومع ذلك ، فإن هذا التلوث نفسه يؤثر على كفاءة أنظمة الطاقة الشمسية بسبب حدوث تلوث على وحدات الطاقة الشمسية الكهروضوئية (PV) . هذا ، يقلل من الإشعاع الذي تتلقاه الوحدة ، ويقلل بشكل كبير من أدائها ويؤدي إلى خسائر اقتصادية كبيرة. تتمحور هذه الأطروحة حول تأثيرات التلوث على أنظمة الطاقة الشمسية في المغرب والهند ، وتقدم توجيهات متنوعة ومهمة حول نمذجتها والتنبؤ بها.

أظهر التحقيق في تأثير التلوث أن هذه الظاهرة محلية إلى حد كبير. لوحظت كثافة تراكم الغبار(الملوثات بصفة عامة) في منطقة العاصمة المغربية في حدود 0.37 جم / م 2 / شهر و 2.86 جم / م 2 / شهر وتراوح انخفاض نفاذية الزجاج بين 1.05٪ شهريًا و 10.04٪ شهريًا. تعتمد هذه الكميات على موقع الترسب ، زاوية الميل وفترة الاختبار. شهد موقع القرية (S2_M) أعلى كثافة وانخفاض في النفاذية مقارنة بالمواقع الأخرى. بالنسبة لولاية تاميل نادوالهندية فكثافة الترسب تتروراح بين 0.03-1.42 جم / م 2 / شهر بينما انخفاض نفاذية الضوء بين 0.35-7.42٪ / شهر وسمك طبقة الغبار المترسب بين 0-9.21 ميكرومتر / شهر. عرفت مدينة ايرود (S2_In) و (S3_In) لتأثيرات تلوث عالية بالمقارنة مع فيلور (S1_In) و نمكال (S5_In) و(S4_In).

أظهر البحث حول تأثير العوامل المؤثرة على التلوث معقد للغاية ويعتمد بشكل كبير على تأثير بعضها البعض ، كمية البيانات المستخدمة وكذلك على الموقع. هذا يجعل من الصعب للغاية التنبؤ بتأتير الملوثات بناءً على المتغيرات التي تؤثر عليها. بالنسبة لكثافة الترسب التي تقل عن 3 جم / م 2 ، لوحظ وجود ارتباط موجب وخطي بين كثافة الترسب وفقدان نفاذية الضوء. ومع ذلك ، هذا يعتمد على مدة ومكان الترسب. من خلال الربط بين كثافة الترسب وانخفاض النفاذية ، تم تطوير ثلاثة نماذج عامة جديدة والتي يمكن أن تتنبأ بانخفاض النفاذية بناءً على كثافة الترسب بشكل أكثر دقة لأنها تغطي العديد من المواقع وزوايا الميل واتجاهات مختلفة وفترات مختلفة. ومع ذلك ، فإن أفضل نموذج لديه أعلى R^2 وأصغر RMSEو MAE هو النموذج الأسي (النموذج الجديد 3(EXP)).

فيما يتعلق بالخصائص الفيزيائية لجزيئات الغبار ، على الرغم من أن بعض الجسيمات لها أشكال غير منتظمة ، إلا أن غالبية جزيئات الغبار لها شكل منتظم. ومع ذلك ، لوحظت الأشكال المنتظمة في الأسطح المائلة أكثر من الأسطح الأفقية. علاوة على ذلك ، يتأثر عامل الشكل بالتكبير ، فكلما زاد التكبير ، تم اكتشاف أشكال أكثر انتظامًا. تركز توزيع حجم الجسيمات في نطاق (3-4) ميكرومتر في منطقة العاصمة المغربية وفي نطاق (0-1) ميكرومتر في ولاية تاميل نادو في الهند.هذا الاخير يتأثر بالتكبير والميل وعدد الصور

الملتقطة على العينة. يؤدي التكبير العالي إلى زيادة الكشف عن الجسيمات الصغيرة. بالإضافة إلى ذلك ، لوحظ التجانس من حيث حجم الجسيمات على الأسطح الأفقية أكثر من الأسطح المائلة. علاوة على ذلك ، فإن التقاط ثلاث صور على سطح العينة أكثر تمثيلاً لتوزيع الأوساخ عليها. انخفاض النفاذية بنسبة المنطقة المظللة يرتبطان ببعضهما البعض ويمكن استخدام هذه الأخيرة لتقدير انخفاض النفاذية. ومع ذلك ، يكون هذا التقدير أكثر دقة عند التقاط ثلاث صور على العينة.

فيما يتعلق بموضوع التحليل الكيميائي لجزيئات الغبار ، تبين ان العينات المحللة تحتوي على نفس التركيب الكيميائي والمعدني تقريبًا ولكن بنسب مختلفة في المكونات. المكونات الموجودة بكثرة في العينات التي تم جمعها من منطقة العاصمة المغربية هي بشكل رئيسي الكوارتز والكالسيت والكاولينيت. أظهرت عينة الغبار المأخوذة من منطقة الرباط ، وهي الاكثر قتامة من حيث اللون و الاغنى بالكربون ، أسوأ تأثير تدهور مقارنة بتلك المأخوذة من أكادير أو الرشيدية الأكثر بياضًا والاغنى من حيث كمية أكسيد الكالسيوم. ومع ذلك ، فإن كثافة الترسب مرتفعة في الرشيدية منها في الرباط. تؤكد النتائج التي تم الحصول عليها أيضًا تأثير التركيب الكيميائي على الارتباط بين كثافة الترسب ونفاذية الضوء. في ولاية تاميل نادو في الهند ، المكونات الرئيسية التي تم العثور عليها هي Si ، Na ، Ca و Mg.

الكلمات المفتاح: طاقة شمسية؛ الوحدات الكهروضوئية ؛ تلوث؛ المملكة المغربية؛ الهند؛ نفادية الضوء؛ كثافة الترسب؛ النمذجة؛ تنبؤ؛ عامل الشكل ؛ التحليلات الكيميائية والفيزيائية.

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- **Ongoing publications**

21- Comprehensive literature review on the modeling and production reduction of soiling effect on solar energy power plants
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Submitted to the call for chapters: "Digital Technologies for Solar Photovoltaic Systems: From general to rural and remote installations" to be published by IET, **2022**

22- Characterization of dust particles over Tamil Nadu state of India and investigation of the influencing factors of soiling images analysis

B. Laarabi, N. Rajasekar and A. Barhdadi
Environmental Science and Pollution Research Journal, **2022**, Under review

23- Waterless cleaning technique for photovoltaic panels on dual-axis tracker
D. Dahlioui, S. Medaghri Alaoui, **B. Laarabi**, and A. Barhdadi
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Main Scientific Communications of the Author

Oral presentations

1. Characterization of dust particles over Tamil Nadu state of India and investigation of the influencing factors of soiling images analysis.
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Nomenclature

ACF	Autocorrelation Function
$adjR^2$	Adjusted coefficient of determination
AFWA	US Air Force Weather Agency
AIC	Akaike Information Criterion
AM	Air Mass
ANN	Artificial Neural Network
AOD	Aerosol Optical Depth
ARIMA	Auto-Regressive Integrated Moving Average
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning
BIC	Bayesian Information Criterion
BNN	Bayesian Neural Networks
CF	Cleanliness Factor
CI	Cleanness Index
CIGS	Copper Indium Gallium Selenide
CMAQ	Community Multiscale Air Quality
CNRST	National Center for Scientific and Technical Research
CPV	Concentrator PhotoVoltaic
CSD	Classical Seasonal Decomposition
CSES	Center for Sustainable Energy Systems
CSP	Concentrated Solar Power
DFA	Dynamic Factor Analysis
DLM	Dynamic Linear Models
DNI	Direct Normal Irradiance
EDS	Electrodynamics Screen
ELM	Extreme Learning Machine
Ew/Ewo	Energy production with snow/Energy production without snow
FF	Fill Factor
FQSD	Fused Air Quality Surface Using Downscaling
FRP	Fixed Rate Precipitation
FTIR	Fourier Transform Infrared Spectroscopy
G	Irradiance
GHI	Global Horizontal Irradiance
GIS	Geographic Information System
GOCART	Georgia Institute of Technology–Goddard Global Ozone Chemistry Aerosol Radiation and Transport
HCPV	High Concentrating Photovoltaic
HCPV TJ	High Concentrating Photovoltaic Triple Junction
HTAP	Hemispheric Transport of Air Pollution emissions
HYSPLIT	Hybrid Single Particle Lagrangian Integrated Trajectory
Icc	Short-Circuit Current
IEA PVPS	International Energy Agency Photovoltaic Power Systems
IES	Institute of Solar Energy

IPA	IsoPropyl Alcohol
IR	Infrared
JB	Jarque-Bera normality test
Jsc	Short-Circuit Current Density
LB	Ljung-Box test
LCA	Life Cycle Assessment
LMA	Levenberg–Marquardt Algorithm
LR	Linear Regression
MAD	Mean Absolute Deviation
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
MBE	Mean Bias Error
ME	Modelling Efficiency
MENA	Middle East and North Africa
MENA	Middle East and North Africa
MISR	Multi-angle Imaging Spectro-Radiometer
MLP	Multi-Layer Perceptron
MLPN	Multi-Layer Perceptron Network
MLR	Multiple Linear Regression
MLRIT	Multiple Linear Regression of Interaction Terms
MS	Markov regime Switching
MSE	Mean Square Error
NARX	Nonlinear AutoRegressive with eXogenous inputs
NASA	National Aeronautics and Space Administration
PCD	Pollution Control Department
PID	Potential-Induced Degradation
PM	Particulate Matter
PM_{10}	Particulate Matter with diamter of 10 µm or less
$PM_{2.5}$	Particulate Matter with diamter of 2.5 µm or less
Pmax	Maximum Power
PRM	Polynomial Regression Model
PS	Partial Shading
PTC	Parabolic-Trough Collectors
PV	Photovoltaic
PVC	Polyvinyl Chloride
Q-Q	Quantile – Quantile plot
R	Correlation coefficient
R & D	Research & Development
R^2	Coefficient of determination
RACM	Regional Atmospheric Chemistry Mechanism
RBFN	Radial Basis Function Network
RH	Relative Humidity
RH	Relative Humidity
RMSE	Root Mean Square Error

RMSEn	normalized Root-Mean-Square Error
ROC	Receiver Operation Characteristic
RS	Series-Resistance
Rs	Indian Rupee
s	span of the local regression
sd	snow depth
SDF	Soil Distortion Factor
SEM/EDS	Scanning Electron Microscopy/Energy Dispersive X-ray Spectroscopy
SHB	Super-Hydrophobic
SMARTS	Simple Model of the Atmospheric Radiative Transfer of Sunshine
SR	Spectral Response
SR	Soiling Rate
SRR	Stochastic Rate and Recovery
Ta	Ambient Temperature
UATRS	Technical Support Units for Scientific Research
UHCPV	Ultra High Concentrating Photovoltaic
US EPA	United States Environmental Protection Agency
UV	Ultraviolet
Vco	Open-Circuit Voltage
VWS	Vertical Wind Speed
WRF	Weather Research and Forecasting
WRF-Chem	Weather Research Forecasting with Chemistry
WRF-DuMO	Weather Research and Forecasting-Dust Model
WS	Wind Speed
XRD	X-ray diffraction
XRF	X-ray Fluorescence

CHAPTER I : GENERAL INTRODUCTION

1. Introduction

This thesis investigates the effects of soiling on solar energy systems in Morocco and India, and presents various and important insights on their modeling and prediction. In this first chapter, the background of soiling of solar energy systems, motivation, objectives and scope of the performed researches are described.

2. Background of soiling of solar energy systems

Evolving renewable energy-based solutions to mitigate today's most critical environmental issues as greenhouse gas emission is of high priority in the global arena. For this reason, the renewable energy market grows faster through the years and many energetic strategies are upfront to implement ambitious projects in short, medium and long terms.

The efficiency of photovoltaic modules has known not only a significant increase, but also a decrease in manufacturing prices. Consequently, in recent years there has been an important rise in investments in the field of solar photovoltaic energy. With that increasing, it is very important to focus research efforts on the efficiency of solar modules. Indeed, the maximum efficiency displayed by these modules has been progressively improved by more than 150 years of scientific effort. Among the most important areas of research on improving the performance of this sacred technology, there is the sector which deals with environmental/meteorological factors such as wind speed, ambient temperature, humidity, precipitation, intensity of the incident solar radiation and the deposition of particles [1]–[3] present in the air or carried by winds. A tricky fact is that the installation sites where the solar energy is abundant are known, in most cases, by severe weather conditions like desert and arid zones. Those desert climates tend to provoke material deterioration and high dust accumulation [4]. This latter is named soiling and it is a phenomenon, which depends strongly on the geographic location and environmental conditions. It is an environmental factor that is sometimes overlooked [5], partly because of its (so far) unpredictable nature and location-specific effects on system performance. Soiling, "*also named dusting, is usually a mixture of small amounts of organic particles and/or minerals from geomorphic fallout such as sand, clay, or eroded limestone. Atmospheric airborne dust (aerosols) is attributed to various sources, such as soil elements lifted by the wind (Aeolian dust), volcanic eruptions, vehicle movement, and pollution*" [6]. This often leads to a huge decrease in electricity production, which highly makes an installation unviable economically and therefore must be alleviated [7]. Soiling losses increase significantly to 4% - 7% which will lead to 4 - 7 billion €

economic losses by 2023 [7]. Studies regarding soiling phenomenon started in 1942 and since then numerous contributions have been made in analyzing soiling effects and research on this topic is increasing over the years [6].

Works on the above subject have been conducted on different solar energy technologies, mainly on PV and CSP. Each work investigates soiling phenomenon following a specific direction and focusing on a precise aspect. The different aspects that are generally analyzed are categorized in Figure I-1. "Assessment" category includes the evaluation of soiling impact or the discussion of the factors influencing soiling [8]–[13]. "Particle properties" include the determination of soiling particles composition, morphology or size [14]–[16]. "Mitigation/cleaning" takes into account the different techniques, systems or methods, whatever preventive or corrective, developed to eliminate, reduce or avoid soiling effect [17]–[19]. "Instrumentation" includes the effect of soiling not on solar energy systems but on instruments such as pyranometers or pyrheliometers [20][11]. "Dust simulators" are mainly instruments that have been developed to simulate soiling effect at indoor conditions [21]–[23]. "Modeling" considers all models established in order to model soiling phenomenon or to predict its effect over time [24]. This latter refers to the establishment of physical, conceptual or mathematical of real phenomenon that is not easy to understand directly which will help to explain its behavior [25].

Figure I-1. The various aspects of soiling phenomenon that have been widely investigated

Research on the effects of soiling on solar system’s performance has been mainly carried out in the MENA region (Middle East and North Africa) [26] and widespread in the United States, Europe, Southeast Asia and India as shown in Figure I-2. In the MENA region, Morocco is especially considered as one of the main potential markets for renewable energy. Similarly, India emerged as the third largest solar market in the world after China and the US.

However, there are reports that India's daily soiling rate is the highest in the world [7]. Given the important effect of soiling phenomenon in India and Morocco, it has known an increased interest in recent years [27]–[32]. India and Morocco are known by the variety of their climate going from the north to the south. The Koppën-Geiger's classification considers the arid-desert-hot (BWh) climate is more pronounced in Morocco, mainly distributed in the south and southeast regions. The three main climatic zones of India are: 1. The savanna climate (Aw) in the southeast, 2. The arid-steppe-hot climate (BSh) in the west and south, and 3. The temperate-dry winter-hot summer climate (Cwa) in the northeast [33], [34].

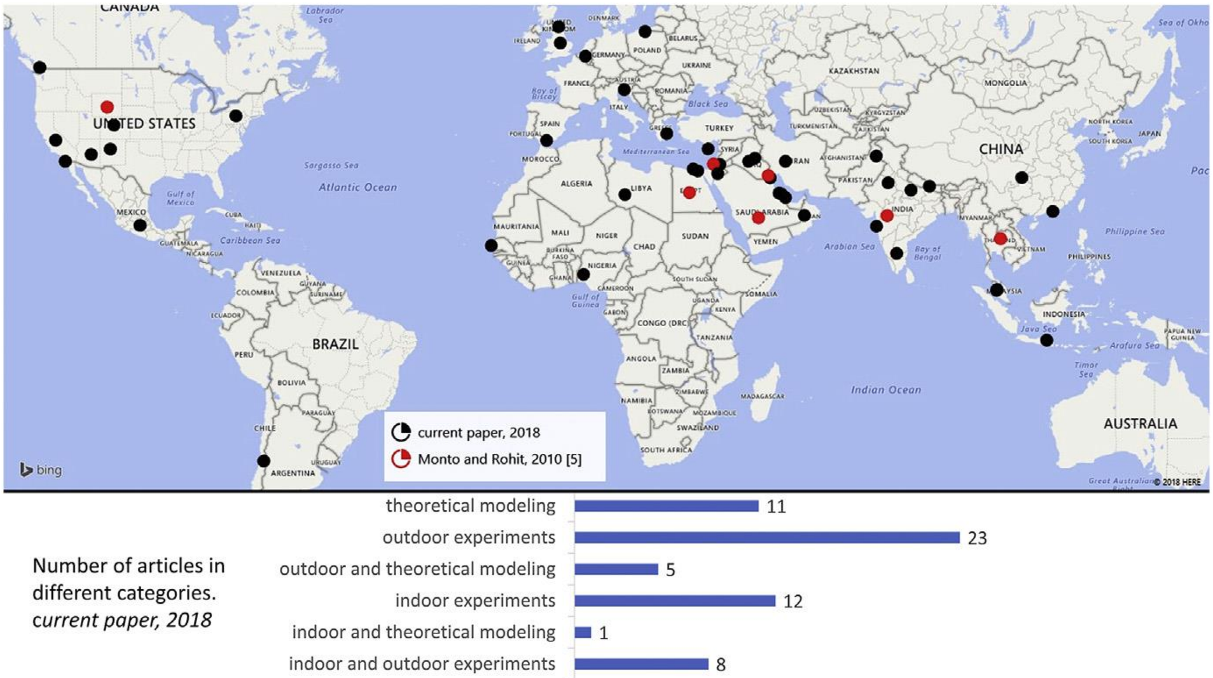


Figure I-2. Geographical spread of investigation on the effect of soiling on the performance of photovoltaic modules. The red dots refer to the distribution in 2010 while the black ones correspond to the distribution in 2018 [26]**.**

3. Motivation and objectives

Even though studies on the subject of soiling phenomenon started in 1942, but this problem was so far overlooked and got important attention only in the last decade. Furthermore, soiling phenomenon is highly depending on location which means that every investigation on this subject will only lead to the best understanding of its complex nature and the prediction of its effect. For this reason, the following objectives have been drawn:

1- Review on soiling phenomenon and their influencing factors (chapter II): this review represents an updated survey on various topics on soiling that includes mainly: summary of the reviews already published, soiling process and the different associated phenomena, the various ways of its quantification, an in-depth investigation on the factors influencing it and the different cleaning methods developed. This work gathered mostly all-important aspects that a new researcher looks for in the topic of solar photovoltaic soiling. Since Morocco and India share the most attractive solar energy systems areas and are among the highly soiling affected ones, hence, the last part of this review presents a summary, first of its kind, of the contributions made so far regarding this phenomenon by the researchers in these two countries. Critical analysis on the various aspects of soiling discussed is made and presented as a survey. This review will serve then as a one-stop reference and will be a paved guide for researchers who are interested in the topic of soiling of solar energy systems.

2- Review on modeling of soiling phenomenon (chapter III): modeling is an aspect of high importance since it will help to estimate the losses and to draw suitable and optimized strategies for soiling mitigation. Even though modeling is very important, the generated models remain only an approximation of the reality. This leads researchers to improve the developed models continuously. For that, an important step is to provide researchers with a comprehensive overview of existing knowledge and gaps on modeling and prediction of soiling, which can be used to define and prioritize further research on this issue. The review work proposed here is part of this step and it is entirely focused on the modeling and prediction of soiling effects on solar power plants.

3- Investigation of soiling phenomenon effect (chapter V): generally, to make comparison of soiling effect between two sites, researchers choose sites which are far from each other and which have almost different climate conditions [29], [35], [36]. Furthermore, soiling losses are usually assigned to the city/region where they have been carried out even that area represents only a small spot in the whole city. For these reasons, we studied soiling in seven sites which belong to the same region, the capital region of Morocco, but characterized by different environmental conditions. The same study has been re-conducted in five sites in Tamil Nadu state of India. An in depth-discussion of the different variables which would affect soiling effect is carried out as well. The effect of other variables that were overlooked is emphasized.

4- Modeling of the correlation between mass density and transmittance loss (chapter V): based on the data of this study, and on a comparison between the models developed so far, new model, more generalized, has been developed which can predict the transmittance loss based on mass density more accurately.

5- Characterization of dust particles and an investigation of the influencing factors of soiling images analysis. These mainly include shape, size, composition analyses, and an investigation on transmittance loss and coverage area relationship.

CHAPTER II : UPDATED REVIEW ON SOILING OF SOLAR PHOTOVOLTAIC SYSTEMS. MOROCCO AND INDIA CONTRIBUTIONS

This chapter is a part of the following published review and has been reused here according to the guidelines of the publisher.

Ref : Laarabi, B., El Baqqal, Y., Rajasekar, N., Barhdadi, A., 2021. Updated review on soiling of solar photovoltaicsystems Morocco and India contributions. J. Clean. Prod. 311, 127608. https://doi.org/10.1016/j.jclepro.2021.127608

1. Introduction

The review represents an updated survey on various topics on soiling that includes mainly 1. Summary of the reviews published, 2. Soiling process and the different associated phenomena, 3. Various ways of quantifying soiling, 4. In-depth investigation on the factors influencing soiling and 5. Soiling cleaning methods. This work gathered mostly all-important aspects that a new researcher looks for in the topic of solar photovoltaic soiling. Since Morocco and India share the most attractive solar energy systems areas and are among the highly soiling affected ones, hence, the last part of this review presents a summary, first of its kind, of the contributions made so far regarding this phenomenon by the researchers in these two countries. Critical analysis on the various aspects of soiling discussed is made and presented as a survey. This review will serve then as a one-stop reference and will be a paved guide for researchers who are interested in the topic of soiling of solar energy systems.

2. Summary of the reviews published

With regard to the review articles, several summaries of the work carried out on the subject of soiling have been published (see Table II-1). Each author has analyzed this research subject from a different point of view. In this section, we present the review articles published on the subject of soiling.

For instance, in 2010, [37] in their review have discussed two phases. Phase I linked to research conducted from 1940 to 1990, focused firstly on the impact of the features of the solar system such as inclination and nature of the surface on the accumulation of dust. Phase II which comprises research after 1990 and represented more comprehensive studies of dust deposition with greater precision in the investigations experimented. In the same context, in 2013, [6] have presented in their review the state of the art of research about soiling during the period from 1942 to 2012. In this review, they have summarized all studies about dust issues for transmissive and reflective surfaces, dust particle analysis and preventive and restorative mitigation techniques. In their research [38] have presented a summary of parameters affecting soiling. These parameters have been gathered into three groups: effect of dust properties, effect of PV system parameters and effect of environmental parameters. In 2014 [39] summarized research carried out over the past 70 years. In addition, they evaluated the patterns of dust repartition in different regions of the world, which show that the worst areas of the accumulation of dust in the world are situated in the Middle East and North Africa. While [40] carried out a review of the meteorological and geographic characteristics of Iraq in order to identify types, specifications and causes of the dust, as well as the equivalent effect on the photovoltaic modules. Whereas [41] carried out an analysis including soiling impact, factors that influence soiling and cleaning techniques. In the same year [42] has published an article which identifies the scientific contributions judged to be representative in the field of soiling impact on PV performances from the first studies in 1942 to recent ones in 2013 with an emphasis on the most cited. [43] presented a study, in 2015, on the impacts of variety types of contaminants on photovoltaic devices performance, considering outdoor and indoor experiments. In 2016 [44] have presented an update of their work [6] and cited all studies performed in 2012–2015 based on their content and interest. The work of [45] examined the factors which influence the ideal performance of the photovoltaic panel, where the authors categorized shading due to fouling into, namely: hard shading and soft shading. [46] examined and summarized the effects of dust on the performance of photovoltaic panels, the factors that affect the deposition of dust on their surfaces as well as the different experiment setups adopted to study soiling phenomenon. In 2017 [47] presented a review on soiling measurement methods. [48] gathered dispersed information on soiling effect and the different factors which affecting it. A depth comparison of mitigation methods encountered is given as well. Also, as a contribution, in 2017, [49] present a review of the soiling mechanism, while focusing on deposition, rebound, resuspension, as well as an appraisal of factors impacting soiling mainly the orientation of the surface and moisture. In 2018 [50] continue their work [44] and update the literature review on soiling of solar energy conversion systems and provide a complete list of the publications of 2016 and some publications of 2017. In 2018, [51] examined the effects of environmental factors on the accumulation of dust on PV panels and also detailed measurements methodologies and cleaning aspects. [52] published a thorough work about the different mechanisms happening in the dust process on modules that could help in the modeling and predictions of soiling effects for PV plants. A different approach has been adopted by [53]; they first proposed a review on climate factors that impact PV modules including dust effect. More, these authors also went through reviews of dust particles chemical characteristics, the mitigation strategies of dust-accumulation along with a discussion of adhesion mechanisms. We also found [54] who presented a detailed review on cleaning techniques . In the same year [55] published a review of studies on soiling in the Middle East and North Africa (MENA region), on cleaning strategies and modeling of soiling phenomenon. [56], in their work published in 2018, have presented a descriptive summary of microscopic and macroscopic factors affecting soiling. This latter comprises the main parameters namely airborne dust concentration, dust characteristics and particle deposition rates. In the same year, two reviews focusing on cleaning solutions have been published. The first one related to self-cleaning methods by [57] while the second one is a general overview on preventive solutions by [58]. In 2019 [59] in 2019 presented a comprehensive appraisal of the impact of all environmental factors, including dust deposition, on the performance of photovoltaic systems. In their review, they highlighted the different effects of fouling on the PV modules performance, some factors which affect dust accumulation and the cleaning frequency and mechanisms. In 2019 as well [60] presented a review on soiling impact on PV modules and cleaning methods. Recently [61], they published a review which highlights the impact of dust on PV modules and the different cleaning methods developed so far to mitigate soiling effect.

Table II-1. Summary of reviews regarding soiling phenomenon with indication of the aspects discussed. (A) All aspects*, (B) Soiling impact, (C) Factors influencing soiling, (D) Mitigation/ Cleaning methods, (E) Adhesion mechanisms, (F) Measurement methods, (G) Modeling

****All aspects mean that the review includes publications related to different aspects (modeling, investigation, composition, mitigation techniques….)***

		Aspects discussed							Year	Comments
		A	B	C	D	E	F	G		
Reviews	[62]	✓							2010	-
	[6]	✓							2013	Period covered 1942 to 2012.
	[38]			✓					2013	-
	[39]	✓							2014	Period covered: the past 70 years. Focus on cleaning methods.
	[40]	✓							2014	Related to Iraq country.
	[41]		✓	✓	✓				2014	-
	[42]	✓							2015	Period covered 1942 to 2013. Focus on the most cited articles.
	[43]		✓						2015	-
	[44]	✓							2016	Period covered 2012 to 2015.
	[45]		✓						2016	Focus on shading by dust.
	[46]		✓	✓			✓		2016	-
	[47]						✓		2016	-
	[48]		✓	✓	✓				2016	Focus on cleaning methods.
	[49]			✓		✓			2017	-
	[50]	✓							2017	Period covered 2016 and some of 2017.
	[51]			✓	✓		✓		2018	-
	[52]					✓			2018	-
	[53]		✓		✓	✓			2018	-
	[54]				✓				2018	-
	[55]		✓ *		✓			✓	2018	* Focus on MENA region.
	[56]					✓			2018	-
	[57]				✓				2018	Focus on self-cleaning.
	[58]				✓				2018	Focus on preventive solutions.
	[59]		✓	✓	✓				2019	-
	[60]		✓		✓				2019	-
	[61]		✓		✓				2020	-

3. Soiling process

Understanding, quantifying and controlling the settling of dust on the front surface of PV modules will highly depend on the comprehension of the processes behind soiling or dust accumulation. The soiling process is based on the following steps [63]: Generation of particles, Transport of particles, Deposition of dust particles and Adhesion of particles to the surface. Figure II-1 presents the soiling process and its steps. Each one of these is presented in detail in the next sections.

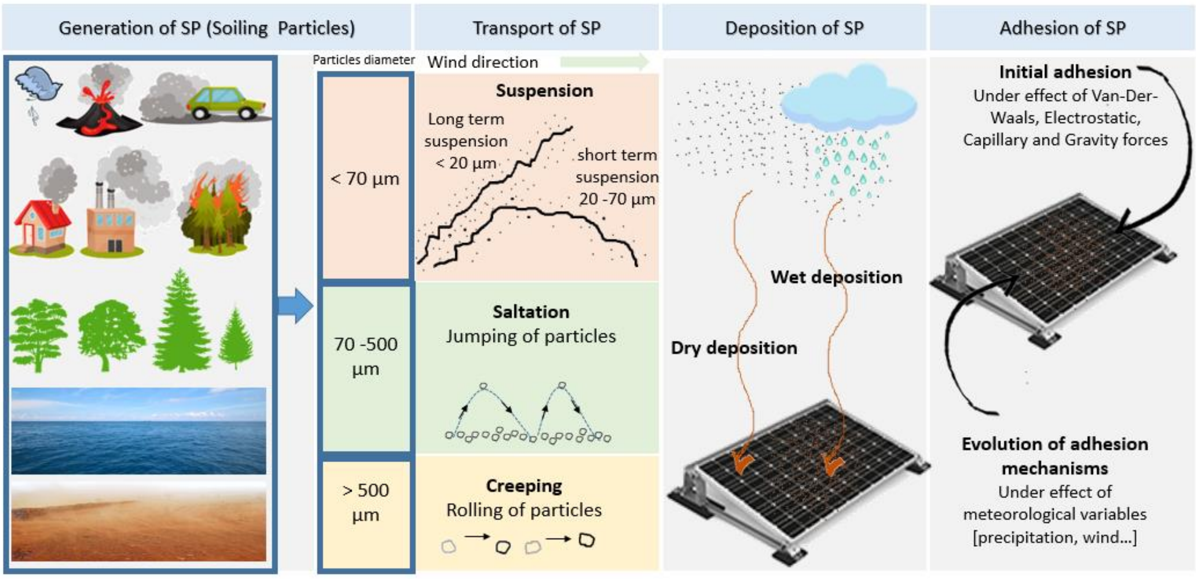


Figure II-1. Soiling process and its steps

3.1. Generation of particles

The origin of dust can be natural, or a result of human activities [64]. The main source of dust in the atmosphere is the Aeolian process, where wind involved in emission, transport and deposition of dust and sand [65]. There are three main sources of natural particles [64]:

- The terrigenous source: under the action of the wind, especially in desert areas, the particles are generated by soil erosion.
- The marine source: droplets of water are projected into the atmosphere under the action of the waves. After evaporation of seawater, sea salts are found in the atmosphere and form aerosols, the composition of which is close to that of seawater.
- The biogenic source: from the direct emission by plants, the biogenic aerosols are generated.

The main human activities which are behind the emission of particles are: agriculture, manufacturing industry (in particular construction sites), the residential / tertiary sector (mainly wood combustion, coal and fuel oil) and transport.

3.2. Transport of particles

The process of transporting dust on the surface of the PV panel is particularly due to the wind, called the wind process [63]. Generally, in the field of wind transport of particles, we mainly define three modes of transport. These three modes depend on the size of the particles and wind speed (see Figure II-1). The process called *saltation* concerns particles of several hundred micrometers in diameter and is defined as a displacement by successive jumps of the particles. The *creeping* process, on the other hand, is associated with the largest particles (> 500 µm). It corresponds to those which are pushed and which roll along the surface, essentially by the impact of the grains in saltation. The third mode of transport is called *suspension* and it concerns the particles with a diameter of less than 70 µm. As the term *suspension* indicates, the small particles governed by this phenomenon are transported in suspension and kept in the air by small turbulent vortices coming from the flow over more or less long distances (*long-term suspension* [< 20 µm], *short-term suspension* or modified saltation [20 to 70 µm]). The phenomenon of suspension therefore induces a notion of transfer [63].

3.3. Deposition of particles

In the atmosphere, the transfer of particles at interfaces can occur by dry deposition (in the absence of precipitation) or by wet deposition (in the presence of precipitation). Although much less efficient than wet deposition, dry deposition becomes the only way for particles transfer in the absence of precipitation [66] (Figure II-1).

- **Wet deposition**

Wet deposition includes several processes and a general distinction is made between wet deposition associated with precipitation (rain, snow, hail) and occult wet deposition associated with the impact of cloud droplets on a mountain or the sedimentation of mist droplets. Rainfall deposits are the most important overall.

- **Dry deposition**

If the wet deposition is an effective sink for aerosols, it is obviously very dependent on the presence of precipitation whose spatial and temporal distribution is very heterogeneous. In the absence of precipitation, the direct deposition of aerosols on the ground, known as dry deposition, plays an important role. We can distinguish the deposit on the surface due to the turbulent flow of aerosols and that due to the flow of sedimentation. The first dominates for small aerosols while the second dominates for large aerosols.

3.4. Adhesion of particles to the surface

The initial adhesion is highly influenced by the dust particle and the properties of the surface, its degree of smoothness or roughness, its chemical composition, its orientation, its electrical properties, its hardness, its optical properties, its mechanical motion, its temperature, and its micro or nano-characteristics [63]. The adhesion forces between solids are mainly forces of electromagnetic origin and of an attractive nature. They are the result of a combination of physical and chemical forces as well as mechanical stresses and tensions. The "surface forces" appear when the particles come into contact with solid walls and strongly attach to them. This is called the adhesion phenomenon. The main adhesion forces include Van-Der-Waals forces, electrostatic forces and capillary forces [65]. The gravity force of the particle can also intervene for the largest particles [63]. As a general rule for particle sizes smaller than 100 µm, the Van-Der-Waals force has the largest contribution [67] (Figure II-1).

Adhesion forces can be influenced by meteorological variables including: temperature, precipitation, wind and humidity, etc. Thus, as these factors change, the soiling effect changes as well. The effect of these factors on soiling is detailed in section 4: Parameters influencing soiling of PV modules.

4. Quantification of soiling of photovoltaic modules

Soiling is also a challenge for forecasting long-term performance and estimated service life [68]. Thus, the understanding of soiling and its quantification becomes an economic issue because of the cleaning costs [69]. There are different ways of quantifying soiling, in the field and in the laboratory, such as measuring the amount of dust deposited, measuring transmittance losses and evaluating the actual response of PV modules.

4.1. Quantification by measuring deposited dust

The most direct quantification of "soiling" is the measurement of its mass [70]. However, collecting dust from the panels requires a lot of work, since it is difficult to collect completely all the dust deposited during the assessment period. On the other hand, glass samples can be weighed effortlessly and precisely before and after dust accumulation. Collecting dirt from the surface makes it possible to analyze other properties such as its chemical composition and its particle size distribution [41], [47], [71].

The characterization of "soiling" by its mass represents directly the amount of particles gathered, which is helpful for investigating the physical processes of soiling. However, the mass of the particles accumulated does not correspond obligatory to the performance of the PV module. Sometimes, the mass has been shown to be proportional to the power loss of the PV module [41] and the reduction in transmittance [6]. Two phenomena can disturb this linearity: firstly, for the same mass of soiling, the smallest particles have more or less different optical properties, so they obscure more light [70], [72], [73] Second, for already soiled surfaces, newly deposited particles can deposit on existing particles and can therefore increase the mass of the deposit, but not the losses in transmittance [74]. In the context of PV performance, methods based on transmittance to characterize soiling are therefore more suitable [47].

4.2. Quantification by measuring transmittance

Soiling can be described by the reduction of light going through a transparent substrate, easily measurable using a Spectrometer [75], Solarimeter [29], [76] or Pyranometer [8], [77]. Generally, transmittance loss refers to the change of transmittance of glass sample when it is cleaned versus soiled [78]. The advantage of measuring transmittance is that it takes into consideration the distribution of particles on the surface.

4.3. Quantification by evaluating the real response of PV modules

The interest of the soiling study is to determine its effect on the energy produced by a photovoltaic devise. This allows the quantification of soiling based on the electrical characteristics of a real PV system, which is a cell or a module. Indeed, several studies have shown that all the parameters of the solar module (Icc, Vco, Pmax and FF) are affected by soiling [72], [79]–[83].

PV modules can have a random distribution of dirt on their surface [41]. Therefore, the benefit of utilizing normal size panels is that they take into account traces and deposition patterns of soiling which cannot be reproduced on small parts such as PV cells or glass samples [47]. The methodology adopted by almost all works on soiling of photovoltaic systems is: the measurement of the electrical characteristics of two photovoltaic modules (having the same surface, the same electrical and optical characteristics), one is naturally accumulating environmental soiling while the other is regularly cleaned. These measurements make it possible to define a soiling rate, commonly noted SR, which can be used as a derating factor (Derate Factor) in the analysis of the performance of the PV system [46], [84]–[87]. The soiling rate is a ratio which can be calculated by two methods, one based on the short-circuit current in case of uniform distribution of dirt, and the other on the maximum power in case of non-uniform distribution.

The three methods mentioned above can be gathered in the following table (Table II-2) by pointing out the advantages and the disadvantages of each one.

Table II-2. Advantages and disadvantages of the quantification methods of soiling losses

Quantification by:	Advantages	Disadvantages
measuring deposited dust	Direct quantification method. Allows performing a physico-chemical analysis.	Dust collection problems. Less representative to the real performance loss of the PV module.
measuring transmittance	Consider the distribution on the surface.	Glass samples required.
evaluating the real response of PV modules	More precise.	No information on the deposit density, the loss in transmittance of the glass and the adhesion of particles to the surface.

5. Factors influencing soiling of PV modules

The detailed assessment of soiling processes and their effect on PV systems performance is really a complex phenomenon due to the influence of many parameters that can be gathered into: parameters linked to surrounding conditions, meteorological conditions, soiling properties, the module characteristics and parameters linked to exposure conditions. These presents a combination of macro and micro & nano scale processes and factors. At the macro level, i.e. system-level, for example, there is wind turbulence in a PV field. At the micro and nano-scale, for example, we find particle size and surface adhesion mechanisms. [88] recapitulates some of these impacting factors in terms of time scales and size (see Figure II-2). The microscopic soiling processes are represented in green while the macroscopic environmental parameters are colored in blue. Controllable factors such as operation and maintenance strategies and module or installation design are indicated in orange.

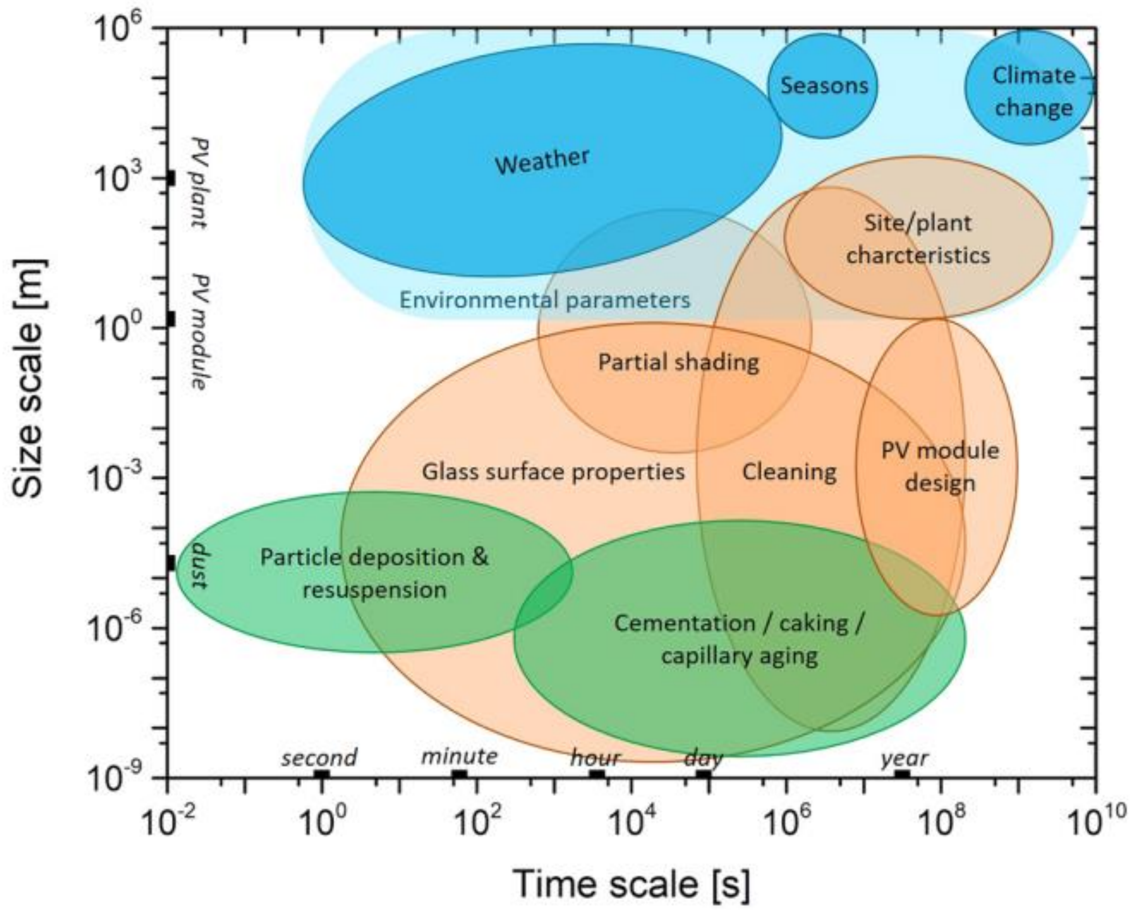


Figure II-2. Factors influencing soiling phenomenon [88]

In what follows, a review of studies carried out on the effect of each of the factors influencing the soiling identified above will be presented.

5.1. Effect of PV module characteristics

5.1.1. Nature of the surface

In general, dust deposits reduce the PV panels' performance, by decreasing the spectral and overall transmissivity of the glass superstrate of the module. However, the accumulation of dust changes from surface to surface as shown in Table II-3. For example, plastic, Polyvinyl Chloride (PVC) and acrylic surfaces generally show a greater loss of transmittance to that of a glass surface [89], [90]. This latter is the most commonly used material for manufacturing PV modules. Nowadays, surface engineering can help increase the amount of light transmitted through the glass layer in the cell and, as a result, the overall performance of the modules improves. Indeed, [91] indicated that it is possible to reduce the soiling effect due to the deposit of dust by approximately 3 to 4% by using an anti-reflective coating and micro-texturing of the surface.

Table II-3. Effect of surface nature on soiling

Study	Glass surface	Location	Effect
[92]	Anti-reflective coating and textured surfaces	Dhahran, Saudi Arabia	Power losses are reduced by 5% using an anti-reflective and texturing coating.
[93]	Super-Hydrophobic coatings (SHB)	Laboratory	The adhesion strength of the dust particles with the glass reduced from 90 to 12 nN due to the SHB coating.
[94]	Glass and plastic plates	India	A greater reduction in transmittance shown by the plastic plate.
[90]	Polyvinyl Chloride (PVC), glass and acrylic sheets	India	The glass sheets showed less reduction in transmittance than that of acrylic, which, in turn, showed less reduction than that of Polyvinyl chloride (PVC)
[18]	Coated and uncoated modules	Malaga, Spain	For coated modules, the energy losses due to soiling during the summer months were 10% and 12% for uncoated modules.
[91]	Coated and uncoated glass	Saudi Arabia	For coated glass, after 40 days of exposure, the transmittance decreases by 30% and by 37% for uncoated glass.

In other works [95], it has been found that the rate of accumulation of particles on a surface is maximum during the first thirty days of their exposure, regardless of the environmental conditions of operation. In fact, during this period, the surface attraction forces are maximum, which provokes the increase in the soiling rate. While beyond this thirty days' duration, these forces tend to decrease. To ensure better resistance to soiling, the surface of the material must have the following characteristics [95][6] : low surface energy in order to decrease the adhesion forces between the dirt and the surface, a smooth surface in order to limit the accumulation of dirt in the slots present in the case of high roughness, a chemically neutral surface of any substance that can promote adhesion with soiling particles; a hydrophobic surface to ensure good wettability of the surface and thus reduce the dirt retention to the surface.

5.1.2. Technology effect

The impact of soiling on the degradation of the optical and electrical performance of PV systems depends on the type of technology used [96]. [97] recorded a daily degradation of generated power of 0.095% for the monocrystalline and 0.071% for the amorphous, which explains why the amorphous PV is more resistant than the monocrystalline PV against the deposit of dust and is therefore better to be implemented in desert climates. [96] found that the average production of polycrystalline and monocrystalline PV modules decreased by 16% and 20%, respectively, for dust deposits of 0.9867 mg/cm². Thus, the percentage reduction in the performance of the monocrystalline module was greater than that of the polycrystalline module. In the case of a polycrystalline panel, the decrease was 3.01% and 3.55% for the monocrystalline panel after 11 weeks of exposure in outdoor conditions. In other studies, amorphous technology has shown the worst loss due to soiling compared to crystalline one [98] [99].

Regarding CPV technology, some experiments have been carried out at the sites: Institute of Solar Energy (IES) and the Center for Sustainable Energy Systems (CSES) in Madrid (Spain) and Canberra (Australia) [100]. The results, in general, show that PV modules are less sensitive to soiling than CPV systems, which their losses were around 14% on average in three different tests carried out at the test sites while for PV modules the average reduction in electrical power is only 4%. Another study was conducted in Saudi Arabia showing that, in a desert environment, soiling has an effect of about five times greater on the UHCPV system compared to a PV system [101]. Similar result has been found for CSP technology that this latter is more sensitive to soiling than PV modules. In the study carried out by [27], CSP technology has been shown a sensitivity to soiling three times greater than that of PV panels.

5.2. Effect of surrounding conditions

The impact of soiling on the photovoltaic modules performance is obvious. However, it highly depends on the location, consequently the composition of the deposit may be different and, therefore, the reduction degree in the performance of photovoltaic modules may vary from one location to another [1], [6], [39], [102]. On a seaside site, the constraints to which the modules are exposed are extremely different from those of a desert site. In addition, in the same installation site, geological constraints may also present differences in the properties of particles responsible about the soiling phenomenon. An installation site located on a plain will never present the same constraints as those of a site located on a hill [51].

5.2.1. Land cover

Land cover has been considered as a factor which increases aerosols in the atmosphere and thus increasing the soiling of solar energy systems [51]. Land cover includes traffic roads, water (ocean, sea…), forest, built-up area, grassland and cultivated areas [103]. Based on a study carried out by [103], the concentration of $PM_{2.5}$ changes according to the existing land cover and according to the corresponding season as well. The distance from the sea has been proposed that it has an inverse exponential relation with the mass deposition flux of sea-salt aerosols [104]. Built-up area as well as the human activities participate in defining the type and the density of particles which are responsible about soiling [82]. Forest in its turn presents an influencing factor by the generation of pollen and dried leaves [71].

5.2.2. Soil texture

Compacted soils tend to generate little dust, even during extreme sandstorms. In contrast, soils containing sand, silt and some clay are an important source of dust generation [105]. A procedure for identifying and understanding the soil properties of sites has been introduced in [105]. X-ray diffraction (XRD) was used to assess the mineralogy of the clay and the relative adhesion capacity of each soil sample from the sites studied. This study concluded that a site is not suitable for a solar power plant if its soil has shown a high adhesion capacity [105].

5.2.3. Bird droppings

Bird droppings are among the problems that affect PV installations performance. This organic matter prevents incident sunlight from reaching the cell [32]. Without cleaning, the areas which are affected remain shaded, creating potential hot spot areas. They can also alter the metal frames of the PV modules by causing corrosion. The degree of the impact of these excrements depends on the climate where the PV modules are installed. Studies have been carried out on this factor to assess the influence of bird droppings deposited on photovoltaic installations. According to [41] the deposit of bird excrement on photovoltaic modules can be a factor of a low impact on the photovoltaic cells performance in semi-arid areas. However in other cases, the effect of bird excrement on the performance of the module can be more important than that of dust deposit [41] . In deserts, dust accumulation is considered to be the main factor in decreasing the panel's performance, on the contrary, off-shore installations, in which bird nesting and excrement are the most predominant restrictive factors.

5.3. Effect of meteorological conditions

5.3.1. Temperature effect

- **Surface temperature**

Generally, if the temperature of the PV panels increases, the energy output decreases. However, in their work [106], based on lab simulation, found that the module with a higher difference in surface temperature has a higher energy output than the modules with a lower temperature difference, due to reduced accumulation of particles. The energy output ratio, which has been defined as the ratio between the energy output of a dirty module and that of a clean one, increased from 0.947 to 0.971 with the increase in the temperature gradient (Figure II-3). The deposition densities of the measured particles were between 0.85 mg/m² and 0.54 mg/m² for temperatures in the range of 20 to 80 °C (Figure II-4) [106]. Thus, the PV panel which has greater surface temperature has a lesser density [107].

Indeed, the photovoltaic module produces electricity when is exposed to sunlight, which provokes the increase of its surface temperature due to the effect of heating. This has a remarkable effect on the temperature difference between the ambient air and the surface of the PV module. This temperature difference engenders a noticeable temperature gradient nearby the surface and creates a force called the thermo-diffusion force. This force can be applied to submicron particles moving towards a cold surface or moving away from a hot surface at a given temperature gradient. Therefore, the increase of temperature difference can decrease the accumulation of dust density and increase the output power of PV panels due to the thermo-diffusion force [107].

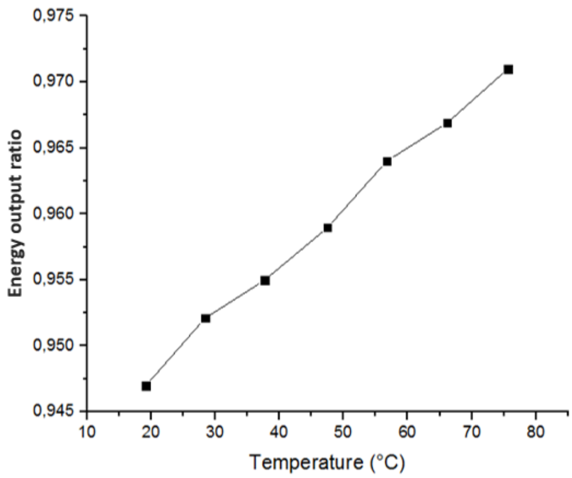


Figure II-3. Energy output ratio under different surface temperatures [107]

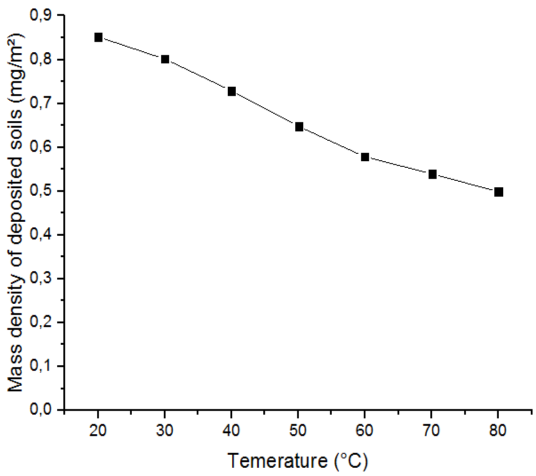


Figure II-4. Particle deposition density under different surface temperatures [107]

- **Ambient temperature**

The ambient temperature of the installation site of solar systems is among the meteorological influencing the soiling rate [108] [109]. Indeed, these influences, alongside the relative humidity, on the dew point temperature of the front surface of the photovoltaic panel from which there is a generation of water drops [95]. Furthermore, it has been found that temperature influences the viscosity of the air, which affects the concentration of airborne particles and therefore influences the soiling rate. In case of a decrease in temperature, the viscosity increases by increasing the concentration of aerosols in the air, and therefore the increasing of soiling rate.

5.3.2. Relative humidity

It has been widely proven that high relative humidity (RH) can increase the adhesion of particles to surfaces [110], [111]. [91] made systematic measurements of the adhesion strength between a 48 µm silica bead and a flat silica surface, under different humidity levels. The results show that the increase of relative humidity from 40% to 80% leads to an increase in the adhesion on the order of 80%, as illustrated in Figure II-5.

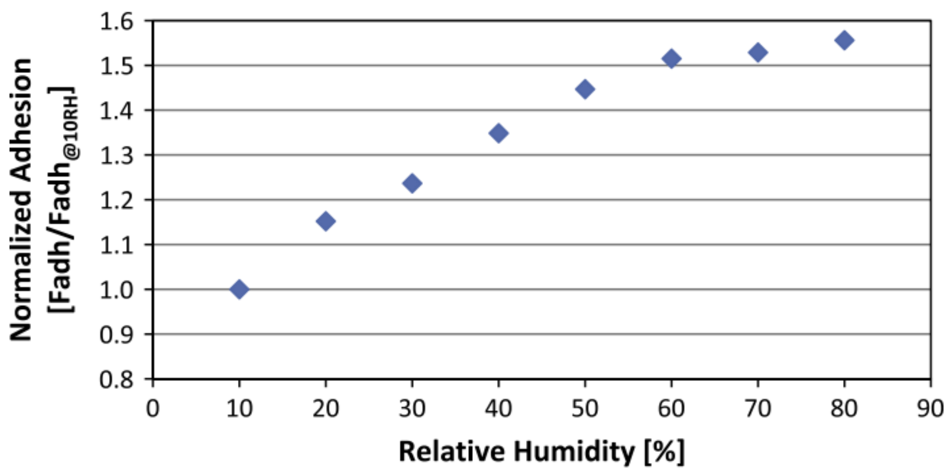


Figure II-5. Effect of humidity on adhesion strength [91]

Humidity can bind particles to the surface by three processes:

- **Cementation**

This process was first defined for solar energy systems by [111]. From this description, cementation has been assigned a significant importance in the soiling problem. Indeed, under humid conditions, the soluble fractions of the deposited dust are partially or totally dissolved by the water present on the surface. And while drying, they solidify causing the formation of a solid bridge (Crust) between the insoluble particles and the glass surface (see Figure II-6). This can provoke strong adhesion of dirt on the PV panels [49].

- **Capillary aging**

When the water vapor condenses in the voids (capillaries) between the particles and the surface, the corresponding capillary forces (Laplace pressure and surface tension) press the particles against the surface so that voids in the contact area may shrink or the particles may deform, causing an increase in the contact area and adhesion [49], [112]. Furthermore, this process can take place not only between the surface and the particles, but also between the particles (see Figure II-6).

- **Particle Caking**

The Particle Caking process increases particle adhesion by rearranging, agglomerating and compacting the particles on the surface (see Figure II-6).

While humidity is high, the water drops which are formed on the surface of the glass provokes small-scale suspensions of particles in the droplets, and when they dry, the suspended particles concentrate in a small volume, until they settle on the surface with larger particles. Small particles, due to the greater movement, will cover the surface and fill the spaces between the surface of the glass and the larger particles. As a result, the contact surface between large particles and the surface of the glass increases considerably, as well as the corresponding adhesion forces [113].

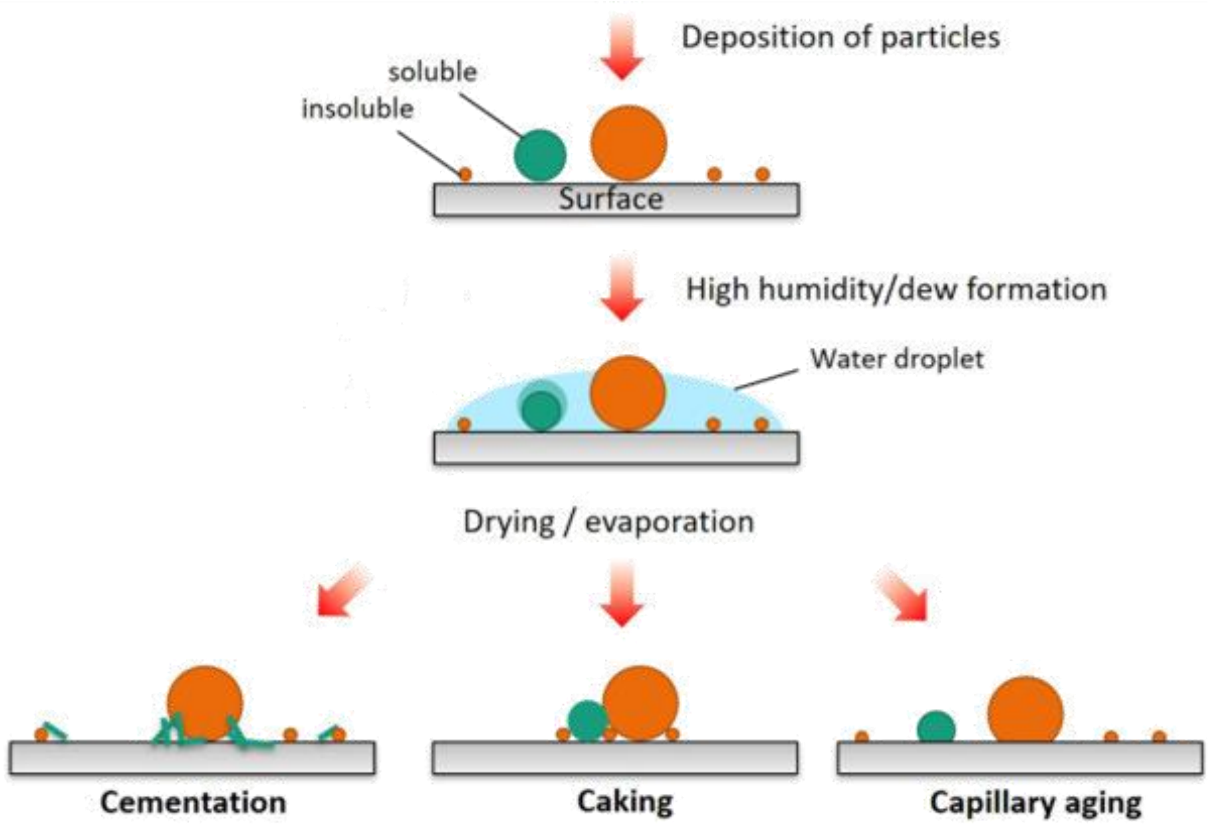


Figure II-6. Mechanisms increasing the adhesion forces [113]

In addition to adhesion, humidity affects the wind transport of particles by influencing the inter-particle forces at ground level. By increasing these forces, the threshold of the wind speed necessary to transport a particle in the air increases, which lead to the reduction of the density of particles in the air and consequently the reduction of the soiling rate. The effect of inter-particle forces on the wind transport of particles is higher when their size is less than 50 μm [95].

5.3.3. Rainfall

The effect of precipitation on the variation of the soiling rate has been evaluated in several research works reported in the literature [6], [71], [119], [72], [76], [101], [114]–[118]. These studies revealed different results on rainfall effect. Indeed, this depends on several other parameters related to the rate of rainfall recorded on the installation site as well as to the speed and direction of the wind accompanied it [95]. Precipitation has been shown to play a dual role in terms of dust accumulation. They can be a good cleaning agent when they occur frequently and abundantly. The cleaning effect is clearly visible for the largest particles (pollen, around 60 μm) [71], while it is less significant for the smallest particles (2 to 10 μm). Conversely, light precipitation tends to drop suspended particles in the atmosphere and generally increases the adhesion of dust to the surfaces of PV modules which increases the effect of soiling [101].

5.3.4. Wind speed and direction

The wind also acts as a natural cleaning mechanism. However, various parameters determine its effectiveness in removing dust. Depend largely on its speed and relative direction to the panel, the size, shape and density of the dust particles and the microstructure of the dust layer. With the purpose of assessing the impact of wind speed on the soiling rate of surfaces, numerous studies have been carried out and reported in the literature [111], [120], [121]. In [122] study, simulations of soiling on glass surfaces exposed to the winds revealed that the density of soiling decreases with increasing wind speed. [111] observed that at a speed of 25 ms^{-1} and a relative humidity of 40%, the wind could remove approximately 80% of the dust particles with a diameter $\geq$ 50 μm, approximately 50% of the particles of 25 μm and < 5% of 10 μm particles. However, the effect of this meteorological parameter on the rate of accumulation of soils has not been fully identified.

5.3.5. Dew formation

Soiling has an impact negative on the performance of solar PV systems which can be a severe problem when it is combined with light rain, moisture or more particularly with early morning dew. This latter promotes the cementation process and makes the dust very hard to remove [123]. Dew can also have a positive impact if it is managed or enhanced to perform the cleaning of the PV modules [56]. However, in order to get more practical results on its effect, the suppression or the enhancement of dew should be more studied.

5.3.6. Airborne dust

Particle matter (PM) is defined by the United States Environmental Protection Agency as "a mixture of liquid droplets and solid particles found in the air. Some particles, such as dust, dirt, soot, or smoke, are large or dark enough to be seen with the naked eye. Others are so small they can only be detected using an electron microscope" [124]. Particulate matter has a considerable effect on the performance of solar energy panels [104] and higher PM concentration lead to a higher dust accumulation [56]. In India and China, they can be responsible for ~1 and 11 GW of solar power reduction [125]. In the study conducted by [126] where they investigated the correlation between environmental parameters and soiling losses, they found that PM has shown the best correlation with soiling with an adjusted coefficient of determination of 70%. In another study of [104] they prove it is the best predictor of soiling losses. On the other hand, [127] they prove the inverse that PM (PM_{10}) has a low correlation with solar energy loss. This is explained by the fact that the effect of PM_{10} is complex due its relationship with other environmental factors.

5.4. Effect of exposure conditions

5.4.1. Tilt angle

Figure II-7 shows an overview of the effect of the angle of incidence on two soiled photovoltaic modules, one with normal incidence and the other with an incidence greater than 0. In general, the soiled module has absorption and reflection losses due to soiling. However, when the incident light at an angle of incidence greater than 0°, there are more losses in reflection [128].

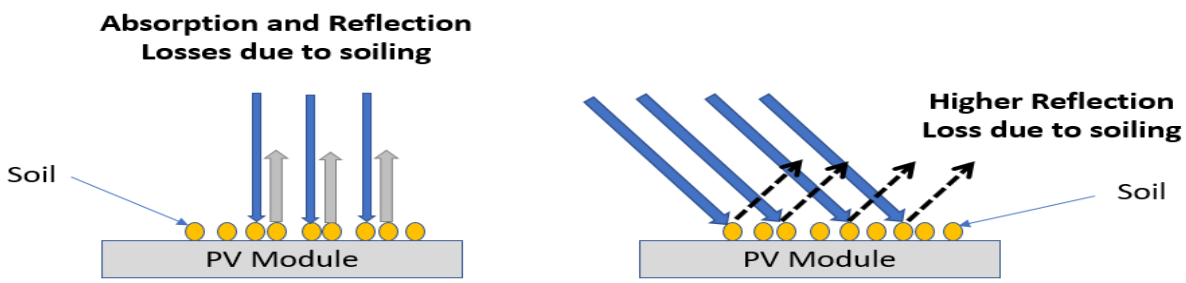


Figure II-7. Effect of the angle of incidence on a dirty module

The angle of inclination of the photovoltaic panels has a high effect on the settling of dust. The transmittance reduction due to soiling decreases when the angle of inclination of the glass sample increases from the horizontal position (0°) to the vertical position (90°) [39], [71], [72], [102], [119], [129]–[131]

5.4.2. Orientation

Orientation of the modules is another factor which influences the accumulation of dust along with tilt angle. When the modules are facing the wind, the accumulation of dust will be more influenced than when they are in the opposite direction [51]. The same conclusion has been drawn by [46], [48], [62], [122]. [102] concluded from their experiment that at the same tilt angle and different orientations, dust accumulation was almost same but slightly high for the sample that was facing the wind. The possibly cause that has been expected to be the reason behind this result is that wind was blowing more dust mainly from a nearest factory of cement on the surface of that sample. On the other hand, in the study conducted by [132], they found that the samples which are facing the wind experienced the least dust accumulation in comparison to those which are in an opposite direction. This has been explained by the fact that wind blowing accompanied by rain always has a positive effect on samples facing the wind direction (Figure II-8). This means that the positive effect of facing the wind direction is conditioned by the presence or the absence of rain.

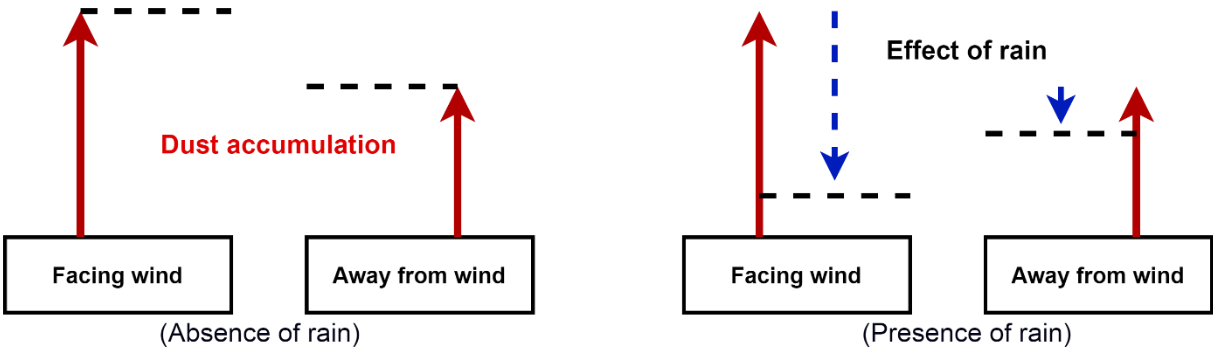


Figure II-8. Schematization of the effect of the wind combined with rain according to the direction of the PV module (reproduced from [132]***)***

5.4.3. Height of the installation

A study on the vertical profile of particles number concentration measured 50 m downwind in a freeway has been conducted by [133]. They have been concluded that the concentration is changing with the height and increased within the 5 m from the ground. In Australia, during a dust event, [134] measured a 500 m vertical profile of PM10 dust concentration. The results obtained have shown that PM10 dust concentration decreased with height and followed an exponential profile. These two studies show that may have an effect on dust accumulation of

PV modules and it should be taken into consideration. More investigation is required to well study its effect on soiling phenomenon.

5.4.4. Tracking effect

Most large-scale photovoltaic panels are installed with a permanent tilt angle. Photovoltaic systems equipped with solar trackers are used to keep as possible the front surface of PV panels perpendicular to the direct solar radiations for producing maximum power and minimizing dust accumulation [41]. The impact of tracking on the variation of the soiling rate has been evaluated in several research works reported in the literature [41], [135], [136]. These studies have shown that fixed photovoltaic systems are the most affected by the soiling phenomenon compared to those with solar trackers.

5.4.5. Season effect

The weather variables mentioned above vary depending on the season. This affects the settling of dust on the PV panels. Consequently, the degradation of the performance of PV systems caused by soiling is different according to the seasons [137]. A study done by [2] in Cyprus has shown that the power of photovoltaic modules is maximum in winter and decreased slightly in spring and autumn. Thus, a significant reduction was observed during the summer months. In the study of [138] in Abu Dhabi, it has been reported that the greatest reduction in the transmittance of solar glass was recorded during the summer. This is due to the greater accumulation of dust resulting from sandstorms and lack of precipitation. In addition to the effect, research has shown that the mineralogical nature of the deposited particles also varies with the seasons. This is explained by the different wind speeds. Indeed, each particle requires a threshold speed to be transported [102].

5.4.6. Exposure time effect

The decrease in power produced by a PV system due to soiling as a function of exposure time is reported in the literature [92], [102], [116], [117], [139], [140]. These studies have shown that this reduction can be up to 50% or less than 2.50% and that the considerable variations in the performance of PV modules depend on the exposure time. In fact, in the absence of any way of cleaning, the dust accumulation on the panels increases with the time, but beyond 30 to 60 days of exposure [95], the accumulation saturates. Which means that increasing the days of exposure will increases the accumulation is only valid in the first two months and after that, this relationship is not valid anymore. Furthermore, in reality, this relationship is hard to be fully followed because the accumulation is influenced by the meteorological variables (rainfall, wind, dew…) that they can reset (clean the panels) or worsen it at any time. As a conclusion, the exposure time does not provide enough information on the reduction of solar radiation due to the accumulation of dust since we cannot say that this number of days is equivalent to this soiling effect.

5.5. Soiling properties effect

The properties of dust, especially chemical, morphology, shape, size and weight, have a very significant effect on its accumulation and on the degree of reduction of transmittance and therefore on the performance of PV systems. Although many studies concern soiling effect assessment, other ones are concerning the properties of the particles responsible for the soiling phenomenon. However, the available information is only valid for the specific location in which the tests were performed.

5.5.1. Chemical composition

The chemical composition and the mineralogical properties of particles deposited on the surface of glasses is a significant factor of soiling phenomenon, particularly optical losses. It also affects cementation processes, due to the fact that the solubility of particles in water and their stability under acidic or basic conditions changes according to the mineralogical and chemical properties [113]. It is dependent on the emitting source and thus reflects the environment from which the soil originates. Studies on the chemical composition of soils collected in different sites around the world show that the composition of dust varies considerably from one region to another due to the environment. Table II-4 shows the observed chemical compositions of the dust collected at different locations, as well as the analysis techniques used. The sand particles based on silicon oxide generally dominant in the desert regions of the Middle East.

Table II-4. The observed chemical composition of the dust collected in different places

Ref.	Site of dust collection	Analysis technique	Chemical composition
[91]	Dhahran, Saudi Arabia	XRD & SEM-EDS	Calcite and quartz represent 60% of the dust particles.
[102]	Helwan, Egypt	XRD	The dominating particles are quartz and calcite while dolomite and clay minerals are present with low amounts.
[141]	1. Perth, Australia 2. Babuin, Indonesia	XRD & SEM-EDS	1. Oxygen (34%) and silicon (29.14%) were the dominating elements. 2. Calcium (32.42%), oxygen (24.59%) and iron (23.37%) were the dominating elements.

[142]	Beni-Suef, Egypt	SEM-EDS & XRD	Silicon and Oxygen were the most dominating elements.
[143]	Sharjah, United Arab Emirates	XRF & XRD	Natural dust studied is composed of SiO_2 (45.53%), CaO (24.62%), Al_2O_3 (10.83%) and others.
[144]	Doha, Qatar	XRF & XRD & SEM-EDS	Dominating minerals were dolomite, calcite, quartz and gypsum.

The chemical composition of dust particles effect on the performance of PV panels has been studied by [70]. Dust particles, with different morphologies, deposited on the PV panel surface and the maximum power output (Pmax) and short-circuit current (Isc) were measured. It has been found that at the same density, the carbon of average diameter 5 µm had a more significant effect on the degradation of Pmax and Isc, followed by the cement of average diameter 10 µm and the three types of limestone particles with an average diameter of 60 µm, 70 µm and 80 µm. [145] also studied the impacts of five types of dust on a PV module performance. The results revealed that ash particles accounted for the highest voltage reduction, followed by red soil, calcium carbonate, silica, and sand.

5.5.2. Particles size

The size of the particles that settle on glass surfaces is a significant factor affecting the effect of soiling, especially on optical losses. It also affects the adhesion forces between the surface and the particles. Indeed, the size of the particles deposited plays a significant role in the absorption, scattering and reflectance of the incident sunlight [146]. For example, larger and porous particles can transmit more light than those of angular and diagonal shapes [141]. Studies conducted in this context often show that the optical losses for the same density of deposited dust are greater for smaller particles [41], [46], [70], [72], [73], [147]. In addition, the adhesion forces of particles vary considerably with the size of the particles [91].

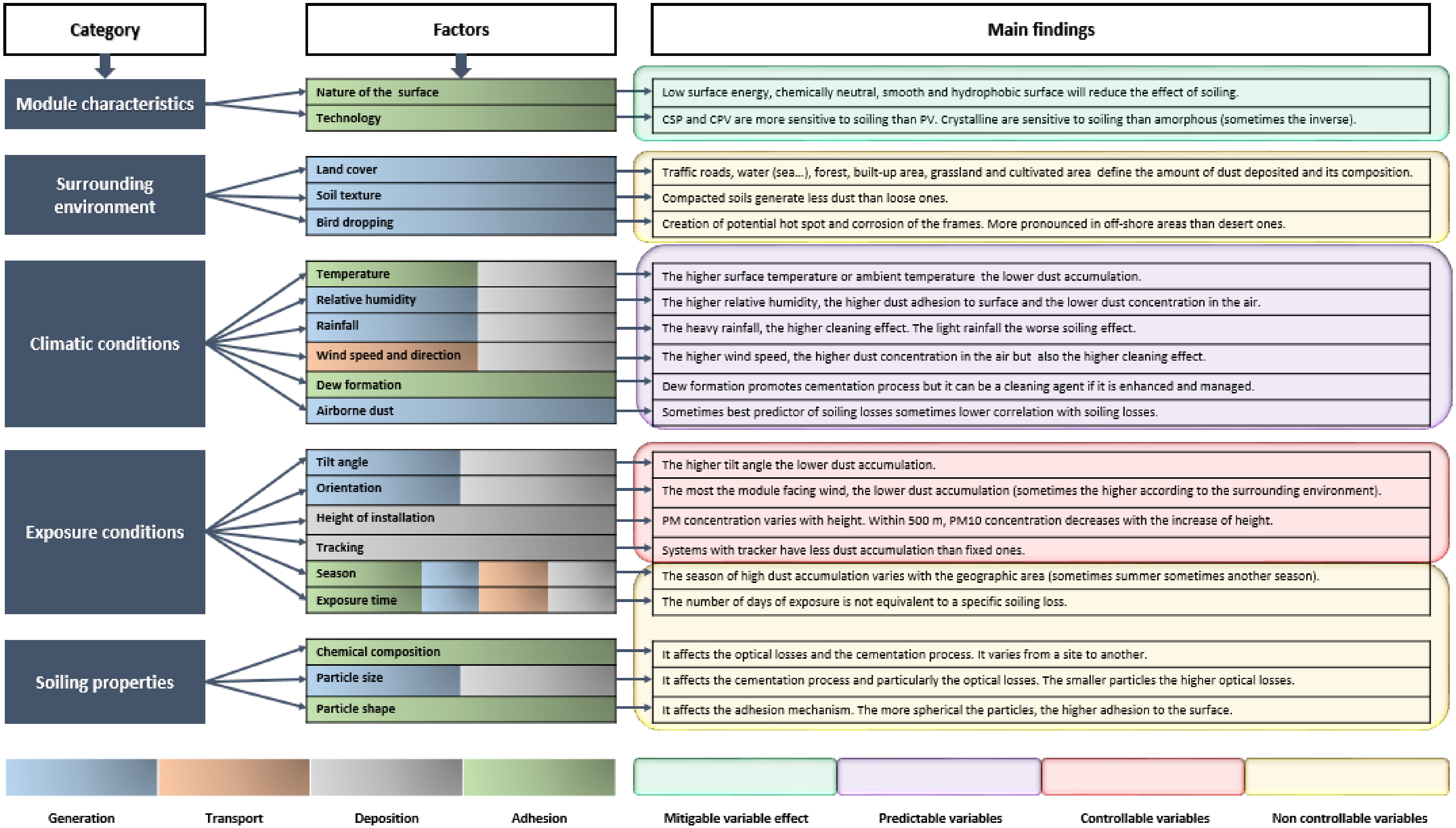
5.5.3. Particles shape

The particles constituting the soils come in different forms, namely round, tubular or even partially or completely sharp. It should be noted that a mineral can come in different forms depending on the nature of its transport [148]. Therefore, the effects of these particles on degradation by soiling are different [141], [149]. Thus, the dust particle shape had a significant impact on the adhesion strength to the surface. The adhesion strength increases as the particles become more spherical; this is due to the fact that spherical particles have higher contact with the surface [150], [151].

5.6. Summary

Figure II-9 presents a summary of the factors influencing soiling of solar energy systems. According to the above literature, the main findings regarding each factor are detailed below. Taking into consideration the soiling process steps (generation, transport, deposition and adhesion), the factors are categorized depending on which steps their effect is present. The figure shows as well another repartition which divides the factors to: mitigable variable effect, predictable variables, controllable variables and non-controllable variables.

Figure II-9. Summary of the factor affecting soiling and their effects



6. Cleaning methods for solar modules

The development of different techniques for the mitigation of soiling and dust effect is the result of the concern to keep the PV modules cleaned. To recover the performance of the PV panel that is reduced because of dust, it is important to conduct periodic cleaning. However, the environmental conditions always play an important role in determining the frequency of cleaning required [53]. Several cleaning techniques are used in removing settled dust particles from the surface of the panels, such as manual cleaning with water and labor, mechanical removal of dust by brushing, blowing, vibrating, ultrasonic, electrostatic and self-cleaning [152]–[154].

6.1. Natural removal of dust

The natural means of cleaning dust from the PV panel's surface are rainfall, wind, and gravity. Water is the best efficient cleaning agent and high rates of rainfall decrease the impact of soiling. Although rainfall recovers the power output of dusty solar panels, it cannot be depended upon for cleaning as it occurs occasionally and minimally in dry regions [53].

Wind can pull dust particles off the PV surface and thus improve the PV system performance. [155] stated that an increase of the wind velocity resulting in a high heat dissipation from the surface of the PV cell and a decrease in the relative humidity that in turn, also result in the improvement of productivity. While wind can have a positive effect, it also cannot be relied upon completely. As well as being unreliable in less windy regions, wind may also increase dust accumulation [53].

Dust deposition on the modules cover is also affected by the angle of inclination. Inclining the PV modules surface can decrease the deposition of dust through the gravity effect, but it can also reduce the solar energy captured by the module [53]. Elsewhere, the increase of the tilt angle has shown reductions in dust accumulation [90], [119].

6.2. Manual cleaning by labor

The manual cleaning by labor represents the traditional way of cleaning dust accumulated on the surface of the PV modules. If arranged in a proper schedule, the method is efficient as it allows removing even hard soiling like bird excrement or cemented dust from the PV module effectively by manpower [156]. However, there are two disadvantages for this method. First, manual operation is hard in the harsh desert areas and water transportation to the power plants is costly [48]. Second, the labor cost for cleaning may be quite expensive especially for large scale PV plants [152], [153].

6.3. Mechanical removal of dust

Mechanical methods to remove dust from the PV modules surface comprise mechanical wiping, blowing, and the use of removable covers. Electromechanical methods encompass shaking or vibrating the PV module panel and using subsonic or ultrasonic waves to break dust adhesion [48].

The brushing methods driven by the machine clean the solar module with a broom or brush which and they are designed in the form of windscreen wipers. However, firstly, the abominable working environment of the solar cell makes the maintenance of the machine difficult. Secondly, because of the small size and the strong adhesion of the dusts, the cleaning method is inefficient. Due to the large area of solar plants, the cleaning machine required huge investment as well. Finally, the solar panels surfaces can be damaged by the brush while wiping. The blowing method cleaning of the solar panels with wind power is an effective cleaning one except the low efficiency, high energy-consumption and the unsatisfactory maintainability of the blower. Removing the dusts with vibrating and ultrasonic is also a valid mechanical cleaning method [152], [153], [157].

6.4. Self-cleaning methods

The method that can be most optimal for removing soiling from surfaces is to apply modifications to the surface to obtain self-cleaning properties. These self-cleaning methods are developed to solve labor costs and take into consideration the areas which are difficult to be reached through labor. Various self-cleaning methods have been developed for soiling mitigation [48]. These are classified into two categories: The first category is altering the morphology of PV modules surface for better efficiency by introducing the super hydrophobic surface and super hydrophilic surface. The second category is the use of electrodynamics screen based on the fundamental concept of the particle's movement due to the electrostatic reaction on the dust [53].

6.4.1. Self-cleaning nano-film

Self-cleaning Nano-films which could be coated on the surface to keep it clean should be transparent and they are usually made of super-hydrophilic material or super-hydrophobic material. This means the self-cleaning mechanism of the Nano-film includes two strategies super-hydrophobic or super hydrophilic.

- **Super-hydrophilic film**

The most known super-hydrophilic film is titanium dioxide TiO_2, which, in addition to the hydrophilic property, also has a photocatalytic characteristic. This self-cleaning method has two steps. The first phase is a photocatalytic process, in which titanium dioxide under the effect of ultraviolet radiation breaks down organic dust. Then in the next step, due to the super-hydrophilic property, raindrops, rather than gathering in one place, spread over the entire surface and wash away the dust particle [158]. Most researchers focused on the preparation, doping and modification of this material. This self-cleaning method cannot be used in solar cell array because they worked mostly in the desert region with rarely rain [152].

- **Super-hydrophobic film**

Super-hydrophobic surfaces such as lotus leaves show extremely low wetting property and greatly high hydrophobicity. Nanostructures of these surfaces could enhance contact angle over 150°. So, the water droplets that hit the surface would quickly roll off, carrying dust and other particles with them [158]. Nevertheless, most studies regarding super-hydrophobic surfaces have focused mostly on enhancing the non-wetting property itself. It is still a question of whether the super-hydrophobic surface can be practically applicable in areas such as self-cleaning surfaces on solar panels [152].

6.4.2. Electrostatic removal of dust

The concept of dust's electrostatic property was used to develop the electrodynamics screen, currently known as EDS. Based on the fundamental concept of the particle's movement due to the electrostatic reaction on the dust, which might come in positively charged or negatively charged condition, the EDS will eliminate the dust whenever it deposited on the surface of the panel from one edge to the other edge. As shown in Figure II-10, when an AC current energizes the EDS electrodes, a traveling wave known as the electric curtain will be created. The charged particles from airborne which settled on the EDS surface will be entrained to move along accordingly to the electric curtain direction until it pushed out at the end of the surface [159].

When there is a high potential on the solar panels surface, the charged and unloaded dust will be attracted to the panels due to electrostatic forces. Then the dust particles will eventually be charged by the solar panels, so that they have the same electrical charge and the electrostatic forces between them are repulsion. Finally, dust particles will float away from solar panels.

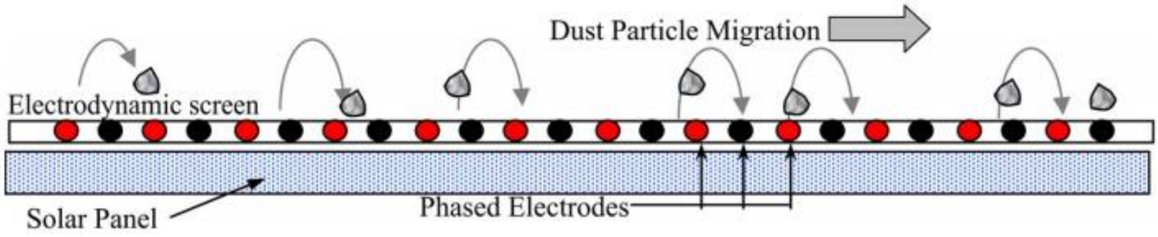


Figure II-10. The working conceptual of EDS [159]

6.5. Comparison of the PV panels cleaning techniques

Based on the comparison of the cleaning techniques conducted by [48], the summary presented in Figure II-11 has been prepared. The main conclusion that can be drawn is that every method has its own strengths and weaknesses. The usage of any method depends on the site/installation characteristics and weather conditions which make some methods perfect for some areas but not efficient in other areas. Some methods are not controllable such natural cleaning and others need more improvements such as self-cleaning.

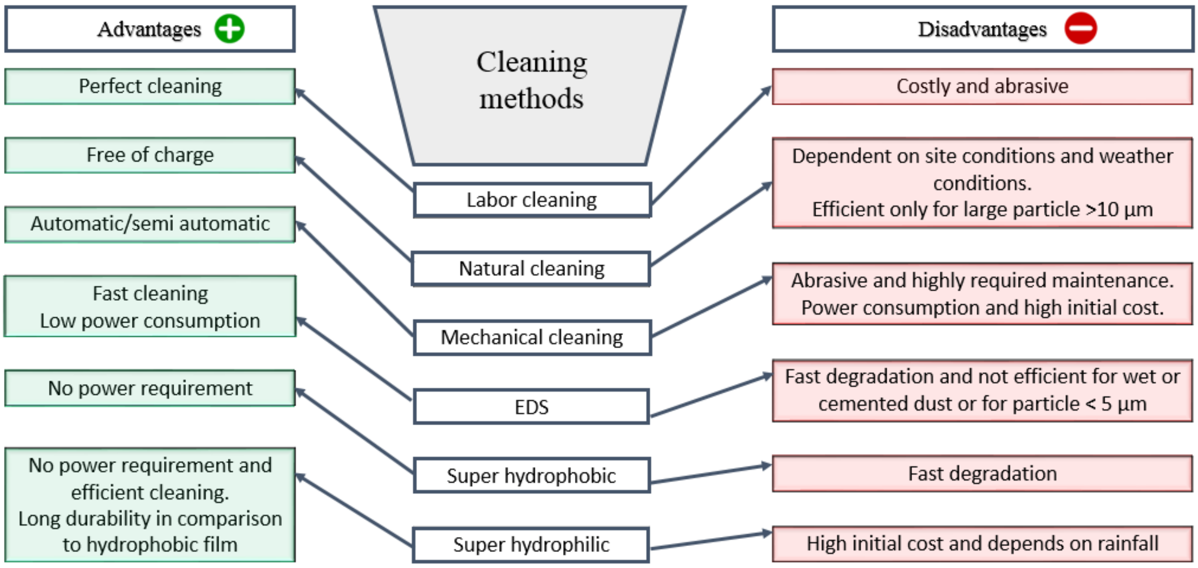


Figure II-11. Summary of the cleaning methods and their advantages and disadvantages

7. Studies conducted in Morocco and India regarding soiling phenomenon

India as China and MENA regions known by high solar potential are also highly soiling-affected. In this section, the main studies conducted in India and Morocco regarding the subject of soiling phenomenon will be presented. Some studies have conducted in other locations than Morocco/India, but we mention only the location in Morocco/India.

The used references include only journal articles or reviews, conference papers and book chapters. The research for relevant publications has been conducted based on the keywords:

solar energy, soiling, India, Morocco, in the databases: SCOPUS, Science Direct, Google, Google Scholar, ResearchGate, Wiley and Springer.

Morocco is considered among the largest potential markets for renewable energy in the Middle East and North Africa (MENA) region. In Morocco, the subject of soiling of solar energy conversion systems has known an increased interest in recent years. Indeed, the number of studies carried out increased in comparison to the beginning of 2017 where the number of publication represents only 25% of the current number [160]. Table II-5 presents a summary of the studies carried out in Morocco, their location, and the technology used as well as the main results obtained.

India is developing as one of the major solar energy markets in the world and in the process of catching up with the two leading countries like China and the US. Currently, India ranks as the third-largest solar market in the world. However, the daily soiling rates reported in India are among the highest ones across the world [7]. Table II-6 presents a summary of the studies carried out in India, their location, and the technology used as well as the main results obtained.

Morocco and India are characterized by different climate zones according to the Koeppen-Geiger classification. The arid-desert-hot climate (BWh) climate is more marked in Morocco mainly in the south and the southeast, while in India three dominating climates can be found. A tropical-savannah climate (Aw) in the south-eastern part, an arid-steppe-hot climate (BSh) in the western and southern part, and a temperate-dry winter-hot summer climate (Cwa) in the north-eastern part of India [33], [34].

Table II-5. Studies conducted in Morocco regarding soiling phenomenon

Ref.	Location	Technology	Period	Main results	Category
[161]	Morocco (exact location not specified)	Irradiation sensors	7 months	The soiling losses recorded are: up to 12% for DNI measurements and 8% for GHI. The soiling effect highly affected by location and sensor type.	Instrumentation
[162]	Marrakech Ouarzazate Oujda Dakhla	PV (CdTe)	1 year	The monthly average change of CdTe PV performance due to soiling estimates are 0 to < -3% with cleaning.	Assessment
[163]	Atlantic Ocean	Irradiation sensors	6 months	Drop of 20% of the initial values of the efficiencies within 5 months.	Instrumentation
[4]	Tantan, Agadir	CSP	6 months	The results revealed that the local linear trend has shown to be the best-fitted model describing the long-term change in the cleanliness. It performs even better when an optimal discount factor of 0.95 is considered.	Modeling
[164]	Tantan, Agadir	CSP	6 months	The results showed that the span of the local regression s = 0.75 is judged appropriate for describing the studied data and their underlying pattern. This has been confirmed by examining the (Q-Q) plot and the (ACF) function.	Modeling
[165]	Oujda	CSP	3 months	During a period of three months, the drop in cleanliness is: 45% and 33% for glass and mirrors in aluminum, respectively in a horizontal position. 14% for both reflectors at an angle of + 45°. For mirrors installed at 0° and - 45° angles remained clean with a purity average of about 97% for both types of mirrors.	Assessment
			-	The analysis of soil particles deposited using XRD technique has shown that the abundant elements are Quartz, Calcite and Muscovite.	Particles properties
[166]	Skoura (40 km from Ouarzazate)	CSP	1 year and 9 months	During the exposure, the soiling rate is a function of the variation of relative humidity and wind speed.	Assessment
[167]	Rabat	HCPV	1 month	The monthly energy gain is 1881 kWh.	Assessment
			-	A semi-automatic system for HCPV modules cleaning has been proposed.	Mitigation/ cleaning
[151]	Rabat	PV	-	Based on X-Ray Diffraction (XRD), X-Ray Fluorescence Analysis (XF), Thermal Analysis and Infrared Spectroscopy (IR) the mineralogical composition dust deposited on PV modules was determined. The mineralogical analysis shows that the dust contains quartz, calcite, kaolinite and dolomite. XF results show that silica, alumina, iron oxide, calcium oxide, magnesium oxide and potassium oxide are the most abundant elements in the dust.	Particles properties
[9]	Rabat	HCPV	3 months	Energy gain of 10%. When tilt angle increases the soiling effect decrease.	Assessment

[168]	Tantan, Agadir	CSP	6 months	The reflectance has been modeled using nonlinear autoregressive with exogenous inputs (NARX) and Bayesian regularization. According to mean square error, the best model found to be the one with 30 neurons and 2 tapped delay.	Modeling
[169]	Rabat	PV (Glass sample)	4 months	The soiling rate is 5% per three months of a dry period.	Assessment
[170]	Seaside site Deseret site	CSP	-	The deposits found on the mirror samples installed in the desert site contain only sand particles while those collected from samples of the seaside site contains salt and sand particles.	Particles properties
[171]	Tantan, Agadir	CSP	6 months	The results shown aluminum mirrors are less vulnerable to soiling than glass mirrors. However, these latter are the best in recovering their reflectance after a rain event.	Assessment
				Based on the Akaike Information Criterion (AIC), the Dynamic Factor Analysis (DFA) found that the best model has two shared trend patterns.	Modeling
[160]	Rabat	PV (Glass sample)	8 months	A correlation between soiling rate of solar PV glass and weather parameters (irradiance, ambient temperature, humidity, rainfall, wind speed and wind direction) using artificial neural networks has been done. The development of the model is based on Levenberg-Marquardt back-propagation algorithm, and the active functions Tansig, and Purline. The accuracy of the model has been estimated on the basis of the Root Mean Square Error (RMSE), the Mean Absolute Percentage Error (MAPE) and the Coefficient of Determination (R2). A sensitivity analysis based on Garson algorithm and PAWN Index has been also used to estimate the effect of each parameter on the soiling rate.	Modeling
[172]	Rabat	PV (Glass sample)	8 months		Modeling
[173]	Rabat, Errachidia Oujda Agadir	PV	-	Based on the analysis of the soil samples collected from various Moroccan cities using DRX, FX and IR techniques, the results shown the existence of almost the same abundant constituents particularly: Quartz, Calcite, Dolomite, Kaolinite whose percentages differ from a climate to another.	Particles properties
[174]	Benguerir	PV (Amorphous) (Monocrystalline)	1 month	The energy drops by 6-7% for the mono-crystalline and 8-9% for the amorphous.	Assessment
[175]	Oujda	CSP	12 weeks	The reflectance drop can reach 30% in dry period.	Assessment
[98]	Rabat	PV (Monocrystalline) (Polycrystalline) (Amorphous)	3 months	The losses due to soiling were 3.5% for monocrystalline and polycrystalline modules while they are 4.5% for the amorphous ones.	Assessment
[176]	Missour Zagora	CSP	2 years and 1 month	Zagora city has experienced a higher erosion risk estimated at 5.9% while in Missour it was only 0.8%.	Assessment

		PV	-	Particles larger than 100 µm present the main volumetric contribution in Zagora while in Missour several small particles are present as well. In Zagora soil, the main constituents are: quartz (73 wt %), followed by some minor percentages of clay and carbonate minerals. In Missour soil, the main constituents are: > 66 wt % of carbonate minerals and around 14 wt % of gypsum. [wt %= weight percent]	Particles properties
[177]	Benguerir	-	-	Presentation of the "DustIQ", instrument for soiling measurements. This has been tested in outdoor conditions at Green Energy Park of IRESEN. The results have shown a stable operation and an increase in soiling in late spring and summer.	Instrumentation
[178]	Rabat	PV (Glass sample)	2 years	The soiling rate marked 7%.	Assessment
[22]	Lab simulation	PV (Glass sample)	-	For indoor simulation of soiling phenomenon, a test bench has been designed. The first tests conducted shown that the test bench approached the mechanism of the deposition of soiling phenomenon.	Dust simulators
[179]	Rabat	PV (on tracking system) (Polycrystalline)	-	Design of a cleaning system for the biaxial tracker of Helioslite. The technique has the form of a telescopic arm connected to rotating brush. A prototype to test the command of the system has been realized.	Mitigation/ cleaning
[180]	Rabat	PV (on tracking system) (Polycrystalline)	-	Design of a low-cost cleaning solution for the biaxial tracker of Helioslite. The functioning of this technique is based on the gravity effect by exploiting the orientation of the tracking system. A prototype of the solution has been realized and the tests carried out on it have given satisfying results.	Mitigation/ cleaning
[181]	Rabat	PV (Glass samples)	1 month	2.25% difference of losses due to soiling between two glass samples exposed in outdoor conditions and tilted at 0° and 45°.	Assessment
			-	Literature survey of the different anti-soiling solutions for PV panels.	Mitigation/ cleaning
[35]	Benguerir	CSP	4 months	Daily dirtiness index of approximately 0.013	Assessment
[182]	Ouarzazate Tinghir Midelt	CSP	-	The adhesion of three soil samples collected from Ouarzazate, Tinghir and Midelt on three types of CSP mirrors (the commercial mirror used at NOOR 1 project, CSP mirror with hydrophobic amorphous AL_2O_3 nano-coating and CSP mirror with hydrophilic TiO_2 nano-coating) is studied. Tinghir dust particles and CSP mirror with hydrophobic amorphous AL_2O_3 nano-coating have shown a low adhesion work equivalent to 42.78 mJ/m² in comparison to the other samples. The kaolinite presents in major quantities in Tinghir sample (XRD analysis results).	Particles properties
[183]	Benguerir	CSP	4 months	For a period of more than 18 weeks: Dust density on the aluminum sample was higher than the glass one. However, aluminum sample (soiling losses range between 0.75 and 0.96) was less affected by dust than the glass one (soiling losses range between 0.65 and 0.98).	Assessment

[184]	Benguerir	PV (Monocrystalline)	6 months	For a period of 6 months: The cumulative power drop is 124 kWh per 16.56 kWp. Average daily power drop is 2.7 kWh and 0.07 kWh during dry and rainy periods respectively. Daily soiling rates of 0.32% and 0.02% during dry and rainy periods respectively.	Assessment
			-	The analysis of the dust deposited revealed the presence of silicon, alumina, calcium, iron (maybe coming from a construction site close to the site of the study) and potassium, magnesium and phosphorus (maybe coming from a close phosphate mine).	Particles properties
[29]	Rabat Errachidia	PV (Glass sample) (Polycrystalline)	2 years	Average annual soiling rate of approximately 4% (Rabat). Daily energy production losses around 2 Wh/Wp per one PV monocrystalline module (Rabat). Soiling losses of 23% per one month (Errachidia).	Assessment
[28]	Benguerir	CSP	4 months	During dry period, the average thermal losses can reach 354 $kW_{th}h$ (kilo Watt thermal hours) (equivalent to 27% of the production).	Assessment
[27]	Benguerir	PV (Glass samples)	13 weeks	Soiling loss can reach 35% after one week of exposure during dry period of CSP mirrors while PV glass samples it reaches 12%. CSP are three times affected by soiling than PV glass samples.	Assessment
		CSP			
[185]	Rabat	_	_	Summary of works [178] [22] [181] [180]	_

Table II-6. Studies conducted in India regarding soiling phenomenon

Ref.	Location	Technology	Period	Main results	Category
[37]	Bangalore	-	-	The review cited many recommendations including metrology, modeling, materials science, mitigation techniques, forecasting, test facilities, standards and certification in order to better assess soiling phenomenon.	-
[186]	Lab simulation in Kolkata	PV	-	For a PV cell of 96 cm², the energy losses were 10%, 16%, 20% respectively for 0.1 g, 0.2 g and 0.3 g of deposited dust.	Assessment
[187]	Lab simulation Bangalore	PV (Polycrystalline)	- 1 day	The open circuit voltage is not significantly influenced by soiling. The short circuit current is highly influenced by soiling. It dropped 30-40% in the indoor setup and 3-4% in the outdoor experiment.	Assessment
[188]	Vellore	PV (Polycrystalline)	1 month	Dust accumulation is highly affected by inclination and exposure period.	Assessment
[189]	Gurgaon	PV (Glass samples)	-	High percentage of carbon observed which is due to refineries and/or vehicular traffic.	Particles properties
[36]	Chennai	PV (polycrystalline)	2 years	Annual soiling losses of 2.3% were observed.	Assessment
[190]	Dust samples from: Gurgaon Hanle Jodhpur Agra & Lab simulation in Mumbai	PV (Polycrystalline) & (Glass samples)	–	The dust simulator realized is a low-cost technique to perform a uniform deposition of dust.	Dust simulators
				For the same density (0.25 mg/cm²), Agra sample showed a higher soiling loss followed by samples from Hanle, Jodhpur, and Gurgaon. Samples Hanle and Jodhpur showed less response in the wavelength 900-1100 nm compared to Agra and Gurgaon samples.	Assessment Particles properties
[99]	Dust samples from: Gurgaon Hanle Jodhpur Agra Pondicherry Mumbai	PV (Crystalline) & (Thin-films)	-	A technique for artificial dust deposition which is low cost is presented. This helps to perform tests taking into account density, composition, and particle size.	Dust simulators
				The highest percentage of particle size less than 4 µm (clay sediments) is observed in Mumbai and Pondicherry dust samples. Soiling effect of Mumbai dust on a silicon solar cell is 17.1% while Jodhpur dust is only 9.8% for the same density 3 g/m². The ranking (from the highest effect to the lowest one) of the spectral effect of the dust samples is: Mumbai followed by Pondicherry, Agra, Hanle, Jodhpur, and Gurgaon. Based on the same density 1.8 g/m² of Mumbai dust, amorphous silicon is the most affected (17.7%), followed by cadmium telluride (15.7%), crystalline silicon (15.4%), and CIGS (14.5%).	Assessment Particles properties

[191]	In India but exact location is not specified	PV	14 days	Soiling losses were 3.2%. Considering the tariff of 7 Rs/kWh, the economic loss due to soiling is 455 Rs (Rs=Indian rupee). The optimized cleaning frequency is 11 days.	Assessment
[192]	Soil samples from: Raghunathgarh Neem-Ka- Thana Khetri Sikar Pilani	PV	-	Correlation between power output of soiled photovoltaic panels, incident irradiance and soil particles size composition based on the Multiple variable regression analysis. The empirical model has been validated using experimental data and the results obtained have shown its efficiency.	Modeling
				When dust particles deposited on the PV panels have the size of 75 µm and below, the deviation from the tilt angle of a clean PV module is 4°. However, when the size is 150 µm and 300 µm the deviation is 8°.	Assessment Particles properties
[24]	Soil samples from: Raghunathgarh Neem-Ka- Thana Khetri Sikar Pilani	PV	-	From the results obtained it has been concluded that neural networks are efficient in predicting power based on particle size composition, but it is the regression models which are convenient in determining the particle size compositions, irradiance with the output power.	Modeling
				At higher irradiance levels (1000-1200 W/m²), particles of size 150 µm highly influence the power output, while at lower irradiance levels (300-500 W/m²) , it is particles of size 75 µm and below that influence more.	Particles properties Assessment
[193]	Soil samples from: Raghunathgarh Neem-Ka- Thana Khetri Pilani	PV	-	A bi-harmonic interpolation is first used to develop analysis of contours to determine interactions between irradiance losses and tilt angle of a soiled panel then those contours are secondly compared to power contours that follow a theoretical power expression.	Modeling
				Soils contain in majority particles with diameters: <75 µm, 75 µm, 150 µm and 300 µm cause angular losses 52%, 24%, 22% and 23.7% respectively.	Particles properties Assessment
[194]	Soil samples from: Raghunathgarh Neem-Ka- Thana Khetri Pilani	PV	-	A hybrid data clustering and a data division technique have been customized for PV power predictions under dusty environments.	Modeling
[125]	Ahmedabad	PV (Polycrystalline)	3 months	Drop in solar energy production by 17-25% due to ambient PM and PM deposited. PM is responsible of 1 GW of solar power reduction.	Assessment
[195]	New Delhi	PV (Polycrystalline) (Glass samples)	-	The accumulation of rice husks on the PV module has led to a minimum power loss equal to 3.88 W. In desert climate, the power loss can reach 60%.	Assessment
				The smaller the particles, the blocked sunlight the higher.	Particles properties
[196]	Chennai	PV (Thin films) (Polycrystalline) (Monocrystalline)	1 year	The performance ratio drop due to soiling is 2.1%.	Assessment

[197]	Soil samples from: Raghunathgarh Neem-Ka-Thana Khetri Sikar Pilani	PV	-	The relationship between the particle size compositions of soil and irradiance received by tilted soiled solar module is established based on a soil distortion factor (SDF). Soils rich with particles with diameters 75 µm (Neem-Ka-Thana), 150 µm (Raghunathgarh) and 300 µm (Khetri and Sikar) cause irradiance losses 10%, 6%, 21% and 22% respectively. Less than 75 µm size particles is the major composition of soil (Pilani) and this causes 12% irradiance loss in 0–60° tilt angle region.	Assessment Particles properties
[75]	Gurgaon	PV	20 days	The performance drop is highly proportional to the dust particles density and size. The soiling effect is affected by the tilt angle. The temperature of the cleaned module is higher than the soiled one. This is because the conversion of irradiance to electricity is high in the case of the cleaned module.	Assessment
[54]	Dehradun	-	-	Review on cleaning techniques. The main findings of this review are as follows: Manual cleaning presents the disadvantage of energy-intensive and time-consuming efforts; Automatic cleaning presents the problem of energy consumption and maintenance; Coating technique still facing the transparency and the stability in outdoor conditions issues; Studies on coating techniques are highly needed; Dew/moisture increases the effect of soiling; Stowing and vibrating techniques are helpful to avoid the cementation of dust; Sensors are highly required to schedule cleaning.	Mitigation/ cleaning
[26]	Bangalore	-	-	Literature review on soiling phenomenon and the factors, which influence it. From this review, it has been concluded that more studies on soiling are still needed.	-
[198]	Chennai	PV	-	The authors suggest a soiling mitigation technique based on electrostatic effect. The method has shown promising results.	Mitigation/ cleaning
[199]	Ludhiana	PV	-	PV modules faults (soiling loss, shading loss and material loss) detection based on a simulation model. The classification of faults and the level of power loss have been done using Artificial Neural Networks.	Modeling
[51]	Kerala	PV	-	Review on soiling phenomenon, which includes influencing factors, measurement methodologies and cleaning aspects. No specific conclusions have been mentioned.	-
[200]	Mumbai	PV (Glass samples)	1 year	Glass samples with different coating materials have been installed in different sites including Mumbai City in India. The results obtained in this latter are as follows: Soiling characterization showed that it is composed mainly by organic materials. The most effective contact-based cleaning procedures to remove soiling are DB (Dry Brush) and WSS (Wet Spong and Squeegee) nevertheless they scrape the coatings. Coating U (polymer) with WSS cleaning procedures seems to be a good soiling-mitigation technique.	Mitigation/ cleaning

[201]	Mumbai	PV (Monocrystalline) (Monofacial &Bifacial modules)	168 days	Vertical position accumulates less soiling. Soiling effect is high on inclined monofacial modules than the inclined bifacial ones. Vertical bifacial modules produce less than inclined ones, but after three weeks, this latter will produce less due to soiling if there is no cleaning meanwhile.	Assessment Mitigation/ cleaning
[202]	Lab simulation in Gurgaon	PV	-	A 3-dimensional simulation has been used to study the relationship between the installation parameters, dust particles size and dust deposition. The results revealed that tilt angle has almost the same effect as azimuth angle. Furthermore, soiling of ground mounted solar PV panels is high than multi-storey building installations. Manipulation of tilt angle can reduce the effect of soiling on the roof mounted installations.	Modeling
[203]	Noida	PV (Polycrystalline)	1 year	After manual cleaning, Pmax improved by 9.8% while for Isc by 6.7%.	Assessment Mitigation/ cleaning
[60]	Faridabad & Murthal	-	-	Review on soiling impact on PV systems and mitigation techniques. It has been concluded that soiling is sever problem affecting solar energy systems and that the amount of dust depends on different variables such as dust properties, geographical location, exposure time and wind direction.	-
	Not specified	PV	1 month	Correlation between the dust layer thickness and the PV panel efficiency. The results obtained showed a high correlation between the thickness of the dust layer and the PV module efficiency. The model developed will be helpful to determine the thickness that will deteriorate the maximum of the efficiency.	Assessment
[32]	Jodhpur	PV (Glass samples)	3 years	The loss in power is observed maximum in March (end of winter) and minimum in August. In the tilt angle region (25 - 60°), the optimal inclination 40° has smaller soiling effect.	Assessment Particles properties
[31]	Chennai	PV (Glass samples)	8 weeks	The spectral characteristics were similar in all locations studied and they could be described by a modified form of the Ångström turbidity equation. Natural soiling is proportionally affecting the visible and infrared (IR) portions of the spectrum compared to the blue and the ultraviolet (UV). The particle size distribution follows the IEST-STD-CC 1246E cleanliness standard. Optical losses of PV modules due to soiling can be estimated from the particle size distribution and the cleanness value.	Modeling Particles properties
[30]	-	PV (Polycrystalline)	-	An automatic washing system is programed to perform cleaning based on Artificial Neural Networks program. This showed good accuracy in data prediction.	Mitigation/ cleaning Modeling

Figures II-12 to II-16 present the repartition of publications per year, location, technology and category. From the body of work performed so far, it can be concluded that the publications are concentrated in the period from 2012 onwards and increasing over time (Figure II-12). This follows the international trend, as it has been found by [6] in their review, soiling phenomenon has had a special interest just after 2010 which grows over the years. The periods of studies vary from 1 month to 25 months in Morocco while in India it varies from 1 day to 3 years. These latter have been applied on different technologies as it is shown in Figure II-15. In the two countries, the majority of studies concerns PV technology and especially crystalline one. In Morocco CSP technology has almost the same share as PV and this is due the CSP plants constructed in Morocco in the frame of his solar plan. The studies have been carried out in Rabat and Benguerir in Morocco while in India they have been carried out mainly in Rajasthan state (Figures II-13 to II-14).

The main studies conducted on CSP technology, have been conducted in Benguerir, Oujda, Tantan, Agadir and Ouarzazate which they belong to semi-arid and arid climates. In dry period, losses can reach 27% and 30% in Benguerir and Oujda respectively [28], [175]. Aluminum mirrors may accumulate more dust than glass ones [183] . However these latter are highly affected by soiling [165], [171], [183]. In Benguerir, CSP technology has been confirmed to be three times affected by soiling than PV technology [27]. For PV technology, the studies are carried out mainly in Rabat and Benguerir belong to semi-arid and arid climates. In Rabat losses can reach 4% per year for glass samples [29] while in Chennai they were 2.3%. Amorphous modules experienced high-soiling effect than monocrystalline ones [98], [99], [174] in both countries Morocco and India. In this latter vertical bifacial modules, when there is no cleaning meanwhile, a promoting results in comparison to the inclined ones are obtained [201]. The mineralogical composition which dominates in the different sites of Morocco [151], [165], [170], [173], [176], [182], [184] is quartz, calcite, kaolinite, dolomite and muscovite with the presence of salt in the seaside sites. The percentages of these dominant components differ from a site to another. The particles size distribution is an important factor highly affect soiling losses. This found to follow the IEST-STD-CC 1246E cleanliness standard and it can be helpful to estimate soiling effect on PV modules [31]. The smaller the particles, the blocked sunlight the higher [193], [195]. However this depends on the irradiance level received by the module [24].

In the two countries, "Assessment" ranks first followed by particles properties, modeling and mitigation/ cleaning (Figure II-16). The effect of many factors such tilt angle [9], [165],

[181], [188], [192], [193] has been tested. The manipulation of the tilt angle can reduce soiling effect [202]. This confirms what has been found by [12] where they suggest a multiple tilt angle configuration for PV modules which will reduce the effect of soiling and hence improving production thought the year. Three attempts to design a mechanic cleaning system have been conducted in Morocco. They concern, PV [179], [180] and CPV on tracking system [167]. The three systems have shown promoting preliminary results. In India, [30] has suggested an automatic cleaning system programed based on an intelligent technique to predict soiling. Other cleaning methods based on electrostatic effect [198] and on coating [200] have been as well studied.

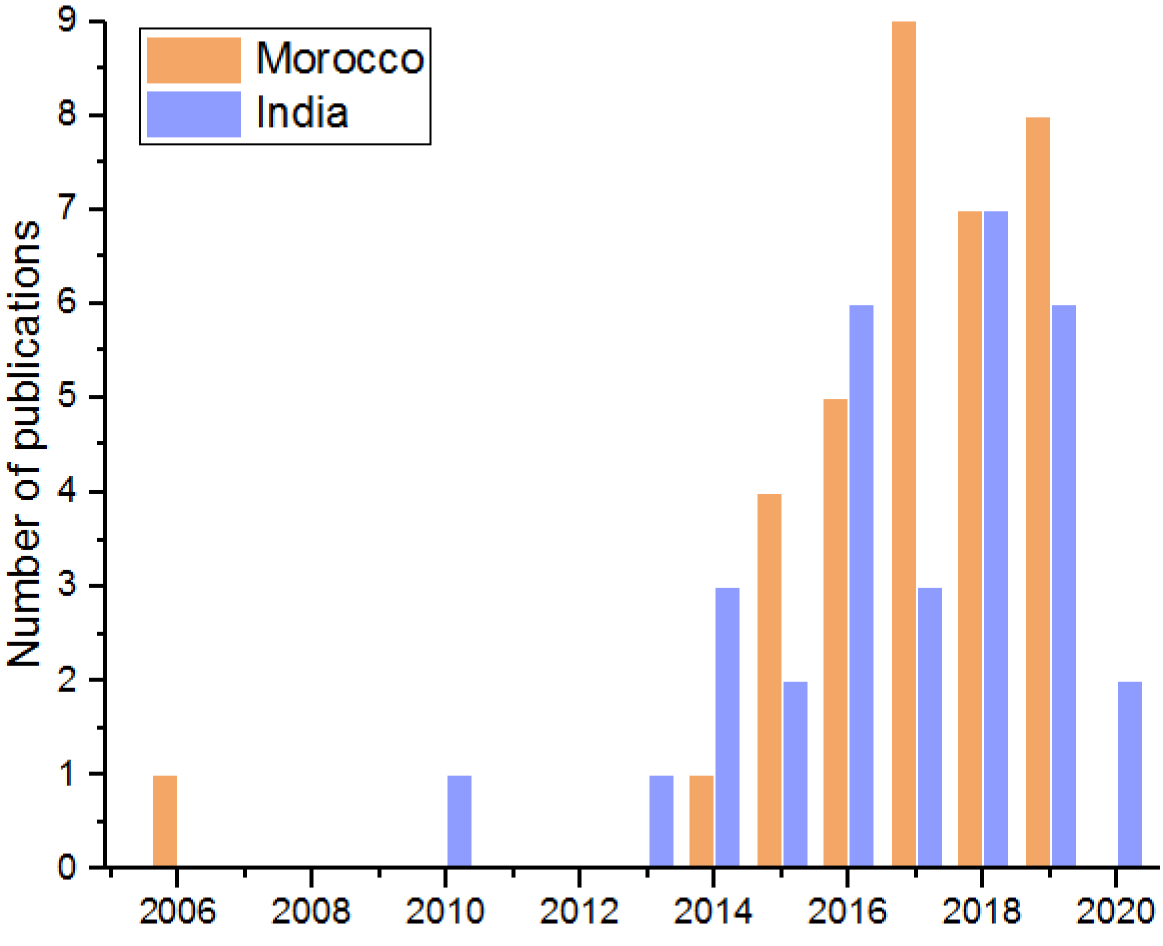


Figure II-12. Number of publications per year in Morocco and India

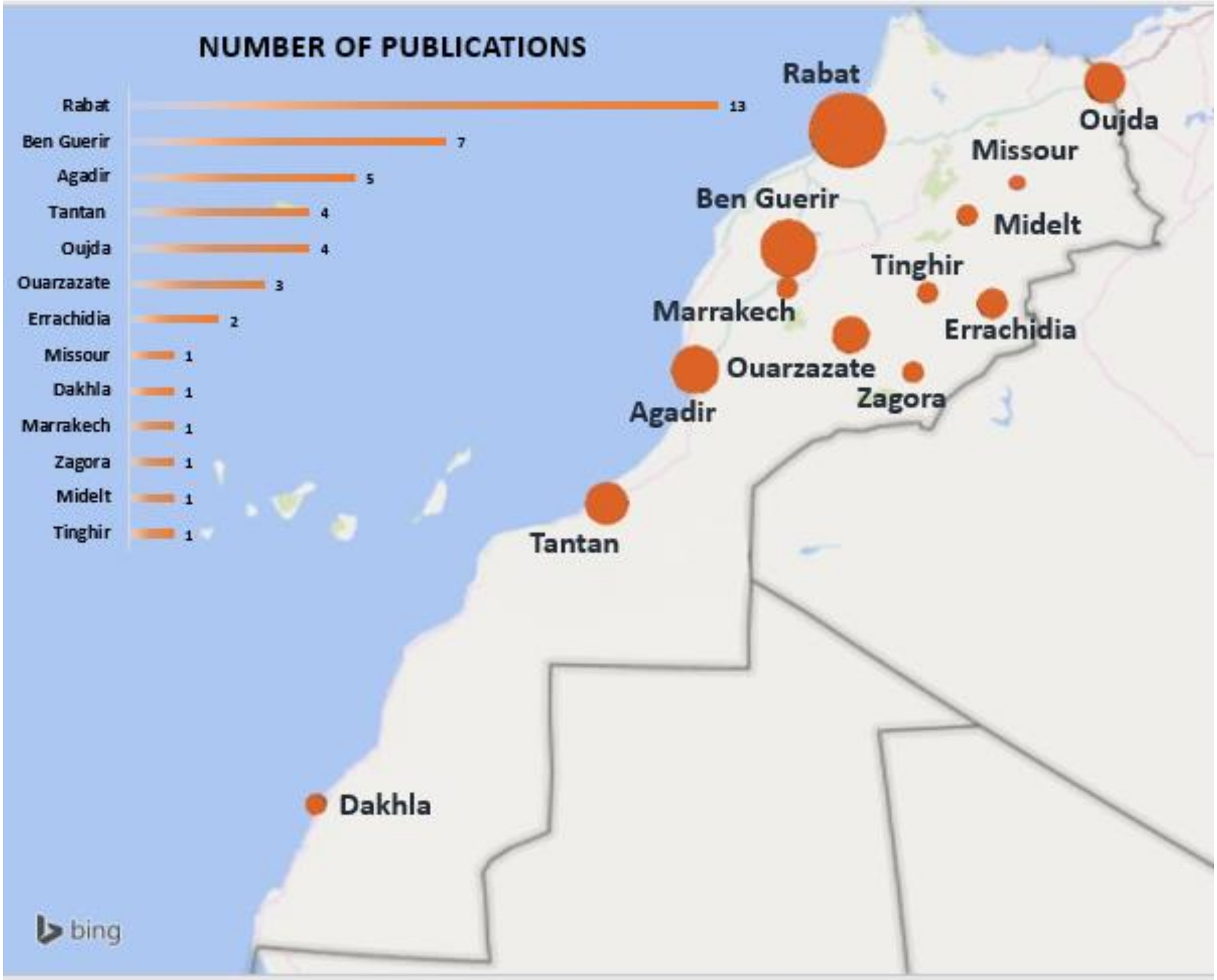


Figure II-13. Location and number of publications on soiling phenomenon carried out in Morocco

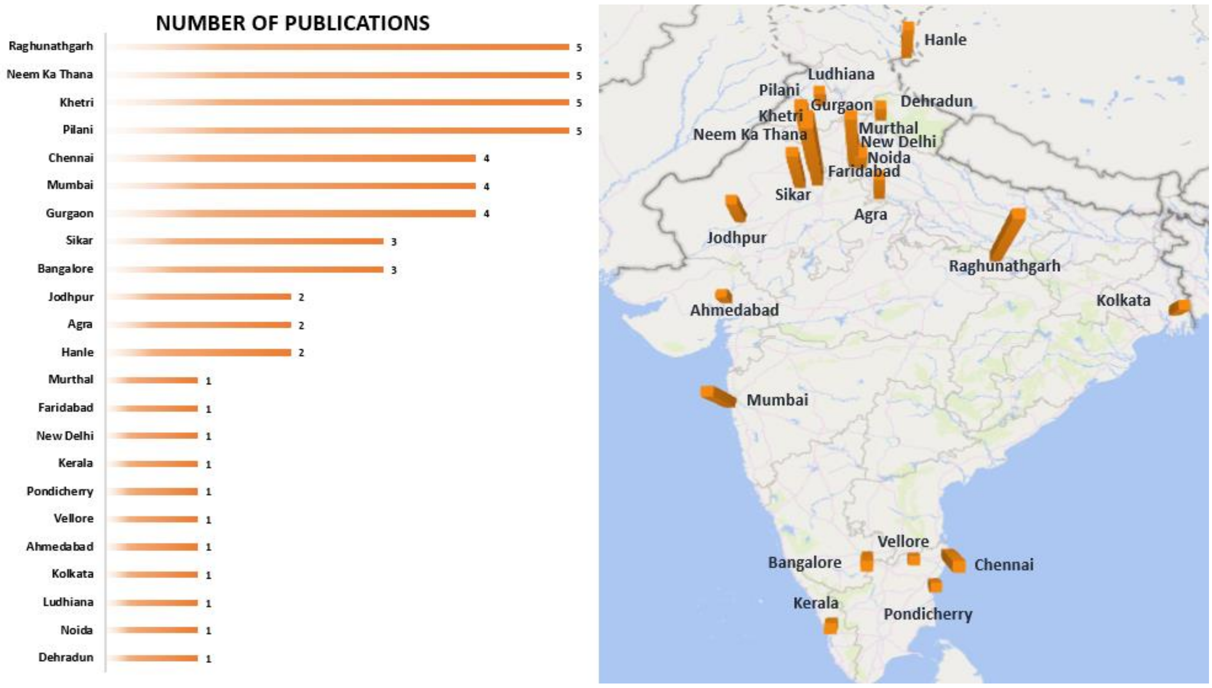


Figure II-14. Location and number of publications on soiling phenomenon carried out in India

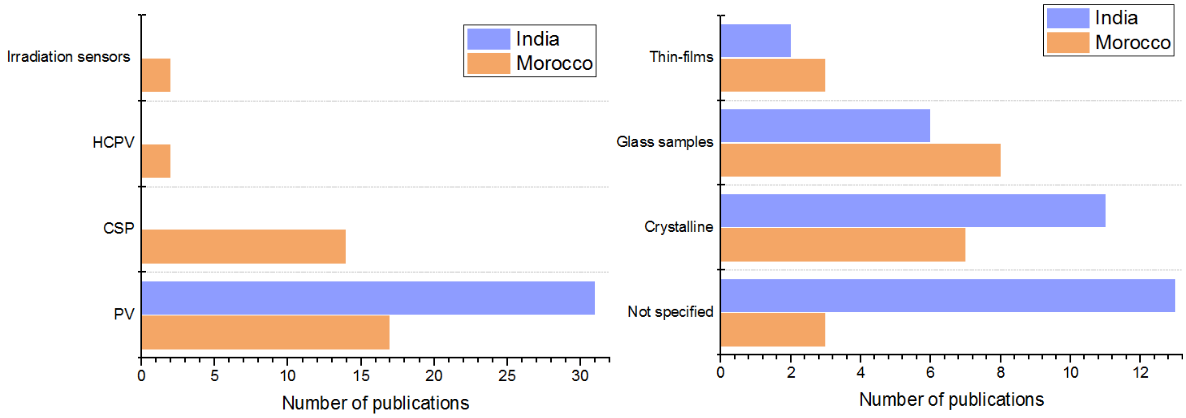


Figure II-15. Number of publication per technology in Morocco and India

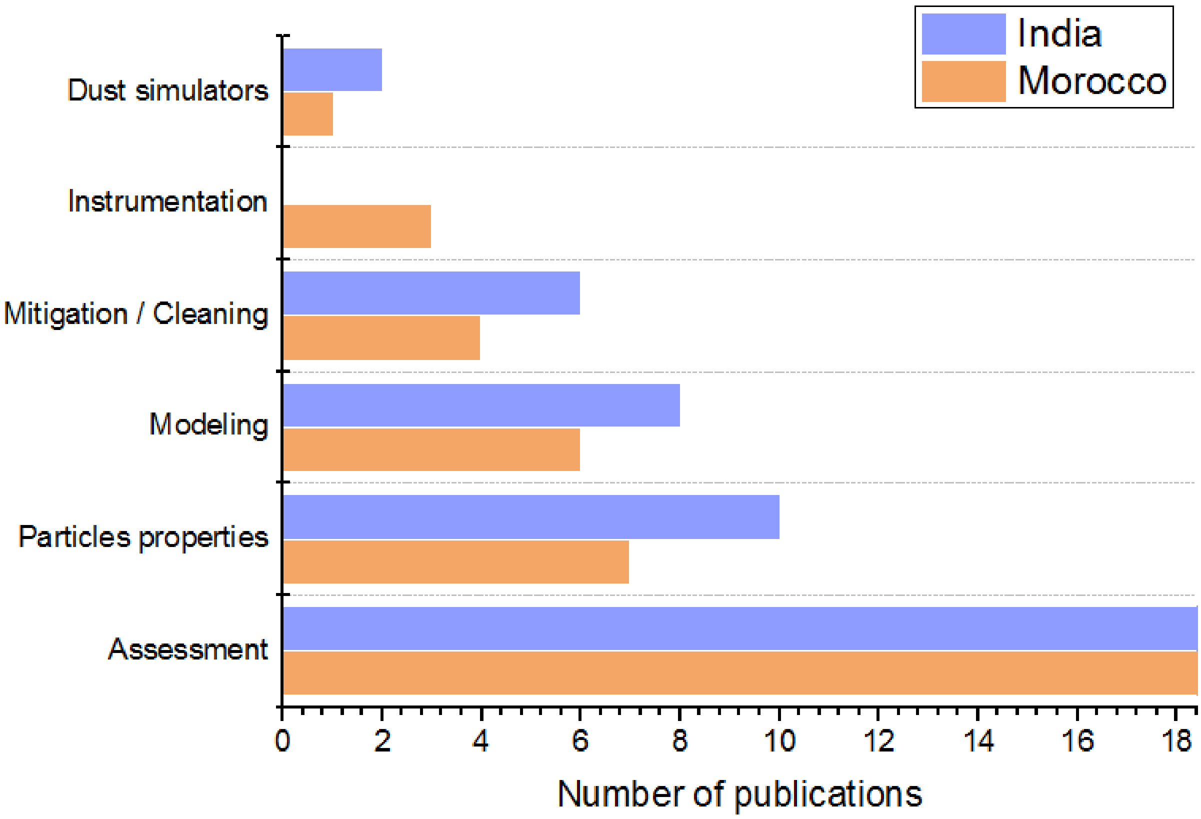


Figure II-16. Number of publications per category in Morocco and India

8. Conclusion

The present chapter is mainly focusing on a review on the presentation of the soiling process, the methods of quantification, the factors which influencing it, the methods to handle it and a literature survey on studies conducted in both countries Morocco and India.

In general, the following conclusions can be drawn from this literature review:

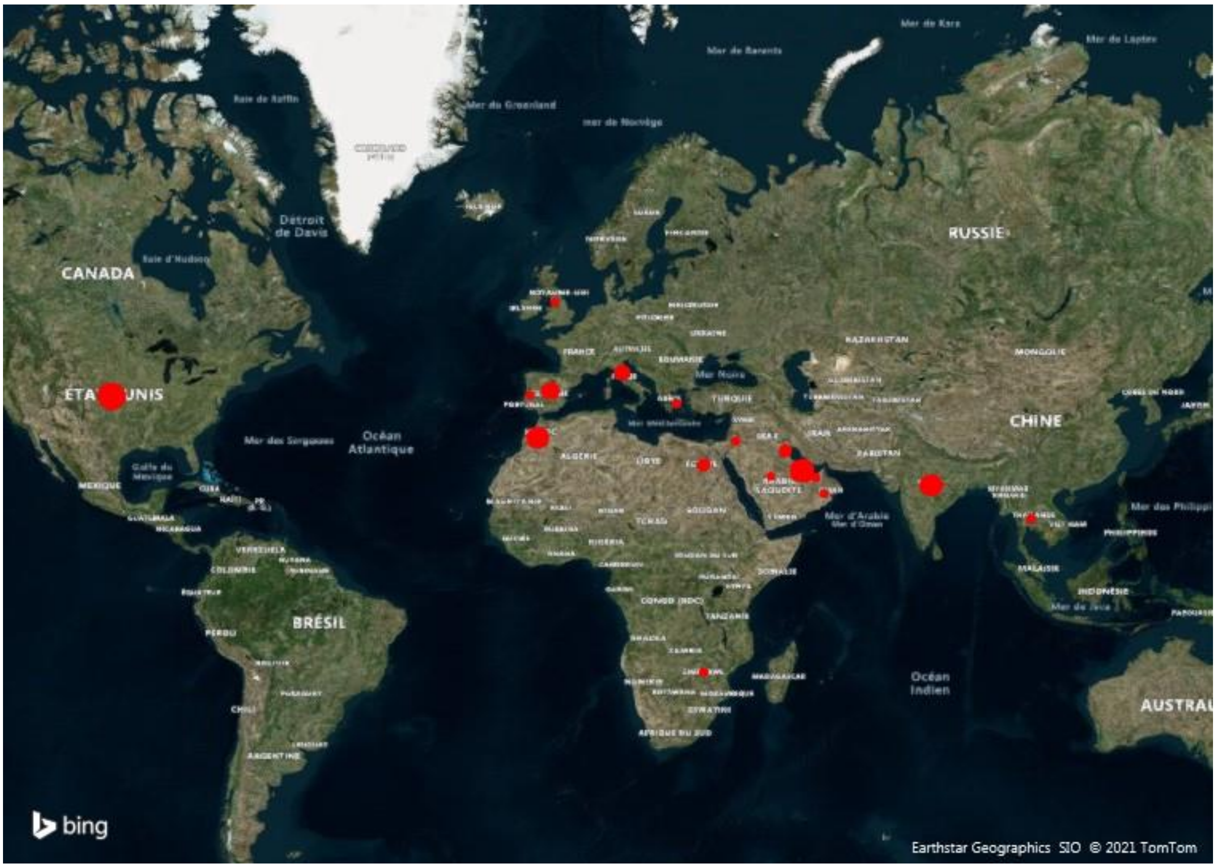
- Dust deposits on the front surface of the module can significantly decrease the solar energy amount received by the panel. The accuracy of mass measurements is a limiting factor in determining the level of loss due to the accumulation of dust. While the reflection and transmittance measurements seem to be sufficient to detect optical changes. However, these two methods do not represent the actual effect of soiling on the reduction of the electrical performance of the photovoltaic module. In order to more precisely quantify the effects of soiling, researchers often use the method based on the electrical characteristics of a real PV system.
- The effect of factors influencing soiling phenomenon is very complex to understand and in most cases each factor has double effect, positive and negative. The effects of these factors are linked to each other which make it highly difficult to isolate and study each factor alone since it will be different than that of the real outdoor conditions.
- Many cleaning techniques and methods have been developed to reduce the impact of soiling. However, a clear map on the usage of each technique is still needed since the efficiency of these methods depends strongly on site/installation characteristics and weather conditions.
- In Morocco as well as in India, soiling phenomenon has an increased interest. Nevertheless, since this phenomenon is highly localized, more studies are still needed in order to reach generalized conclusions.

CHAPTER III : COMPREHENSIVE LITERATURE REVIEW ON THE MODELING AND PREDICTION OF SOILING EFFECTS ON SOLAR ENERGY POWER PLANTS

1. Introduction

Through all the reviews aforementioned in the previous chapter, it is obvious that, although modeling of soiling is an important aspect, it is rare when it is reviewed. Nevertheless, studies on this subject are continuously published. Based on the literature survey conducted in this review, these studies are summarized and presented in the following map (Figure III-1) according to their geographic location of measurements. A high number is attributed to lab works. This latter and "Unknow" which refers to unknown locations have been added to the legend in order to show the other publications to where they belong. From Figure III-1 it can be seen that the studies are mainly concentrated in the middle built known by high insolation and high dust concentration as it can be seen in Figure III-2.

For a better understanding of the work in this review, articles on the topic from 1998 to early 2020 are exhaustively summarized with specific points highlighted. The first section shows the different paths, presented as categories, which can be followed to model soiling phenomenon. The second section provides a description and a summary of the models applied per each category. These have been discussed and analyzed in the third section. The last section dedicated to the conclusions and recommendations of this review.



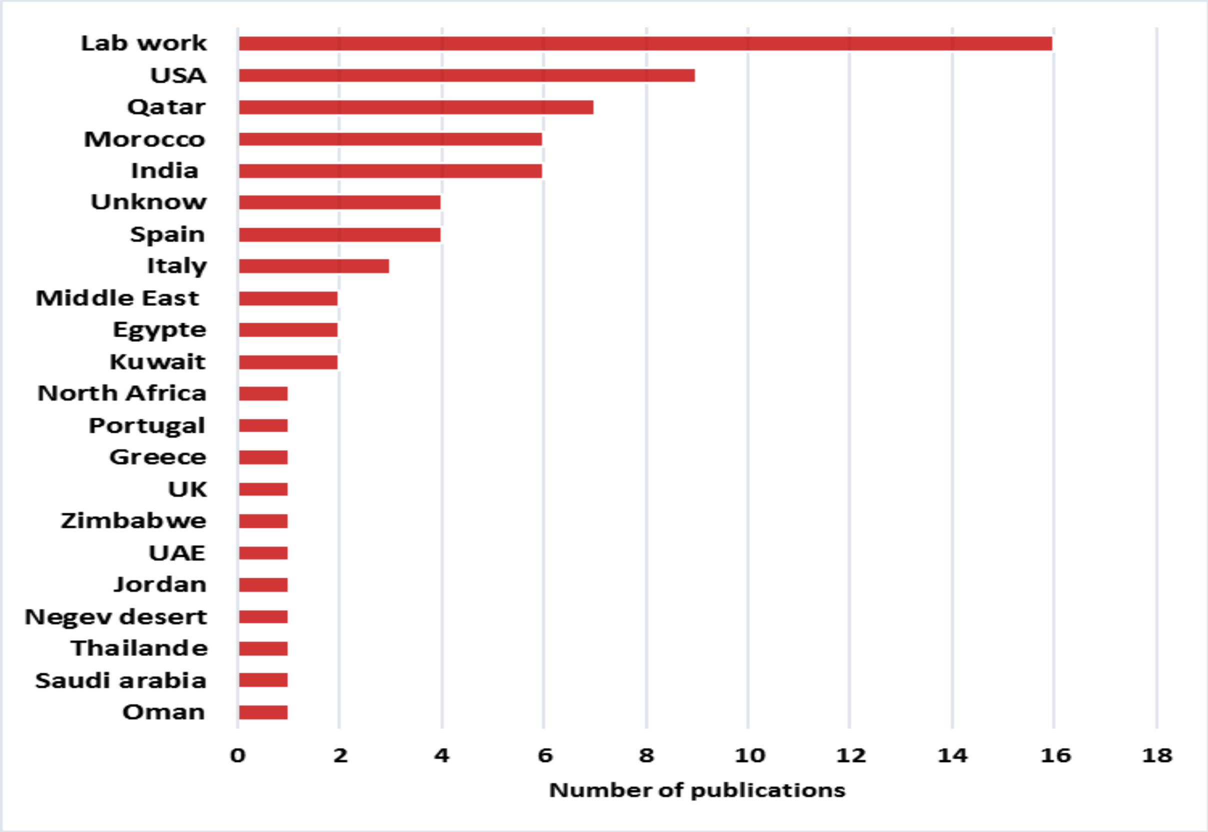


Figure III-1. Statistics of scientific publications on modeling and prediction of soiling and their geographic locations. "Unknown" refers to unknown location

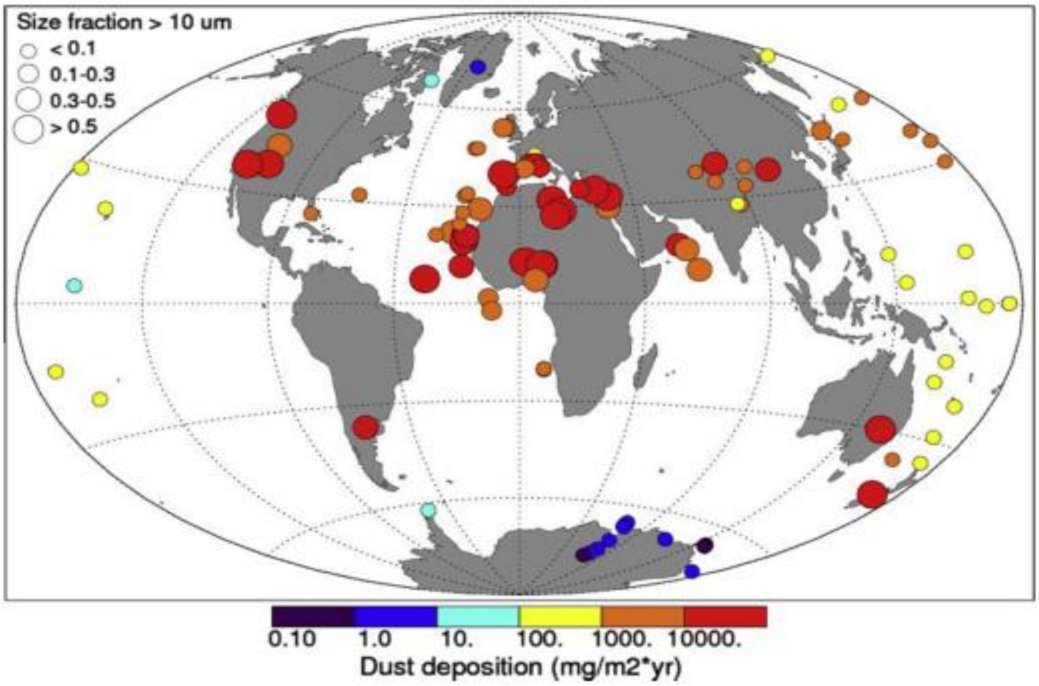


Figure III-2. Size and density distribution of dust aerosols [204]

The used references include only journal articles or reviews, conference papers and book chapters. The research for relevant publications has been conducted based on the keywords: solar energy, soiling, India, Morocco, in the databases: SCOPUS, Science Direct, Google, Google Scholar, ResearchGate, Wiley and Springer.

2. Modeling of soiling, which path to follow?

According to the recommendation of [205] the modeling of soiling should be done in two parts; the first one should concern the model which will predict the amount of dust mass deposited according to the meteorological conditions while the second part should focus on the model which will correlate the amount of dust mass deposited and PV modules losses due to soiling. The classification presented in Figure 4 has been done based on that statement. From what is shown, the models are divided into six groups to which different letters (A, B, C, AB, AC, BC) and colors have been assigned to highlight parts. “A” refers to the models which deal with the prediction of soiling potentials and dust concentration, “B” the models which study the interaction of the deposited pollutants and the surface while “C” corresponds to the models which determine the patterns of losses due to soiling. “AB” groups the models that use weather conditions variables to predict the deposited pollutants, “BC” the correlations between the deposited pollutants and the soiling losses, whereas “AC” is related to the correlations between weather conditions and the soiling losses (Table III-1).

Figure III-3 shows the share of groups in the gathered papers. Based on this figure, it can be seen that the highest percentage belongs to the group BC followed respectively by AC, C, A and AB. The two models suggested by [205] are AB and BC and these two types of modeling are complementary to each other. For part B which is about deposited pollutants, many published papers describe and model the interaction between particles and the surface as it can be seen in [56]. This part is also an important one but it is far beyond the scope of the present review paper.

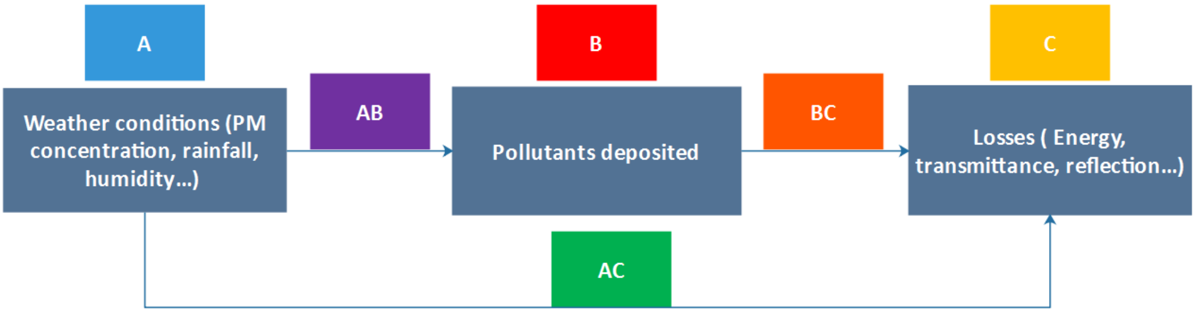


Figure III-3. Classification of publications according to the desired objective of modeling

Table III-1. Classification of publications according to the desired objective of modeling

A	Modeling and prediction of soiling potentials/ dust concentration.	[206]–[209]
C	Determining the patterns of losses due to soiling	[4], [31], [164], [171], [210], [211]
AB	Use of weather conditions to predict deposited pollutants.	[212]–[215]
BC	Correlation between losses due to soiling and deposited pollutants (mass, composition…).	[1], [21], [216]–[225], [24], [226]–[229], [192]–[194], [205], [212], [213], [215]
AC	Correlation between weather conditions and losses due to soiling.	[10], [87], [230]–[239], [104], [240], [241], [120], [125], [126], [160], [168], [172], [214]

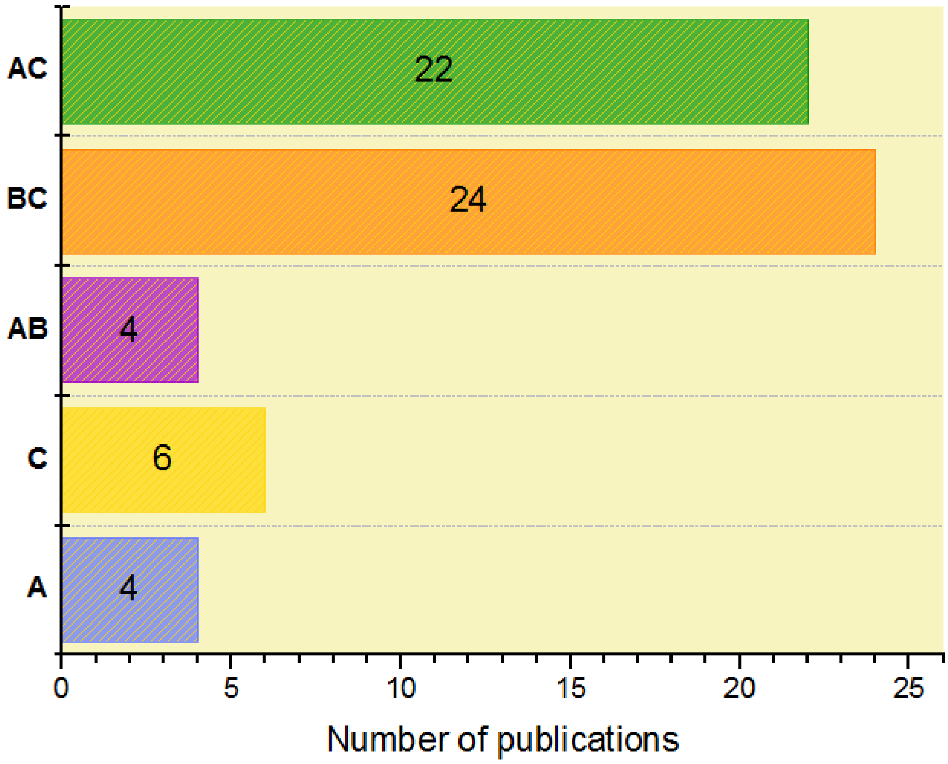


Figure III-4. Share of each group in the published papers

In the following section, a summary of the different applied models per each category is presented. Table III-2, Table III-3, Table III-4, Table III-5 and Table III-6 present the different and miscellaneous studies conducted in the framework of modeling and prediction of soiling phenomenon from 1998 until 2019 (including the beginning of 2020) for each category. They give a short summary related to the performance of the model based on the conclusions drawn by its authors. They highlight the applied technology as well as the experimental place of these studies when specified by authors, just to help the interested to have a quick look at the geographical location or to know if it is a laboratory simulation.

3. Applied models per each category

3.1. Modeling and prediction of soiling potential/ dust concentration (Category A)

[206] performed dust risk map for solar energy systems in arid area based on the correlation between Aerosol Optical Depth (AOD), provided from the Multi-angle Imaging Spectro-Radiometer (MISR) (NASA satellite data), wind regime and air temperature. While [207] presented a simulation of dust events based on the model WRF-DuMO which has been already applied by [242]. Following the same path, [208] used the Geographic Information System (GIS) as a base for modeling the distribution of soiling potential in the Middle East and North Africa (MENA). Similarly, in the article [209], a soiling risk maps have been created using Geographic Information Systems (GIS) in order to expect the area or regions where dust emissions are highest. In this model soiling has been defined as a function of the following meteorological and environmental factors: land cover, vegetation, land use, soil type and soil texture, precipitation, wind speed and wind direction, humidity.

Table III-2. Summary of articles published on modeling of soiling phenomenon (Category A). The performance of each model discussed based on the conclusions drawn by the authors of each work

Ref.	Location of measurements	Technology	Main conclusions
[206]	Oman	All solar energy systems	No comment about the performance of the model. The rate of dust deposition could be estimated from the open source HYSPLIT-Hybrid Single Particle Lagrangian Integrated Trajectory Model has been presented as a perspective.
[207]	Middle East	Useful for all technologies	The dust model implemented was performant enough; it has been improved by applying a salt effect correction and the use of the salt map.
[208]	Middle East and North Africa	PV glazing (useful for other technologies)	The results presented are preliminary and more studies should be conducted in order to validate the used model.
[209]	Western Saudi Arabia	PV-Modules (useful for other technologies)	Field tests should be done in order to evaluate the spatial assessment of the real soiling risk.

3.2. Determining the patterns of losses due to soiling (Category C)

Based on the theoretical analysis proposed by [243], [210] proposed a model which calculates the reflection losses in PV modules. For CSP aluminum mirrors, there are the works [4], [164], [171], [211]. The modeling of the cleanliness factor (CF) of CSP aluminum mirrors has been studied in [164] using locally weighted regression (loess). CF factor refers to the reflectance of a soiled mirror divided by the reflectance of a clean one. The CF data have been treated as time series with the time index as a regressor. Two cases have studied based on the span s of the local-regression (the number of data points considered for each local regression); s = 0.2 and s = 0.75. Two tests have been used to examine the normality of the residuals and their independence, the Quantile-Quantile (Q-Q) plot and the autocorrelation function (ACF). Likewise, the work of [4] concerns the analysis of the cleanliness of the solar reflectors exposed outdoors. This has been performed using the free R software for statistical computing and graphics together with DLM (Dynamic Linear Models) package, the zoo package [244] for indexing the time series and Amelia's package for multiple imputations [245]. A comparison between three models has been conducted; the local level model (that is, a first-order polynomial model), the local linear trend model (that is, a second-order polynomial model) and the local level with intervention model by including an intervention variable. The selection criteria used are: MSE (Mean Square Error), MAD (Mean Absolute Deviation), MAPE (Mean Absolute Percentage Error), AIC (Akaike Information Criterion) and BIC (Bayesian Information Criterion). In order to detect the most important exposed mirror material trends and the impact of weather factors when taken into consideration as explanatory variables, the Dynamic Factor Analysis (DFA) has been applied on the cumulative soiling of CSP mirrors [171]. [211] proposed a set of 7 non-linear time series models based on Markov regime Switching (MS) to model the soiling of solar reflectors regularly cleaned. The models have been evaluated using the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC). Moreover, a diagnostic of the model's residuals has been done based on the Jarque-Bera (JB) normality test [246] in order to check the normality assumption and the autocorrelation function (ACF) and the Ljung-Box (LB) test [247] in order to check the independence of the residuals. After the evaluation of the models, a simulation of 30 MW parabolic-trough collectors (PTC) plant without thermal storage has been conducted and different scenarios based on the chosen models have been developed.

In 2020, an investigation of the spectral and optical characteristics of various types of soiling has been conducted [31]. Four correlations or comparisons have been studied. First, the hemispherical transmittance vs. wavelength correlation is compared to the Ångström turbidity equation (based on the Mie-scattering theory). Second and third, the size distribution and the fractional coverage area have been compared to IEST-STD-CC 1246E cleanliness standard. Fourth, the transmittance has been correlated to the fractional coverage area.

Table III-3. Summary of articles published modeling of soiling phenomenon (Category C). The performance of each model discussed based on the conclusions drawn by the authors of each work

Ref.	Location of measurements	Technology	Main conclusions
[210]	South of Navarre (Spain)	PV plant	Losses were correctly estimated for tracking and also horizontal surfaces, each one with its performance but there were no specific comments about the performance of the model.
[164]	Southwest Morocco	CSP aluminum mirrors	The results showed that s = 0.75 is judged appropriate for describing the studied data and their underlying pattern. This has been confirmed by examining the (Q-Q) plot and the (ACF) function.
[4]	Agadir, Morocco	CSP solar reflectors	The results revealed that the local linear trend has shown to be the best-fitted model describing the long-term change in the cleanliness. It performs even better when an optimal discount factor of 0.95 is considered. The model could be improved by including different explanatory variables (like weather conditions) and taking into account the effect of seasonality.
[171]	Tantan, Agadir Morocco	CSP	Based on the Akaike Information Criterion (AIC), the Dynamic Factor Analysis (DFA) found that the best model has two shared trend patterns.
[211]	Almeria, Spain	CSP mirrors	The approach proposed in the paper presents a promising method to model the soiling of CSP reflectors as it takes into consideration the seasonal soiling and the washing cycle frequency. Nevertheless, the model should be tested on a real CSP plant.
[31]	Golden in Colorado and San José in California (USA), Chennai and Tezpur (India), Jaén (Spain), Penryn (UK) and El Shourouk City (Egypt)	PV	The main findings are: the hemispherical transmittance can be described by the Ångström turbidity equation, the particle size distribution follows the IEST-STD-CC 1246E cleanliness standard and the optical losses of PV modules due to soiling can be estimated from the particle size distribution and the cleanness value.

3.3. Use of weather conditions to predict deposited pollutants (Category AB)

Authors of the work [212] presented in their study a model to predict soil mass accumulated from its morphology. A correlation between particulate matter (starting with PM10 concentration, then PM20 concentration, then PM dry deposition) and the variation in the PV energy yield taking into consideration the effect of humidity, ambient temperature, wind speed and wind direction is suggested by [214]. The particulate matter has been modeled based on the WRF-Chem (Weather Research Forecasting with Chemistry), the GOCART aerosol scheme (Georgia Institute of Technology–Goddard Global Ozone Chemistry Aerosol

Radiation and Transport) and the RACM chemistry (Regional Atmospheric Chemistry Mechanism), the HTAP (Hemispheric Transport of Air Pollution emissions) and the AFWA emission scheme (US Air Force Weather Agency).

Another model to predict soiling losses has been established by [215]. This model is based on the evaluation of the deposited dust based on the particulate matter concentration (PM10 and PM2.5). This latter is adjusted using rainfall data and the soiling ratio or transmittance loss is estimated based on the correlation carried out by [119]. The modeled data were compared with the experimental data from [248].

In 2019 [213] presented a correlation between soiling losses and particulate matter (PM) dry deposition estimates from the Community Multiscale Air Quality (CMAQ) model [249]. The initial and boundary conditions have been provided from [250] while the meteorological input data were provided from the Weather Research and Forecast (WRF) model [251]. The deposition measurements and transmittance losses were provided from the study of Boyle et al. [252], [253].

Table III-4. Summary of articles published modeling of soiling phenomenon (Category AB). The performance of each model discussed based on the conclusions drawn by the authors of each work

Ref.	Location of measurements	Technology	Main conclusions
[212]	Measurements at Doha, Qatar and theoretical modeling	PV modules	There are no comments on the performance of the model as it has been validated, only on a typical day.
[214]	Doha, Qatar	PV modules	The model showed a good correlation between the change in the PV energy yield and the PM dry deposition against PM10 and PM20 concentrations. However, the test of the model in other environments and for longer periods is still needed to validate it.
[215]	Arizona, and Central/southern California states, USA	PV modules	The model was judged performant. However, to be more accurate, the model should include other impacting factors such as wind, dew formation and particulate matter larger than 10 µm, also the performance of the model should be checked in more geographic areas.
[213]	Simulation and field measurements in three locations (two in Colorado and one in Texas) USA	Solar PV glass	The particulate matter (PM) dry deposition estimates are minor than the field measurements because of the underestimation of the ambient total particle concentration and the underestimation of the deposition rates (due to the underestimation of surface wind speed input and more frequent precipitation input). However, it shows a strong correlation between the transmittance loss and the total particle deposition.

3.4. Correlation between losses due to soiling and deposited pollutants (Category BC)

As for our knowledge, the first model established has been published by [21]. This evaluates the transmittance coefficient for beam light based on the estimation of the amount of sand dust particles per unit area of glazing surface, the size of the particles, beam light incidence angle and wavelength. A continuity of this work has been conducted in [216] where they validated their model [21] using field measurements and the equation which links the decrease in the PV panels efficiency and the increase in the sand dust particles amount has been presented.

In 2001 [227] has performed a correlation between the reduction factor of transmittance and dust accumulation taking into account the tilt angle and number or days of exposure since the last cleaning. The accuracy of the multi-variable nonlinear regression model has been evaluated based on the Mean Absolute Error MAE and the Root Mean Square Error RMSE. While [217] estimated dirt effect on the transmittance, which depends on the shape and size distribution of particles and incident angle, based on the calculation of the probability that a single particle will cover a given area on a surface (overlapping model proposed by NASA). In the same year [1] correlate between the energy yield and dust deposited based on an artificial soiling composed of three pollutant types. The results obtained from the artificial soiling have been compared with a natural one. From these results a model (exponential regression) has been developed.

Authors of [219] correlate between the free fractional area A (area not covered by particles) of the glass and the quantities of dust deposited using two models:1st model: Analytical model based on [21] and use a grain threshold algorithm in the software package Gwyddion, 2nd model: Simulation using Monte Carlo method. While [218] correlate between spectral transmittance and dust density based on ‘Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS)’ code to account for the tilt angle of the surface plane [254] combined with a MATLAB code (MathWorks, Natick, MA, USA).

Based on the International Energy Agency Photovoltaic Power Systems TASK 2 - Performance, Reliability and Analysis of Photovoltaic Systems (IEA PVPS Task 2) [255] and the dust accumulated on PV modules using Dust-fall jar methods from Pollution Control Department (PCD) and standard for detecting dust by US EPA Method 5 of the United States Environmental Protection Agency (US EPA: US Environmental Protection Agency), a mathematical model for the analysis of the efficiency is performed by [222]. Optical modeling of the impact of dust on PV panels’ performances by simulating the electromagnetic wave propagation in a three-layer surface (air-dust-glass) using COMSOL Multiphysics software has been proposed by [220] . The model is based on the analysis of the transmission and reflection coefficients at the limits of each layer of the structure (air-dust-glass). A linear regression model has been adopted by [221] in order to describe the relationship between dust mass accumulation and transmission loss for different angles and different locations.

In 2016, a correlation between the power output of soiled photovoltaic panels, incident irradiance and soil particles size composition based on the Multiple variable regression analysis is conducted by [192]. In the work of [24] they tried to predict the power output of soiled PV panels. To do this, two models have been chosen. The 1st model, artificial neural networks based on Multi-Layer Perceptron (MLP) model: the ANN has been implemented using MATLAB with feed forward network that uses Levenberg–Marquardt algorithm (LMA) for training. MSE (mean square error) and Gradient have been used to test the performance of the model. The percentage of different particle sizes present in the different types of soil collected and the horizontal irradiance value have been used as inputs for training the network while the power generated has been used as output. 70% of the data collected was used for training, 15% for validation and the rest 15% for testing. The 2nd model is a multiple linear regression model and the analysis was performed using regression add-on in Microsoft Excel. The percentage of different particle sizes present in the different types of soil collected and the horizontal irradiance value have been used as independent variables while the power generated has been used as dependent variable. The analysis has been tested using the coefficient of determination R^2. In the same year, a hybrid data clustering and a data division technique studied by [194], have been adapted for PV power predictions under dusty environments. The same authors suggested a bi-harmonic interpolation which is first used to develop an analysis of contours to determine interactions between irradiance losses and tilt angle of a soiled panel then those contours are secondly compared to power contours that follow a theoretical power expression [193]. [223] analyzed a tilted PV panel with dust depositions on its front surface based on two models: 1st: Optical modeling which presents a combination of three studies; [21], [243], and [119]; to find a new correlation based on different incident angles of a tilted PV module, and 2nd : Thermal modeling based on the general form of the energy conservation equation in order to estimate the absorbed energy from dust and other layers like glass.

Authors of the work [212] presented in their study a model to predict soil mass accumulated from its morphology. A numerical simulation has been performed by [224] where an accurate model to predict the output power of a panel is proposed. Thanks to this model and also by assuming that dust accumulation follows a Poisson distribution with a constant arrival rate which depends on the location considered. Two relative transmittance models were developed to assess soiling: one considers the radius of a single dust particle while the other considers the whole particle size distribution. Based on the works of [1], [216], [256], [205] tried ,somehow, to overpass some limits of those works. The model developed is a mass-dependent model for low and moderate naturally deposited dust concentration has been validated using data from literature. Two other models have been proposed by [225] and have been compared to experimental measurements: 1st model: Multiple scattering (the two-stream approximation) [257], and 2nd model: Monte Carlo method [258]. The models and measurements concern a correlation between transmittance and mass density of dust under different monochromatic light and for two types of dust (absorbing and non-absorbing). A model to predict the soiling of PV modules based on the theoretical modeling of particle deposition is presented in [226].

Another model to predict soiling losses has been established by [215]. This model is based on the evaluation of the deposited dust based on the particulate matter concentration (PM10 and PM2.5). This latter is adjusted using rainfall data. The soiling ratio or transmittance loss is estimated based on the correlation carried out by [119]. The modeled data were compared with the experimental data from [248]. A continuity of the work [259] in presented in [228]. The model suggested, highlights the relationship between the reflectance and cleanness variation with the incidence angle. The model is based on the attenuation of radiation taking into consideration the reflector cleanness, the type of dust, the spatial distribution and the homogeneity of the dust sample. [213] present a correlation between soiling losses and particulate matter (PM) dry deposition estimates from the Community Multiscale Air Quality (CMAQ) model [249]. The initial and boundary conditions have been provided from [250] while the meteorological input data were provided from the Weather Research and Forecast (WRF) model [251]. The deposition measurements and transmittance losses were provided from the study of [252], [253]. In their paper, the authors present a Mie-scattering theory based model that evaluates the soiling optical losses from the particle mass density [229]

Table III-5. Summary of articles published modeling of soiling phenomenon (statistical modeling). The performance of each model discussed based on the conclusions drawn by the authors of each work

Ref.	Location of measurements	Technology	Main conclusions
[21]	The theoretical model has been compared with the results of an indoor simulation	PV module (glazing surface)	After almost 50% decrease of light transmittance a disagreement between the calculated and measured values. The mathematical prediction could be improved if the real shape and the transparency to incident light of the particles have better analyzed.
[227]	Minia, Egypt	Glass plates	The model showed a good performance. However, an application on other climate types would be valuable.
[216]	Theoretical model and field measurements in Shuwaikh, Kuwait	PV modules	The results showed a good correlation between the model and the measurements. However, the model is limited to 1.5 g/m² of the amount of sand dust particles.
[217]	Theoretical study	PV panels	The shape and the size distribution of particles should be more analyzed in order to better estimate the impact of particle deposition on transmittance.
[1]	Simulation and field measurements in Athens, Greece	PV modules	The model is judged to be quite performant. However, the test of the model on different applications and different pollutants is still needed. The test of long-term prediction capability of the model is still required as well.
[219]	Laboratory simulation	PV modules	Good agreement between the models and the results of the indoor simulation. Other variables should be taken into consideration such as moisture, wind speed and tilt angle in order to approach the models to the real behavior of dust settlement.
[218]	Kuwait	PV modules	No comments about the performance of the model.
[222]	Thailand	PV module	No comment on the performance but results obtained allowed development of a mathematical relationship between dusts on PV modules and the reduction in the electrical energy output.
[220]	Lab Simulation	PV module	No comment on the model's performance.
[221]	Colorado, USA	Glass samples	The model was found acceptable.
[192]	Soil samples collected from Shekhawati region in India were used in an artificial soiling experiment	Photovoltaic panels	The empirical model has been validated using experimental data and the results obtained have shown its efficiency.
[24]	Shekhawati region, India	PV modules	From results obtained it has been concluded that regression models are useful in determining the relationship between the particle size compositions, irradiance with power output but it is the neural networks that are efficient in power prediction based on the particle size composition.
[194]	Experiments conducted in India	PV module	The model was found robust, especially in stochastic and dynamic conditions.
[193]	Experiments in India	PV panel	The model was performant enough.
[223]	Theoretic method tested by field	PV systems	This model can practically predict module performances under different weather conditions.

	measurement in an unknown location		Further investigations about particle size, particle material and PV module type factors are needed.
[212]	Measurements at Doha, Qatar and theoretical modeling	PV modules	There are no comments on the performance of the model as it has been validated, only on a typical day.
[224]	Numerical simulation	PV panel	The model shows a good accuracy.
[205]	Theoretical modeling	PV modules	The model proposed, has been judged to be applicable on the majority of cases met in an urban and non-urban polluted areas. The authors recommend that the modeling of soiling should be done in two parts: The first part: concerns the model which will predict the amount the dust mass deposited according to the meteorological conditions The second part: concerns the model which will correlate between the amount of dust mass deposited and PV modules losses (to which their proposed model belongs)
[225]	Laboratory simulation	Glass slides	The theoretical models show a good agreement with the measurements. However, to be completed, models to forecast the mass density of particles deposited per unit area are still needed.
[226]	Theoretical modeling and simulation	PV modules	Based on the results obtained the model shows a satisfactory accuracy to predict performance losses due to soiling. However, the effect of the solar PV module type, the particles deposited composition and the solar density need to be included considering their important impact. Furthermore, in areas with highly soiling potential, the linear relation between the dust deposition density and performance loss has to be reviewed.
[215]	Arizona, and Central/southern California states, USA	PV modules	The model was judged performant. However, to be more accurate, the model should include other impacting factors such as wind, dew formation and particulate matter larger than 10 µm, also the performance of the model should be checked in more geographic areas.
[228]	Negev desert	CSP glass reflectors	The model presents a new way to assess the losses due to soiling in reflectors. The model can be improved by the application on a large plant with different compositions of dust. The application of the model can also be extended to predict the optical losses of photovoltaic panels.
[213]	Simulation and field measurements in three locations (two in Colorado and one in Texas) USA	Solar PV glass	The particulate matter (PM) dry deposition estimates are minor than the field measurements because of the underestimation of the ambient total particle concentration and the underestimation of the deposition rates (due to the underestimation of surface wind speed input and more frequent precipitation input). However, it shows a strong correlation between the transmittance loss and the total particle deposition.
[229]	Southern Spain	CSP and PV	The model showed promising results. However, the authors thought that its performance is less because the following assumptions are made: spherical particles, low soiling level (<2g/m²), no agglomerations, constant size distribution and the optical properties of the dust considered,

3.5. Correlation between weather conditions and losses due to soiling (Category AC)

[230] proposed a polynomial regression model to estimate the power generated by dirty and cleaned modules based on ambient temperature and global irradiance. This has been compared with a Bayesian Neural Networks (BNNs) in [231]. This last model has three layers: an input layer, a single hidden layer, and an output layer. The first layer has two inputs (the solar irradiance and the cell temperature), while the output layer has one node which is the power produced by the PV plant. 4800 samples have been divided into three subdivisions: 70% for the training, 20% for testing and 10% for validation. The effectiveness of the model has been evaluated using the mean correlation coefficient R, the Root Mean Square Error (RMSE), the Mean Absolute Error (MAE) and the Mean Absolute Percentage Error (MAPE). In the same paper, another comparison has been made also between the BNNs, the Multi-Layer Perceptron Network (MLPN) and the Radial Basis Function Network (RBFN). In the paper of [232] the power produced by a PV panel is estimated on the basis of solar irradiance and cell temperature [260]. The difference between the estimated power and the measured power presents the losses due to the effect of aging and dust.

B. Guo et al. tried in their paper [120] to correlate between daily change of the cleanness index and the daily ambient environmental conditions (dust concentration, wind speed, and relative humidity) has been examined using a multi-variable linear regression model. This has used these parameters as independent variables to predict the dependent variable (cleanness index). Based on this, in [10] the accuracy of the linear multivariate regression model and a semi-physical model for the prediction of daily change in cleanness index is evaluated.

Soiling effect has been studied as well on HCPV TJ cells by [233]. While in the work of [168], the reflectance has been modeled using Nonlinear AutoRegressive with exogenous inputs (NARX) (special class of ANN) and Bayesian regularization. The inputs were humidity, temperature, rainfall, wind velocity and direction. The accuracy of the model has been tested using the correlation coefficient (R) and Mean Square Error (MSE).

Based on PV production data, ambient temperature, plane-of-array irradiance, daily precipitation totals, the median daily soiling rates are extracted [234]. The method is built considering and using the robust Theil-Sen estimator for slope extraction. A continuity of this is presented in [237]. In this study, the quantification of energy losses due to soiling is determined based on the interplay between soiling, precipitation, and solar resource patterns. Based on this, authors in [87] proposed a field-data-based soiling assessment algorithm that they named Stochastic Rate and Recovery (SRR). An improvement of this is suggested by authors of [240]. This improvement is manifested by taking into consideration the seasonal change of the soiling deposition rate.

A correlation between meteorological parameters (irradiance, ambient temperature, humidity, rainfall, wind speed and wind direction) and soiling rate of solar PV glass using artificial neural networks has been proposed by [160], [172]. The model developed is based on Levenberg-Marquardt back-propagation algorithm, and the active functions Tansig, and Purline. The estimation accuracy of the model has been measured based on the Root Mean Square Error (RMSE), the Mean Absolute Percentage Error (MAPE) and the Coefficient of Determination (R2). In [172], a sensitivity analysis based on Garson algorithm [261] has been also used to estimate the effect of each parameter on the soiling rate while in [160] the sensitivity analysis based on PAWN index [262].

Data recorded at 20 sites around United State of America USA have been used by [104] in a linear regression between two environmental and meteorological parameters (particulate matter and precipitation) and soiling losses occurring on PV panels. This study has been extended in [126]. The authors tried to correlate between soiling ratio and parameters such as particulate matter (PM) and rainfall based on the measurements of different stations and different databases. Two models have been used: the single-variable regression and two-variable regression. The quality of the correlations has been tested using the adjusted coefficient of determination (adjR^2), the Root-Mean-Square Error (RMSE) and a normalized Root-Mean-Square Error (RMSEn). The particulate matter (PM) data have been extracted from the US Environment Protection Agency (US EPA) database [263], the Fused Air Quality Surface Using Downscaling (FQSD) [264] and from the Dalhousie model [265]. The rainfall data have been recorded from Oregon State University's PRISM database [266].

Authors of [125] present in their study a model to estimate the influence of particulate matter (estimated based on NASA GISS ModelE2 [267]) and dust on the transmittance based on their work [268]. In the same year, a correlation between environmental conditions (PM10, relative humidity (RH) and wind speed (WS)) and PV soiling in terms of Cleanness Index (CI; a measure of PV performance losses due to soiling) has been studied by [235]. Based on this correlation an Artificial Neural Network model has developed in order to predict the daily cumulative PV soiling losses as a function of environmental parameters. The model has compared to the multivariable linear regression model in order to evaluate the prediction accuracy. Another correlation between particulate matter (starting with PM10 concentration, then PM20 concentration, then PM dry deposition) and the variation in the PV energy yield taking into consideration the effect of humidity, ambient temperature, wind speed and wind direction is suggested by [214]. The particulate matter has been modeled based on the WRF-Chem (Weather Research Forecasting with Chemistry), the GOCART aerosol scheme (Georgia Institute of Technology–Goddard Global Ozone Chemistry Aerosol Radiation and Transport) and the RACM chemistry (Regional Atmospheric Chemistry Mechanism), the HTAP (Hemispheric Transport of Air Pollution emissions) and the AFWA emission scheme (US Air Force Weather Agency).

A comparison between three models to predict losses due to soiling based on weather conditions (Particulate Matter PM0.5-2.5, Particulate Matter PM0.5, Vertical Wind Speed VWS, Temperature T and Relative Humidity RH) have been studied in [236]. 1st model: Multiple Linear Regression MLR; 2nd model: Multiple Linear Regression of Interaction Terms MLRIT and 3rd model: Artificial Neural Networks ANN. The models have been tested using the coefficient of determination (R^2) the adjusted coefficient of determination (adjR^2), the Root-Mean-Square Error (RMSE) and the Mean Square Error (MSE). Similarly, the authors in [239] predict PV output based on irradiance of clean and soiled panels using two models: multiple linear regression and neural networks. The accuracy of the models has been evaluated based on the coefficient of determination (R^2) and the Root Mean Square Error (RMSE). Almost same models have been used in [238] in order to correlate between environmental parameters and performance losses due to soiling of PV modules. The two based techniques are: ANN and MLR (Multi-variable Linear Regression). The selection of the environmental parameters to take into consideration has been done using Burota algorithm [269]. The performance of the models has been evaluated based on the criteria: R2adj, MAPE, ME (Modeling Efficiency), MBE (Mean Bias Error) and RMSE. Following the same path [241] proposed a model to predict soiling loss profiles based on weather generation algorithms. In this work, the authors tried to predict the PV panels performance based on the soiling and temperature effects. The effect of soiling is considered as the number of exposure days. Five models have been applied; Multivariate Linear Regression, Artificial Neural Networks ANN, Extreme Learning Machine ELM and the optimized versions of ANN and ELM. The performance of the models has been tested based on the coefficient of determination (R^2) the adjusted coefficient of determination (adjR^2), the Accuracy and the Mean Square Error (MSE).

Table III-6. Summary of articles published modeling of soiling phenomenon (Category AC). The performance of each model discussed based on the conclusions drawn by the authors of each work

Ref.	Location of measurements	Technology	Main conclusions
[230]	Countryside of southern Italy	PV plants	The coefficient of correlation is more than 99% which shows the effectiveness of the model to estimate the power.
[231]	Southern Italy	PV plant	The accuracy of the BNN model is higher than the polynomial one, which can be influenced by the size of the database. A large database is required to adjust better the polynomial coefficients, while in the case of BNN; a 4000 samples dataset is largely sufficient to adapt the weights and bias of the network. Concerning the comparison between BNNs, MLPN and RBFN, the three models have practically the same MAPE (1.1%), but the BNNs present the most sample structure.
[232]	Lab Simulation and real condition measurements, Italy	PV module	No indication of the performance of the model in estimating the effect of soiling.
[120]	Doha, Qatar	PV-Modules	More works are needed to better understand and to better predict the effect of dust and weather conditions on PV performance losses.
[233]	Lab Simulation & measurements	HCPV TJ cells	Good results were obtained for the predictions but the variation noted for spectral response represents a challenge in performance modeling and monitoring.
[168]	Tantan, Agadir, Morocco	CSP	According to mean square error, the best model found is the one with 30 neurons and 2 tapped delay. However, the model would give better results if a large amount of data will be used and by joining multiple architectures of NARX.
[234]	Field measurements (but no indication of the location)	PV systems	The model used was judged as consistent and robust. Further on its comparison with least-squares linear regression, the Theil-Sen estimator makes the proposed method more easily scalable to large numbers of sites without the need for an anomaly filtering.
[237]	Field measurements (but no indication of the location)	PV systems	The model is judged robust and low cost since the need for new hardware is not required.

[125]	Gandhinagar in Ahmedabad, India	PV modules	No comments about the accuracy of the model. This latter is limited as it considers a linear relationship between the change in transmittance and PM mass flux. The authors believe as well that further studies which include more influencing parameters are still needed.
[10]	Computational simulations based on field measurements in Doha (Qatar)	PV module	The models were found sufficiently accurate and performant.
[235]	Doha, Qatar	PV modules	The ANN model has been recognized as a suitable tool to model the complex relationship between soiling losses and environmental conditions. The ANN model has shown, significantly, a better prediction of soiling loss against the multivariable linear regression model. The correlation coefficient between the measured and the ANN predicted value was not highly significant which could be explained by the presence of other parameters affecting the soiling such as the probability of dew formation and condensation, the physicochemical properties of dust, the residence time of dust particles on the critical surfaces and the prevailing effect of dust loading.
[172]	Rabat, Morocco	Solar PV glass	The results obtained show a good correlation between the soiling rate and the weather conditions. It also shows that rainfall and wind direction impact more the soiling rate.
[160]	Rabat, Morocco	PV modules	The results have shown a good correlation between the soiling rate and the weather conditions. The sensitivity analysis indicates that the relative humidity, followed by wind direction, are the most influential parameters among the inputs used on the soiling rate.
[104]	Data were recorded at 20 sites around United State of America USA	PV systems	No comments about the performance of the model but the results have shown that the annual average of the mean daily particulate matter values recorded are the best predictors of soiling losses.
[87]	Field measurements (United States) and simulation	PV systems	The method outperforms the commonly used FRP (Fixed Rate Precipitation) method.
[214]	Doha, Qatar	PV modules	The model showed a good correlation between the change in the PV energy yield and the PM dry deposition against PM10 and PM20 concentrations. However, the test of the model in other environments and for longer periods is still needed to validate it.
[236]	Evora, Portugal	CSP mirror	Based on the results obtained, the comparison between the three models has shown that ANN is a promising tool to predict soiling losses. However better results would be achieved if more data, variables and different time-scales have been taken into consideration. The MLRIT model is also important as it helps to understand more how the variables interlinked with each other how they affect the output.

[126]	USA (California, Oceanic Islands (Hawaii and Virgin), East Coast and the Southeast)	PV modules	The results obtained have confirmed that environmental parameters such as particulate matter and rainfall can be used to estimate soiling losses in USA. Further studies and a larger number of data points are still needed to improve the model and to make it more general.
[241]	Zarqa, Jordan	PV modules	The results revealed that both the optimized models of ANN and ELM managed to predict the efficiency of the PV panels. However, the optimized ELM was more accurate.
[238]	Harare, Zimbabwe	PV modules	The two models ANN and MLR have shown a good performance in modeling of soiling of PV modules.
[240]	Arizona and California states, USA	PV modules	The improvement applied on the method [87] has led to a better estimation of the optimal cleaning day and the energy gains. The other model judged well in predicting the week where the cleaning should be applied. However, to reach better results, the authors believe that their methods should be applied on a large number of sites and data and also the use of more robust weather generation algorithms.
[239]	Sharjah, UAE	PV modules	The results have shown that no difference in accuracy shown between the two models. Both models showed good accuracy.

4. Analysis and discussion of the applied models

From the summary of models performed so far, it can be concluded that many models have been used to study the soiling phenomenon. These latter have been applied on different technologies as it is shown in Figure III-5. From this, it can be seen that PV technology is ranked first and reaches 79% of the share of models conducted on it. This result is almost similar with a slight decrease to what has been found recently by S. C. S. Costa et al. [50], where they said that 85% of publications on soiling concern PV technology. The slight decrease is probably due to the fact that the effect of soiling on other technologies particularly CSP is getting more attention. The last part of the graph that is "All technologies" includes models that we expect their usefulness for all technologies as they concern the simulation of soiling potential.

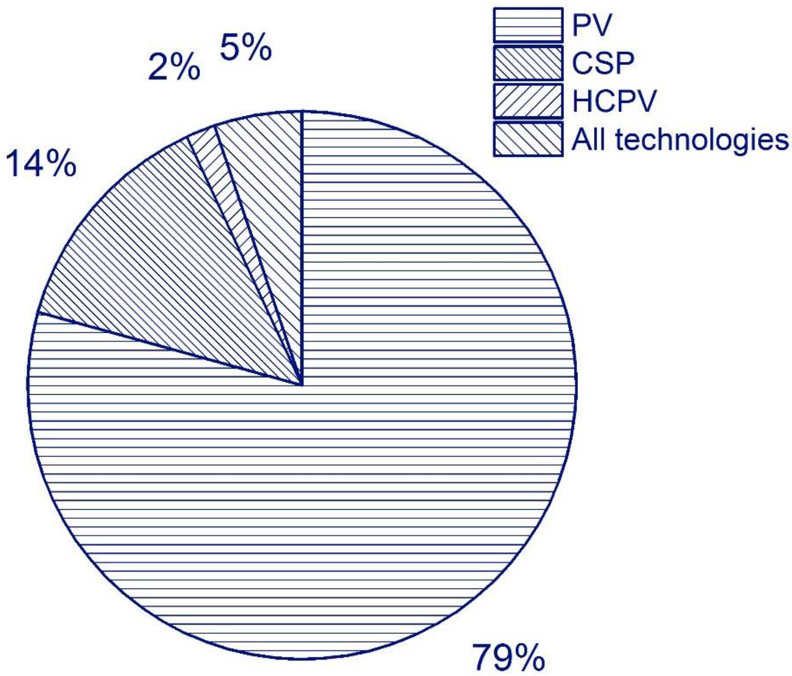


Figure III-5. Share of models performed according to the technologies on which they have been applied

4.1. Theoretical modeling/statistical modeling

To be able to better analyze the state of the art, the articles gathered and summarized above have been divided into two groups:

- Theoretical modeling: this category presents all models based on physics laws.
- Statistical modeling: this category focuses on models based on a statistical analysis of data.

The different applied models have been gathered in Table III-7. Among the theoretical models, there is the work proposed by [21], [216]. Their research focused on a mathematical correlation experiment which results should have improved the predictive capability of simulation models accounting with the sand dust accumulation on PV surfaces. [210] have also proposed a method based on a theoretical model to calculate the optical losses resulting from soiling. In the work of [220], the weather conditions were considered to estimate by simulation the attenuation of the light reaching a glass surface. The simulation model proposed took into account the 'air-dust-glass' structure; different values were put for the thickness of the dust to assess the impact on modules performance. In the paper of [223] an optical-thermal model of a dusty tilted panel has been performed. The authors used a six-layer module in the modeling. This later allowed to reasonably predicting the performance of the module in different weather conditions. In reference [217] the computational model that is given evaluates how particles deposition on surfaces leads to a decrease in performance. Recently [31] found that the transmittance is following the Ångström turbidity equation. This relevant result can be useful to characterize soiling losses in different PV panels.

Concerning the statistical modeling, the soiling phenomenon has been treated in different ways. Some studies were aiming at the correlation between the power generated by a soiled PV module/ soiling rate or losses and parameters such as solar irradiance, temperature, rainfall, wind speed and direction, humidity and dust characteristics (size and composition) [24], [87], [104], [160], [192], [194], [231], [234], [237]. While in other studies, the authors were interested more in the correlation between the dust accumulated and the transmission losses or the output energy of a PV module [221], [222]. In other works based both on CSP and PV technologies, the main considered factor was the cleanness index/factor which was correlated to parameters like dust concentration, wind speed, and relative humidity [4], [10], [120], [164], [235]. Apart from this, other studies were interested in generating, representing or simulating the dust events, the soiling potential and soiling risk maps which will help to have an idea about the amount of settlement that a module could receive [206]–[209].

Table III-7. Analysis of articles published from 1998 to 2019 (including the beginning of 2020) about modeling and prediction of soiling phenomenon

	Based techniques	Ref.
Theoretical modeling	Laws of solar radiation attenuation through the atmosphere (absorption, emission, reflection, transmission, Rayleigh scattering, Mie scattering…) [21], [210], [212], [216], [220], [223], [225] [228] [229]; ASHRAE incidence angle modifier [212], [217]; Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS) [218], [233]; Grain threshold algorithm in the software package Gwyddion [219]; General form of the energy conservation equation [223]; PV power generation models [224], [232]; Van Der Waals adhesion, particle-particle collisions, particle-surface collisions, electrodynamics, the fluid (air), and gravity forces [226] [215]; Ångström turbidity equation [31];	[21], [31], [224], [228], [229], [232], [233], [270], [210], [212], [215]–[218], [220], [223]
Statistical modeling	Polynomial regression [230], [231]; Linear regression [87], [104], [126], [216], [221], [234]; Multi-variable/Multiple linear regression [24], [120], [126], [192], [215], [227], [235], [236], [238], [239]; Multivariate Linear Regression [10], [241] Exponential regression [1], [205]; Bayesian Neural Networks BNNs [231]; Artificial Neural Networks ANNs (Levenberg Marquardt back propagation) [24], [160], [172], [235], [236], [238], [239], [241]; Monte Carlo approach [219], [225], [237]; ANNs (Hybrid data clustering and data division techniques) [194]; ANN (Nonlinear Auto-Regressive with exogenous inputs NARX) [168]; ANN (Extreme Learning Machine ELM) [241] Simulation of dust event and soiling potentials (Dust-fall jar methods from Pollution Control Department (PCD) [222], United States Environmental Protection Agency (US EPA) database [126], [222], WRF-DuMO and GIS [207]–[209], NASA GISS ModelE2 [125], Community Multiscale Air Quality (CMAQ) model [213], Fused Air Quality Surface Using Downscaling (FQSD) [126], Dalhousie model [126], Weather Research Forecasting with Chemistry (WRF-Chem) [214], Georgia Institute of Technology–Goddard Global Ozone Chemistry Aerosol Radiation and Transport (GOCART) aerosol scheme [214], Regional Atmospheric Chemistry Mechanism (RACM) [214], Hemispheric Transport of Air Pollution emissions (HTAP) [214], US Air Force Weather Agency (AFWA) emission scheme [214]); Dynamic Factor Analysis DFA [171] ; Dynamic Linear Models [4], [240]; Contours analysis [193]; Sensitivity analysis (Garson algorithm [172], PAWN algorithm [160]); Theil-Sen estimator [234], [237]; Markov regime Switching (MS) [211]. IEST-STD-CC 1246E cleanliness standard [31];	[1], [4], [160], [164], [168], [171], [172], [192]–[194], [205], [207], [10], [208], [209], [211], [213]–[216], [221], [222], [227], [24], [230], [231], [234]–[241], [31], [87], [104], [120], [125], [126] [219], [225], [237]

The research papers gathered here show that approximately 73% of studies conducted concerns the statistical modeling based on the analysis of data, while just 27% were about theoretical modeling based on physics laws (Figure III-6). Figure III-6, presents as well the share of publications per theoretical modeling/statistical modeling per year. It shows, on the one hand, that research regarding soiling phenomenon increases through the years. On the other hand, it confirms as well that the focus on the statistical modeling increases in the last years against the theoretical one. This last part shows a variety in terms of used models with high use of solar radiation attenuation through the atmosphere laws (Table III-7). The analysis of this revealed that the construction of this type of modeling is based on some hypotheses that are in most cases far from reality. This explains the low percentage of use of this kind of modeling. For instance, in the study of [21] ,which was the basis of many conducted studies, they assumed that:

- The particles are spherical and have the same size,
- The particles distribution is uniform,
- The second layer of particles is deposited or formed just after the full formation of the first layer.

Those assumptions might not be true in all cases in real operating conditions, hence results obtained by [21].

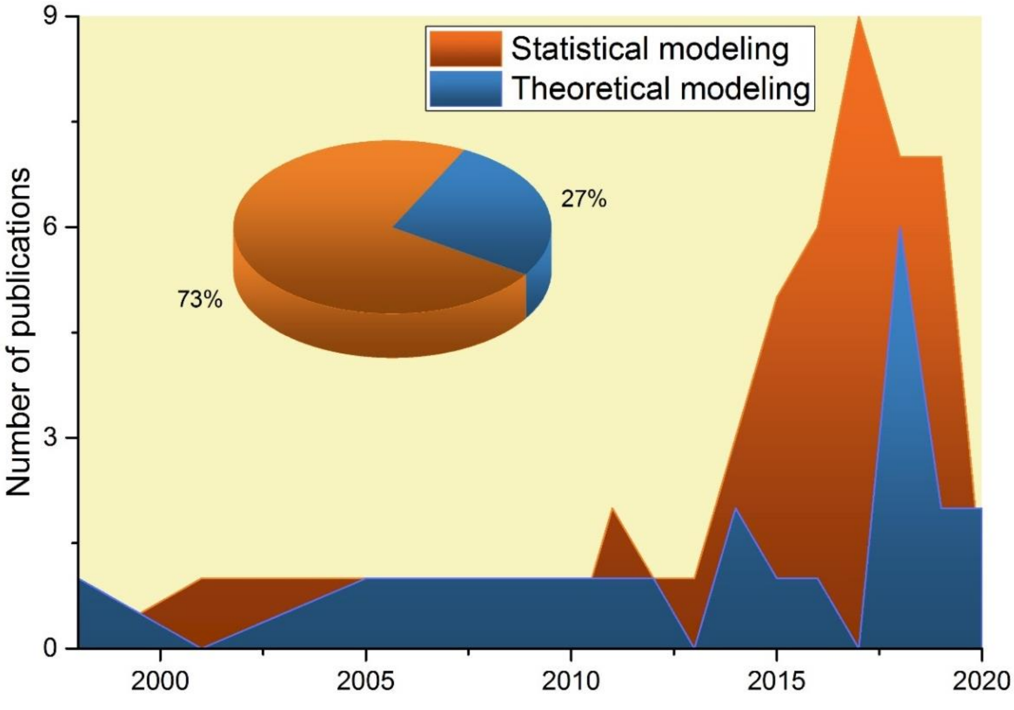


Figure III-6. Repartition of the different studies conducted on the subject of modeling and prediction of soiling effect

For the statistical analysis, the repartition of the applied models is presented in Figure III-7. From this, it can be seen that most of the applied models were based on the regression analysis with a percentage of 42 %. However, all comparisons conducted between neural networks and a regression analysis have shown that neural networks were more accurate and reached better results as it can be seen in the studies [24], [231], [235], [236].

In some works such [10], [120], [160], [235], [236], the authors were interested to predict the soiling effect based on weather conditions. This can be a very valuable work if all the parameters affecting soiling phenomenon are taken into consideration. This can help to forecast the losses due to soiling everywhere is available a station with the necessary sensors with the same inputs. In other works [87], [104], [126], [234], [237], the authors were more interested to predict soiling losses based on PV plant's production. Though they made field measurements, models and methods that they proposed can be very useful everywhere a PV plant is available. The simulation of dust event and soiling potential also have a non-negligible share in the publications about soiling as it can be seen in Figure III-7. Furthermore, it has been reported by [104] and [56] that the dust concentration in the air seems to be a useful parameter for predicting soiling rate changes between different locations. From this and from what we have found, the simulation of dust event and soiling potential is expected to have more attention in future studies. Finding the model linking these potential to the losses due to soiling will maybe end the need to do on-site measurements.

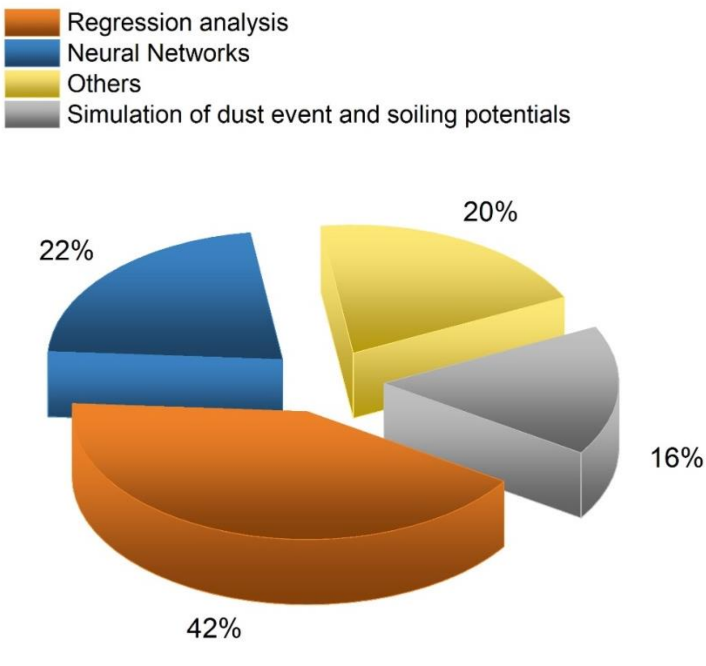


Figure III-7. Repartition of the different studies conducted on the subject of statistical modeling of soiling effect

4.2. Modeling based soiling influencing factors

From the summary conducted by [271], the factors that influence soiling phenomenon can be categorized and summarized as follows: module characteristics (nature of the surface, technology), surrounding environment (land cover, soil texture, bird dropping), meteorological conditions (temperature, relative humidity, rainfall, wind speed, wind direction, dew formation, airborne dust), exposure conditions (tilt angle, orientation, height of installation, tracking, season, exposure time) and soiling properties (chemical composition, particle size, particle shape). Based on this summary and based on Table III-1, from which we selected the papers of "Category AB" and "Category AC", we determined the factors that have been used widely to predict soiling and those that are rarely taken into consideration and present them in Figure III-8. From this, we can clearly see that the factors that are mostly used are the ones that belong to the category of meteorological conditions especially temperature, relative humidity, rainfall, wind speed and airborne dust. This can be explained by the fact that with almost every solar installation, a weather station will be available which makes it easy to consider the weather conditions. Exposure conditions, module characteristics and the surrounding environment are mostly fixed for every model due to difficulty to obtain data for all conditions. However, this represents the lack in almost all the models and in many papers; this has been considered as one of the causes to obtain low performance of their models.

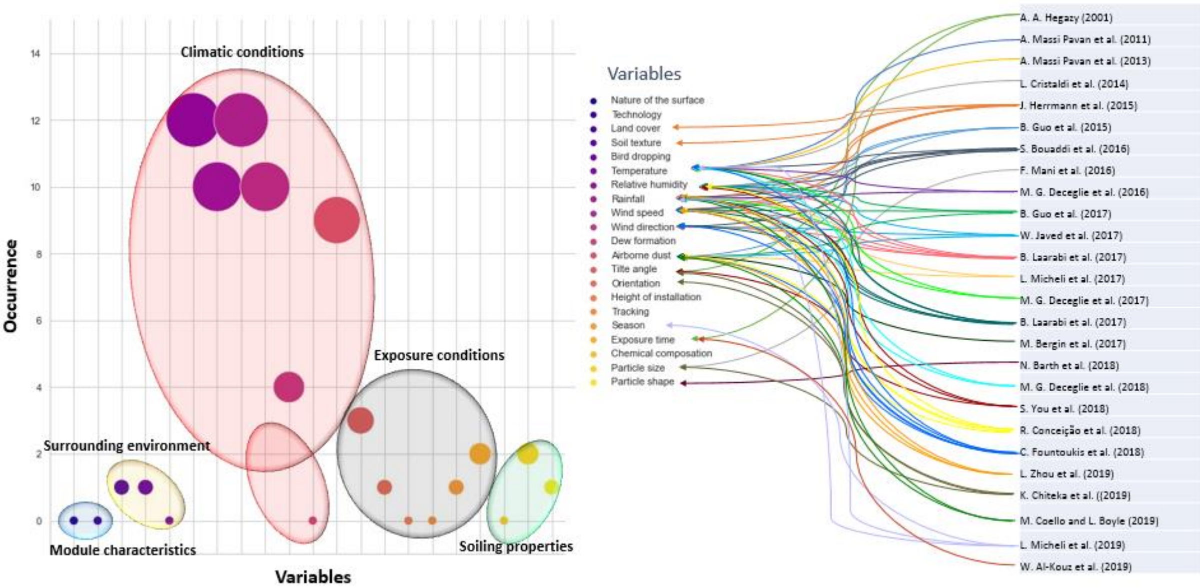


Figure III-8. Factors influencing soiling and their occurrence in the models investigated

4.3. Evaluation metrics

Varieties of criteria have been applied to evaluate the accuracy of the models developed. The choice between one criterion and another depends on the nature of the models. These criteria are gathered in Table III-8 along with their corresponding equations.

Table III-8. Evaluation metrics applied for accuracy and performance assessment

Criterion	Symbol	Equation	
The coefficient of determination	R²	$R^2 = 1 - \frac{\sum_{i=1}^{N}(\hat{x}_i - x_i)^2}{\sum_{i=1}^{N}(x_i - \bar{x}_i)^2}$	(III-1)
Mean Absolute Error	MAE	$MAE = \frac{1}{N}\sum_{i=1}^{N}\lvert\hat{x}_i - x_i\rvert$	(III-2)
Root Mean Square Error	RMSE	$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(\hat{x}_i - x_i)^2\right]^{1/2}$	(III-3)
Mean Absolute Percentage Error	MAPE	$MAPE = 100 \times \frac{1}{N}\sum_{i=1}^{N}\left\lvert\frac{\hat{x}_i - x_i}{\hat{x}_i}\right\rvert$	(III-4)
Mean Square Error	MSE	$MSE = \frac{1}{N}\sum_{i=1}^{N}(\hat{x}_i - x_i)^2$	(III-5)
Akaike Information Criterion	AIC	$AIC = 2k - 2\ln(\hat{L})$ *k : the number of model parameters* $\hat{L}$ *: the maximum value of likelihood function of the model*	(III-6)
Bayesian Information Criterion	BIC	$BIC = 2\ln(\hat{L}) + k.\ln(n)$ *n : the number of observations* *k : the number of regressors* $\hat{L}$ *: the maximum value of likelihood function of the model*	(III-7)
Modeling Efficiency	ME	$ME = 1 - \left(\frac{\sum_{i=1}^{N}(\hat{x}_i - x_i)^2}{\sum_{i=1}^{N}(x_i - \bar{x}_i)^2}\right)$	(III-8)
Mean Bias Error	MBE	$MBE = \frac{1}{N}\sum_{i=1}^{N}(\hat{x}_i - x_i)$	(III-9)
the Receiver Operation Characteristic analysis	ROC	The ROC is a method for visualizing, organizing, and selecting classifiers based on their performance [272]	

5. Conclusion

In the present chapter, a review of the different studies conducted to model soiling phenomenon has been presented. A summary of the most important information about each model has been provided. The papers summarized have been analyzed and gathered into groups to better present the trend that research on this phenomenon follows.

The review shows a variety of the applied models and methods. Each model has its own strengths and weaknesses. Five groups were identified, depending on the purpose of the modeling. These, describe the different parts of the cycle of soiling, from weather conditions to end up in the losses. These parts are complementary to each other and will help researchers to identify on which path they will focus on.

The results of the analysis of the applied models showed that statistical modeling was applied more than theoretical modeling. The analysis of the latter revealed that studies conducted most often take into consideration hypotheses that were far from reality. The results showed as well that in the statistical modeling itself, although regression analysis has been used more frequently, neural network approaches performed better in prediction of soiling phenomenon.

The analysis performed also revealed that two kinds of modeling were involved in the works performed. The first is about predicting soiling effects based on influential factors and the second is inferring soiling losses from the data of existing solar plants. These models can be very valuable respectively when a station with the necessary sensors is available and only when a solar plant exists.

However, in order to approach the complex behavior of the soiling phenomenon and to predict it over time accurately, more data for long periods are still needed. Moreover, all parameters affecting soiling should be taken into consideration. Additionally, it is highly recommended that the same model should be tested in different climates and on different technologies to validate its usefulness. Furthermore, as it has been proved that the dust concentration ranks first in predicting soiling losses, the use of existing databases of soiling potential adjusted using weather conditions from existing databases or from meteorological stations seems to be a low cost and valuable method to predict soiling losses. This will be achieved, however, only after finding the accurate relationships between the parameters and validating them on the site. Finally, it is highly recommended as well that instead of suggesting new models, it will be wiser to test the published models that have proved good results in different sites and technologies to overcome their limits and to achieve the accurate and well-tested model.

In conclusion, the review presented here summarizes almost all models applied in the framework of studies of soiling effects on solar systems from 1998 until 2019 (including the beginning of 2020). This review will help researchers working on this topic gain an overview of the models applied. It will also help to better choose the right direction in modeling and predicting soiling phenomenon. Understanding and mastering this phenomenon will not only prevent investments from losses but also save the precious natural resource “water” by determining the mitigation techniques wisely.

CHAPTER IV : MATERIALS AND METHODS

1. Introduction

This chapter presents a description of the methodology followed, the measurements conducted as well as the analyses carried out.

2. Principle of the study

The study presents a quantification of soiling in two regions in two different countries. The first is Rabat-Sale-Kenitra, the capital region of Morocco and in Tamil Nadu state of India.

The investigation was over a total exposure period of 5 months (from the end of March 2019 until the beginning of September 2019) in Rabat-Sale-Kenitra region. This quantification is based on the use of glass samples of dimensions 25 mm × 28 mm × 1 mm (width × length × thickness) exposed in real conditions. In Tamil Nadu state, India, the study was over a period of approximately 5 months (from the beginning of June 2020 until mid-October 2020) due to the pandemic Covid-19 situation. The glass samples have the dimensions 25.4 mm × 76.2 mm × 1 mm (width × length × thickness).

Based on the comparison between the methods to quantify soiling conducted by [47], PV modules should have been used as they represent the real quantification method of soiling. However, in this study, the practical advantages of using glass samples instead of PV modules are: transmittance measurement, deposit mass measurement without collection, SEM/EDS or microscope analysis of soiled surfaces, the possibility of installation of several samples with different inclinations and in several places, easy sampling and reduced space needed for exposure and cost less expensive.

The use of solar glass is essential for a better representation of the phenomenon of soiling of PV modules. However, the unavailability of several samples of solar glass with the same characteristics (composition, surface structure and dimensions) obligates the use of samples of ordinary (simple) glass. Indeed, the use of solar glass is not perfectly representative of the effect of soiling on all types of PV modules, given the availability of several brands of solar glass. In addition, the main objective of this work is to study the variation of the effect of soiling as a function of inclination, location, exposure period and meteorological parameters, whatever the type of glass used. As a result, the essential requirement is the use of glass samples with the same characteristics.

After being cleaned, the glass samples are fixed on the holder and then exposed in outdoor conditions. After each exposure period, and with minimum agitation, the sample holders are kept in boxes and transported very carefully to the site of measurements. Then, transmittance, mass and thickness measurements are carried out on the glass samples. During transport, the samples do not know any extra dust deposition and they are stored in the laboratory for one or two days until measurements. Before measurements, the dried glue is carefully removed from the back surface of the glass samples using glass detergent, and then wiped using IsoPropyl Alcohol (IPA) liquid to remove any remaining glue. After, new samples are stuck on the wooden samples-holder and the exposure continues for another period. The overall methodology followed in this study is presented in Figure IV-1.

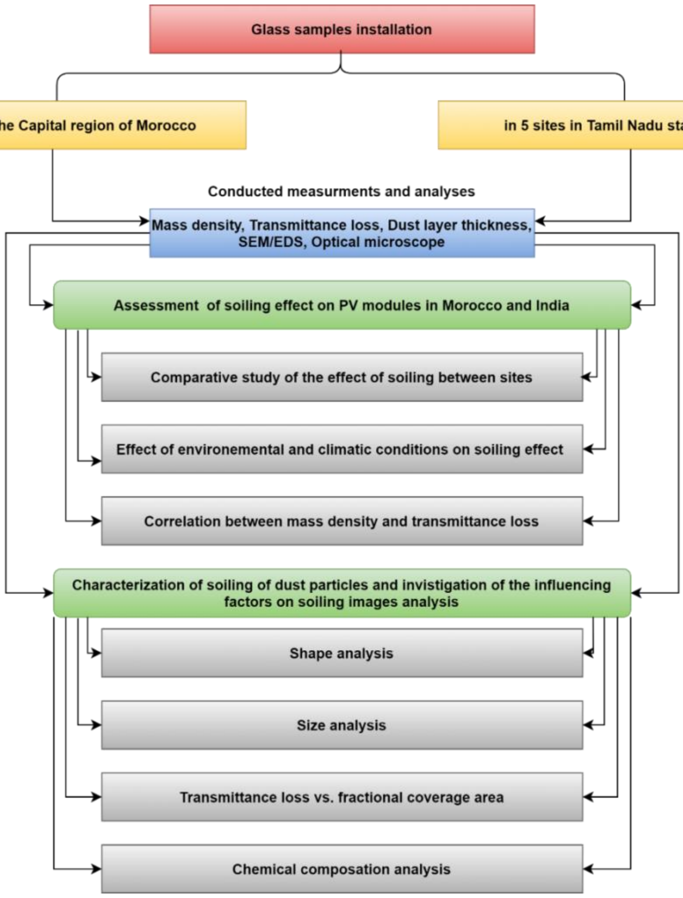


Figure IV-1. Flowchart of the methodology followed

3. Selected sites and their geographical and environmental characteristics

In this section, the geographical and environmental characteristics of each site are described. The geographic and environmental characteristics of the sites selected in each country are more or less dissimilar (Figure IV-2). Table IV-1 gives the geographical characteristics; mainly longitude, latitude, altitude and distance from the ocean of the selected sites.

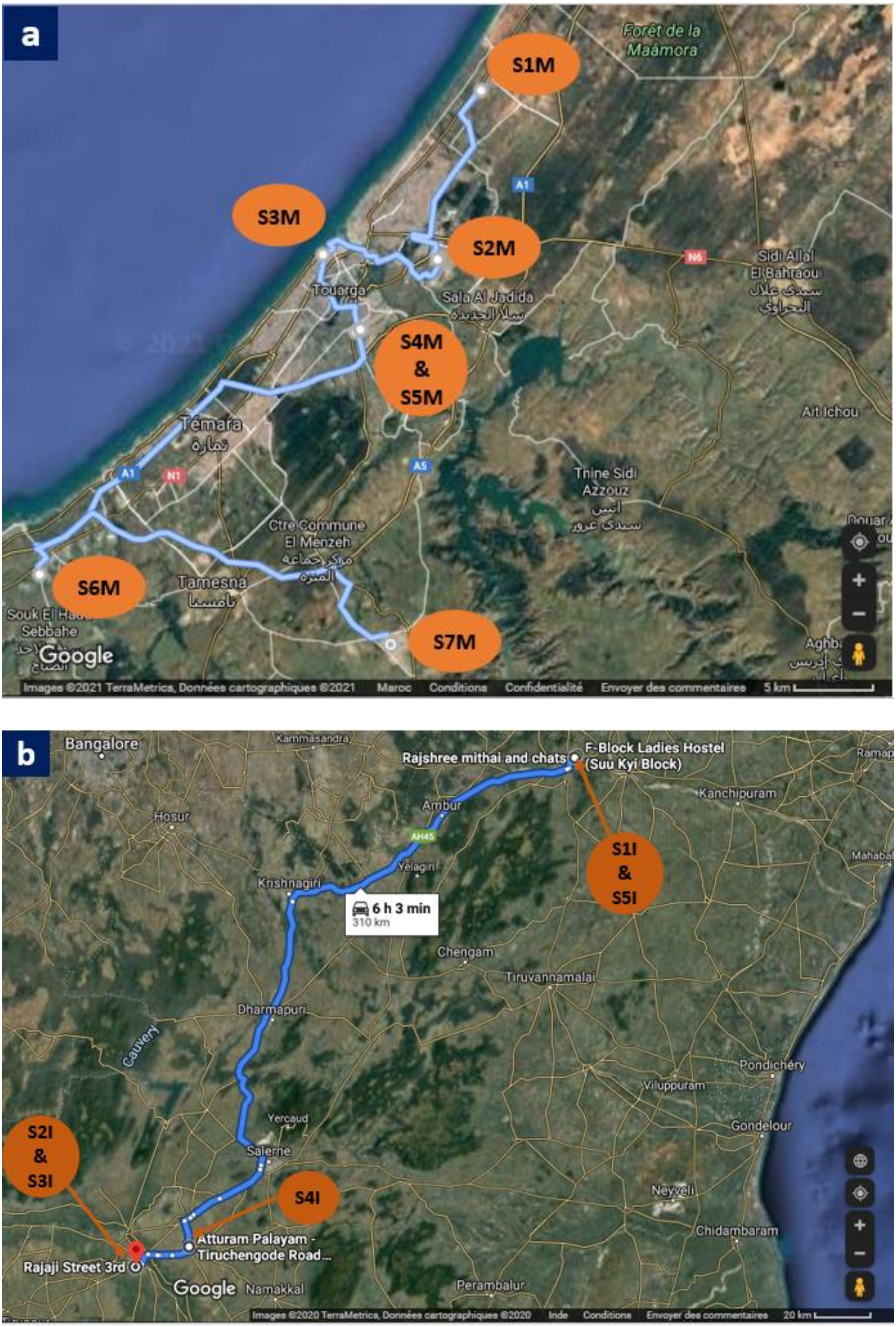


Figure IV-2. Selected sites for samples installation [source Google Maps]. a) the sites in the capital region of Morocco https://urlz.fr/aHrh while b) those of Tamil Nadu state of India https://bit.ly/34UNMjx

Table IV-1. Geographical characteristics of the selected sites

Country	N°	Site	Longitude [°]	Latitude [°]	Altitude [m]	Distance from the ocean [km]
Capital region of Morocco	S1M	Sidi Bouknadel, Sale	-6.740931	34.116976	26	1.7
	S2M	Alkarya, Sale	-6.77071	34.020111	89	6
	S3M	Ocean, Rabat	-6.849853	34.023077	27	0.3
	S4M	Takaddoum 1, Rabat	-6.827451	33.979221	88	5
	S5M	Takaddoum 2, Rabat	-6.827451	33.979221	88	5.2
	S6M	Skhirat	-7.045912	33.840282	57	3.5
	S7M	Ain Aouda	-6.802916	33.799892	237	20.5
Tamil Nadu state of India	S1I	VIT Vellore	*79.162733*	*12.971312*	*208*	*118*
	S2I	Erode 1	*77.707838*	*11.324348*	*183*	*207*
	S3I	Erode 2	*77.707838*	*11.324348*	*183*	*207*
	S4I	Namakkal	*77.882395*	*11.390894*	*238*	*205*
	S5I	Vellore	*79.156727*	*12.966668*	*201*	*119*

There are three main sources of natural particles:

- The terrigenous source: these particles are generated by soil erosion under the action of the wind, especially in desert areas.
- The marine source: under the action of the waves, droplets of water are projected into the atmosphere. After evaporation of seawater, sea salts are found in the atmosphere and form aerosols, the composition of which is close to that of seawater.
- The biogenic source: the biogenic aerosol comes from the direct emission by plants.

The main human activities responsible for the emission of particles are: agriculture, manufacturing industry (in particular construction sites), the residential / tertiary sector (mainly wood combustion, coal and fuel oil) and transport.

Table IV-2 shows the location of each site on Google Maps and illustrates its surrounding environment. All open spaces that do not contain green spaces, buildings or roads are considered as terrigenous source. The marine source is considered in Table IV-1 as "Distance from the ocean" while biogenic sources and agriculture are considered as green spaces in Table IV-2. Green spaces include all grassland areas, forests or any cultivated area. As for transport, this means that the area is known by heavy traffic. As far as construction is concerned, it refers to all nearby fields where construction/destruction of a new building/old building is in progress. A description of the characteristics of this environment has also been detailed in the table.

The surrounding environment covers a circular area with a radius of 1 km. The symbol "+" was used to compare the different sites. It presents a simple description of the nearby particle's sources based on the visual inspection and satellite images from Google Maps and does not belong to any calculation or standard. For more details on each site please visit the links on google maps given in Figure IV-2. The + symbols can be translated by the following meanings: [+++] means a significant presence, [++] means a medium presence, and [+] means a low presence. The description of a site by one of the three symbols is always related to other sites.

Table IV-2. Environmental characteristics of the selected sites. [+++] for a significant presence, [++] for a medium presence, and [+] for a low presence. M refers to Morocco while In to India

Country	**N°**	**Site**	**Particle sources**			
			Terrigenous	**Transport**	**Green spaces**	**Construction**
Capital region of Morocco	S1_M	Sidi Bouknadel, Sale	+++	+	++	+
	S2_M	Alkarya, Sale	+++	++	+	++
	S3_M	Ocean, Rabat	+	+++	+	++
	S4_M	Takaddoum 1, Rabat	+	+++	+++	+
	S5_M	Takaddoum 2, Rabat	+	+++	+++	+
	S6_M	Skhirat	+++	+	+++	++
	S7_M	Ain Aouda	+++	+	++	+++
Tamil Nadu state of India	S1_In	VIT Vellore	++	+	+++	++
	S2_In	Erode 1	+	+++	+	+++
	S3_In	Erode 2	+	+++	+	+++
	S4_In	Namakkal	+++	++	++	+++
	S5_In	Vellore	++	++	++	++

4. Description of the samples holder and the exposure periods

In the capital region of Morocco glass slats (25 mm x 28 mm x 1 mm) are attached to rigid transparent plastic, and then the whole is fixed on the sample's holder (Figure IV-3a). The sample holder is made of wood and has two facades, one of which is horizontal while the other is inclined by 30 ° (equivalent to the angle of inclination of the PV modules in the study area). Four glass samples were attached to each side of the samples-holder in order to have more precision in the measurements. At each site and at each period, a samples-holder is installed. The samples-holder is oriented in the same way as the PV modules; the inclined surface is oriented to the south. In Tamil Nadu state of India, glass samples have the dimensions (25.4 mm × 76.2 mm × 1 mm) and the sample holder has the dimensions presented in Figure IV-3b.

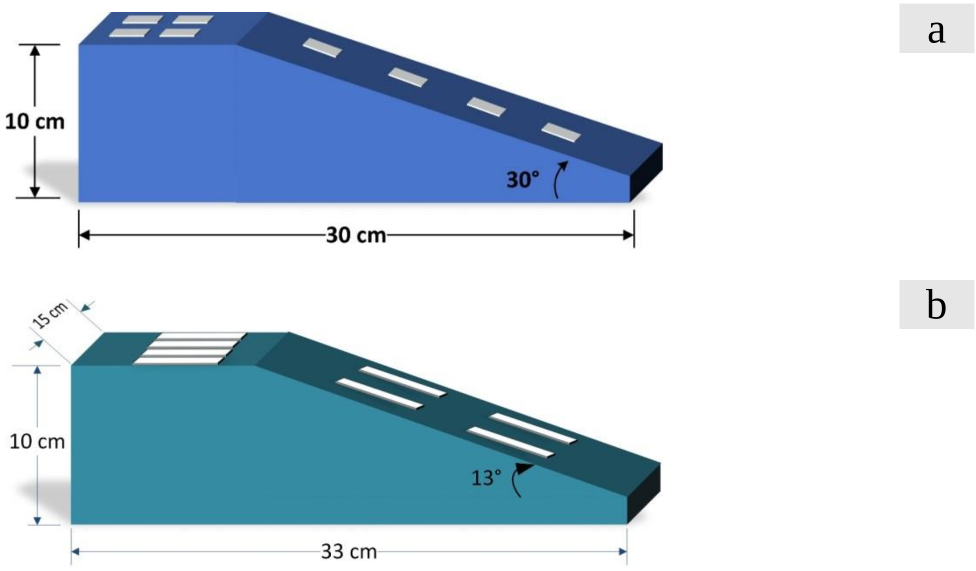


Figure IV-3. Shape and dimensions of the samples holder

Table IV-3 below shows the date of exposure and sampling of the samples-holder installed in the different sites. The sign (-) in the table indicates the absence of measurements caused by the destruction of the samples during the corresponding exposure period. For the fourth period of exposure in the capital region of Morocco, the duration exceeded a month, and this is it because of the summer holidays. The duration of all the periods is between 30 to 40 days.

Table IV-3. The different exposure periods of the study

	N°	Site	Exposure period				
				P1	**P2**	**P3**	**P4**
Capital region of Morocco	S1M	Sidi Bouknadel, Sale	Start date	31/03/2019	11/05/2019	15/06/2019	19/07/2019
			End date	01/05/2019	15/06/2019	19/07/2019	03/09/2019
	S2M	Alkarya, Sale	Start date	27/03/2019	01/05/2019	30/05/2019	-
			End date	01/05/2019	30/05/2019	10/07/2019	-
	S3M	Ocean, Rabat	Start date	30/03/2019	08/05/2019	10/06/2019	11/07/2019
			End date	08/05/2019	10/06/2019	11/07/2019	26/08/2019
	S4M	Takaddoum 1, Rabat	Start date	-	09/05/2019	11/06/2019	11/07/2019
			End date	-	11/06/2019	11/07/2019	27/08/2019
	S5M	Takaddoum 2, Rabat	Start date	05/04/2019	09/05/2019	12/06/2019	14/07/2019
			End date	05/05/2019	11/06/2019	12/07/2019	27/08/2019
	S6M	Skhirat	Start date	30/03/2019	07/05/2019	16/06/2019	23/07/2019
			End date	07/05/2019	16/06/2019	23/07/2019	08/09/2019
	S7M	Ain Aouda	Start date	26/03/2019	29/04/2019	28/05/2019	01/07/2019
			End date	29/04/2019	28/05/2019	01/07/2019	02/09/2019
Tamil Nadu state	S1I	VIT Vellore	Start date	08/06/2020	09/07/2020	18/08/2020	16/09/2020
			End date	09/07/2020	12/08/2020	16/09/2020	17/10/2020
	S2I	Erode 1	Start date	11/06/2020	12/07/2020	22/08/2020	17/09/2020
			End date	12/07/2020	21/08/2020	17/09/2020	23/10/2020

	S3I	Erode 2	Start date	11/06/2020	12/07/2020	22/08/2020	17/09/2020
			End date	12/07/2020	21/08/2020	17/09/2020	23/10/2020
	S4I	Namakkal	Start date	07/06/2020	09/07/2020	20/08/2020	18/09/2020
			End date	09/07/2020	18/08/2020	18/09/2020	24/10/2020
	S5I	Vellore	Start date	14/06/2020	14/07/2020	17/08/2020	16/09/2020
			End date	14/07/2020	13/08/2020	16/09/2020	16/10/2020

5. Procedures and measuring instruments

At the end of each period, exposed samples are subject to the following measurements and analyzes: a) Determination of the mass of deposited soil, b) Determination of transmittance loss, and c) Determination of the soiling thickness d) SEM/EDS and microscope analyses.

In assessing the impact of meteorological conditions on the phenomenon of soiling, it is necessary to take into consideration the meteorological factors. In this study, these variables were recorded from the international weather database https://power.larc.nasa.gov.

5.1. Conducted measurements

The measurement of the deposited soil mass is calculated using the following formulas:

$$d_{(H,I)} = \frac{1}{3}\sum_{j=1}^{3} d_j \quad \text{(IV-1)}$$

$$d_j = \frac{m_s}{S} \quad \text{(IV-2)}$$

$$m_s = m_s - m_r \quad \text{(IV-3)}$$

with:

$d_{(H,I)}$: Average areal mass density per a horizontal/inclined surface, per site and per period (g/m^2);

d_j: Areal mass density of a simple j (g/m^2);

S: Glass sample surface (m^2);

m_s: Mass of deposited soil (g);

m_{sample}: Mass of the sample after exposure (g);

m_{ref}: Mass of the cleaned sample (g).

The effect of soiling is also investigated through transmittance measurements, performed by measuring irradiance through clean glass and soiled one. In order to determine more precisely the transmittance of the sample, the irradiance transmitted and that received are measured 3 times at 3 points on the glass (Eq. IV-7). The transmittance of the sample equals to the average of the transmittance at these 3 points (Eq. IV-6). The reduction of the transmittance of the soiled sample against to that of the cleaned one is calculated using Eq.

IV-5. This is averaged from three samples to get the final value per horizontal/inclined surface, per period and per site (Eq. IV-4).

$$\Delta TR_{(H,I)} = \frac{1}{3}\Delta TR_j \tag{IV-4}$$

$$\Delta TR_j = 1 - \frac{TR_S}{TR_r} \tag{IV-5}$$

$$TR_{(r,s)} = \frac{1}{3}\sum_{i=1}^{3} TR_i \tag{IV-6}$$

$$TR_i = \frac{G_{ti}}{G_{ri}} \tag{IV-7}$$

with:

$\Delta TR_{(H,I)}$: Average transmittance loss per a horizontal/inclined surface, per site and per period (%);

ΔTR_j : Transmittance loss of a sample j (%);

TR_S : Transmittance of the soiled sample (%);

TR_r : Transmittance of the cleaned sample (%);

TR_i: Transmittance of a spot i in the sample (%);

G_{ti}: Transmitted irradiance in a spot i in the sample (W/m²);

G_{ri}: Received irradiance to a spot i in the sample (W/m²).

For the thickness, the layer of dust is calculated based on the equations (Eq. IV-8, Eq. IV-9 and Eq. IV-10). The thickness of three points on the cleaned and soiled glass samples is measured. Further, the average per the soiled and the cleaned glass is calculated. The difference between the average thickness of the soiled and the cleaned glass gives the average thickness of the dust layer per one sample. Then the average per three samples is computed to get the thickness of the horizontal and the inclined surfaces. Then the thickness of soiling per site, per period and on a horizontal or inclined surface is averaged from the thickness of three samples (Eq. IV-8)

$$\Delta Tk_{(H,I)} = \frac{1}{3}\sum_{1}^{3} \Delta Tk_j \tag{IV-8}$$

$$\Delta Tk_j = \left(Tk_s - Tk_r\right) \tag{IV-9}$$

$$Tk_{(r,s)} = \frac{1}{3}\sum_{i=1}^{3} Tk_i \tag{IV-10}$$

with:

$\Delta Tk_{(H,I)}$: Thickness of the glass sample per a horizontal/inclined surface, per site and per period (µm).

ΔTk_j : Thickness of the dust layer of a sample j (µm);

Tk_s : Thickness of the soiled glass, either for horizontal or inclined surfaces (µm);

Tk_r : Thickness of the cleaned glass, either for horizontal or inclined surfaces (µm);

Tk_i : Thickness of the dust layer of a spot i in the sample (µm);

For the study conducted in the capital region of Morocco, the measurement of the mass was carried out using a high-precision scale Mettler Toledo 'AE240'. The received and transmitted irradiance are measured using a solar-power meter SPM72.

For the study conducted in Tamil Nadu state of India a *PVM210/Megger* solar power meter is used for the transmittance measurements. For the mass, an *AS 220/C/2 RADWAG* weighing balance is used. A *C/N 293-281-30 MITUTOYO* instrument is used for thickness measurements.

5.2. Quantification of uncertainties

To measure a quantity is not simply to seek the value of this quantity, but also to associate it with uncertainty in order to qualify the quality of the measure. This uncertainty is associated with measurement errors, which may be due to the measuring instrument, the operator or the variability of the measured quantity. The different types of the uncertainties are summarized in Table IV-4 [273], [274].

Table IV-4. Types of uncertainties and their method of calculation

Type of uncertainty		Calculation method
Standard uncertainty	Random measurement error: uncertainty Type A	A type A uncertainty u_A is evaluated by statistical methods which involve the standard deviation s. It results from the use of a large number, denoted n, of measured values. $u_A(x_i) = s(\overline{X_i}) = \sqrt{\frac{1}{n(n-1)}\sum_{k=1}^{n}(X_{i,k} - \overline{X_i})^2}$ (IV-11) with $x_i = \overline{X_i} = \frac{1}{n}\sum_{k=1}^{n} X_{i,k}$ (IV-12)
	Systematic error: uncertainty Type B	In a single measurement, the accuracy of the measuring device, how it is used and the quality of the measurement must be taken into account. The corresponding error is the systematic error and the associated uncertainty is said to be type B, denoted u_b. Evaluating this requires looking for all sources of error and assessing the uncertainty associated with each source.
Combined standard uncertainty		The combined standard uncertainty of the measurement result y, designated by $u_c(y)$ and taken to represent the estimated standard deviation of the result, is the positive square root of the estimated variance $u_c{}^2(y)$ obtained from: $u_c{}^2(y) = \sum_{i=1}^{n}(\frac{\partial f}{\partial x_i})^2 u^2(x_i)$ (IV-13) Eq. (IV-13) is based on a first-order Taylor series approximation of the measurement equation Y = f $(X_1, \ldots, X_n)$ and is conveniently referred to as the law of propagation of uncertainty.
Expanded uncertainty		Although the combined standard uncertainty $u_c(y)$ of the measurand Y

	may be suitable for expressing the uncertainty of a measurement result, there is almost always a need for an interval within which a large fraction of the distribution of values that could reasonably be attributed to the measurand. As a result, one can be led to express an expanded uncertainty U, such as: $U = k \times u_c(y)$ (IV-14) where k is the coverage factor. The value of k is chosen based on a required confidence level for the interval [y - U , y + U]. In most cases, it is recommended to take k equal to 2 for a confidence level of 95%.

In order to determine the uncertainty of the values measured in this study, n = 30 measurements were taken under repeatability conditions. It is obtained by repeating measurements on the same measurand while retaining the same measuring conditions: same method of measurement; same operator; same measuring instrument; same place; same condition of use and repetition for a short period.

In the statistical study of the observation's series of the measured quantity, the average of the observed values can be considered as random and of normal distribution. The average of this law is then considered as the "real" value of the observed quantity. The dispersion of the law then informs on the error of observation [275]. In general, when the number n of observations (measurement) increases the probability density of the variable approaches the bell curve of the normal distribution to which it can be assimilated when $n \geq 30$ [276]. The results of assessing the uncertainty of the protocol for measuring the transmittance and the mass of the glass samples are presented in Table IV-5.

Table IV-5. Evaluation of measurement uncertainties

		Mean	***Standard deviation***
Capital region of Morocco	Mass density [g/m²]	2.18310	0.00014
	Transmittance loss [%]	14.4917	1.8209
Tamil Nadu state of India	Mass density [g/m²]	$1.9000\ 10^{-4}$	$0.0412\ 10^{-4}$
	Transmittance loss [%]	2.8066	0.0025
	Thickness [µm]	1.3111	0.4226

5.3. Images analysis

The SEM/EDS analysis of the glass samples collected in the capital region of Morocco has been conducted using an environmental FEI Quanta 650 model, equipped with an EDAX Instruments Apollo SDD EDS detector (USA). The selected samples are attached to a carbon adhesive double-sided support and to avoid any accumulation of electrical charges that decrease the quality of the image, they are metallic in carbon before being introduced into the microscope chamber. The observations are made under vacuum in BSE mode.

For the glass samples collected from Tamil Nadu state of India, they were analyzed using Scanning Electron Microscope (SEM) of EVO 18 model - Carl Zeiss. The features of EVO 18 are: X-ray geometry with Energy Dispersive X-Ray Spectroscopy (EDS) & Wavelength Dispersive X-Ray Spectroscopy (WDS) ports, five segment BSE detector to visualize topographical information. The sample considered under study was an environmental soil accumulated microscopic glass which was placed at different locations of sites. These samples are examined under vacuum in BSE mode at microscopic level (--) to understand the particle structures. Further, EDS is performed to characterize the material composition by X rays emitted by bombardment the electron beam on the sample. Olympus U-MSSP4 microscope has been used as well for image analysis. The images have been taken under 10x and 20x magnification. Image parameters (brightness, contrast, texture, color and lighting) have been adjusted to capture images in optimal conditions [31][277]. For each sample, two or three images been captured.

The resulting images have been processed using ImageJ software [278] where grayscale images have been generated automatically. The thresholding has been done manually by comparing with the original images. The elements included below the threshold are considered to be the substrate while the elements above the threshold are considered to be the objects to be analyzed (in our case it is dust).

5.4. Supplementary analysis

Apart from the selected sites abovementioned, dust samples have been collected from different sites in Morocco. The aim is to identify the composition of soiling spontaneously and randomly accumulated on the front surface of PV panels installed in various climate zones (Figure IV-4).

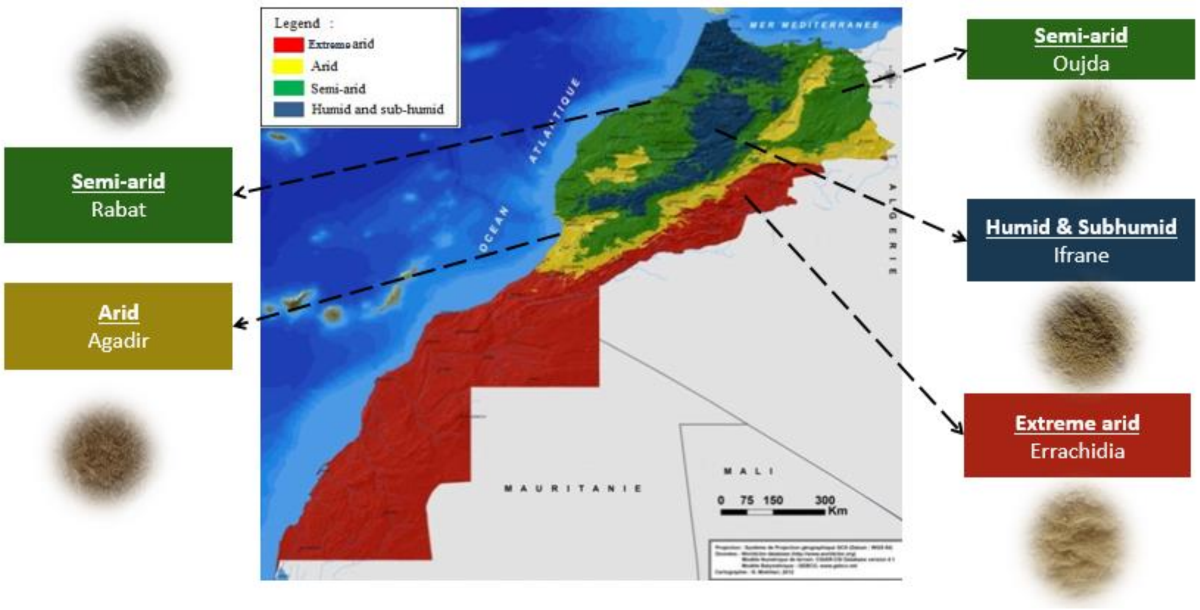
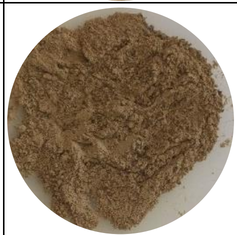
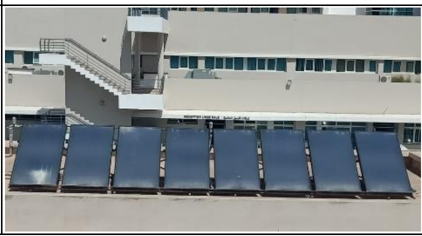
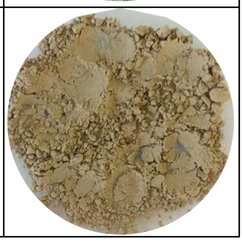


Figure IV-4. Topographic map of soiling samples collection sites

Table IV-6. Location of the PV panels from which soiling samples have been collected

Climate zone	City	Site of soiling sample collection	PV installation	Soiling sample
Extreme arid	Errachidia	PV panels, installed on a farm in Errachidia		
Arid	Agadir	PV panels installed at Solar Platform of Materials and Renewable Energies Laboratory in the Faculty of Sciences of Agadir.		
Semi-arid	Rabat	PV panels, installed at R&D Solar Energy Platform of Physics of Semiconductors and Solar Energy Research Team (PSES) at ENS-UM5 in Rabat.		
	Oujda	PV modules installed on the roof of the University Hospital Center in Oujda.		

Humid and sub-humid	Ifrane	PV panels installed at Al Akhawayn University in Ifrane.		

The soiling samples were collected from the front surface of PV modules that were not cleaned for a long time in order to take into consideration the seasonal composition variations of soiling (Table IV-6). Two different collection methods, dry and wet, have been applied depending on the soiling quantity. The dry method refers to removing manually the dirt and dust directly from the modules surfaces without using any kind of cleaning. The wet method consists of draining the dirt by a water jet, then removing the water-soiling mixture by passing a sweet squeegee to prevent surface micro-scratching. The water-soiling mixture is then put into a Petri dish and dried carefully. After the collection, the samples were crushed and sieved to get a fine powder of less than 0.25 mm particles diameter.

In order to determine the chemical and mineralogical composition, three analytical techniques were applied. The analyzes have been performed at the Technical Support Units for Scientific Research (UATRS) from the National Center for Scientific and Technical Research (CNRST) in Rabat, and at the Materials Physico-Chemistry Laboratory from ENS-UM5R of Rabat. These analyzes are as follows:

X-Ray Diffraction Analysis (XRD): carried out using a PANalytical X'PERT-Pro graphite rear monochromator Theta-Theta Powder Diffractometer.

X-Ray Fluorescence Analysis (XRF): performed on an Axios dispersion wavelength dispersion spectrometer.

Fourier Transform Infrared Spectrometric Analysis (FTIR): conducted using the Bruker ALPHA platinum spectrophotometer.

6. Conclusion

In the present chapter, the methodology followed is detailed. This includes the geographical and environmental characteristics of each site, the samples holder as well as the exposure periods. Then, the procedures and measurements mainly the mass density, the transmittance loss, the thickness of the dust layer and their corresponding uncertainties. Finally, a description of the SEM/EDS and optical microscope techniques and the corresponding analyses conducted on their resulting images.

CHAPTER V : ASSESSMENT OF SOILING EFFECTS ON PV PANELS IN MOROCCO AND INDIA

1. Introduction

In this chapter, we present the first section of the results obtained. These include a comparison of soiling effect between the different chosen sites, an assessment of the impact of the environmental and meteorological conditions on soiling effect, and finally a correlation between the mass density and the transmittance loss and a deep investigation on its modeling.

2. Comparative study of the effect of soiling between the sites

In this section, a comparison between the effects of soiling between sites is conducted. On the basis of the measurements carried out, the monthly mass density of deposit and transmittance loss for each site are calculated. Indeed, each measurement of mass density / transmittance loss corresponds to a known exposure period, which is generally around 30 days. Assuming that there is proportionality between the duration of exposure and the mass density/ transmittance loss, a monthly value of measured quantity more or less representative of each period in each site is calculated. This approach does not necessarily represent reality; it is just an approximate method.

The results show that the mass density varies from site to another and from period to period and ranges from 0.37 to 2.86 g/m²/month in the capital region of Morocco as can be seen in Figure V-1. During the two periods P2_M and P3_M, the samples installed at the site S2_M underwent the largest deposit (2.86 g/m²/month). Figure V-1 also show that the loss in transmittance varies according to the location and the period of exposure. However, this variation is less significant than in the case of the mass density. The transmittance losses are in the range of 1.05 – 10.04 % / month, and again site S2_M during periods P1_M and P2_M experienced the highest values.

The results obtained can be explained by the environment of this site S2_M which is characterized by high human activity (especially in the summer, knowing that the two periods P2_M and P3_M represent the end of spring and summer) with the presence of vast grounds generating dust in the atmosphere.

For all sites, the cleaning effect of the rainfall that occurred during the first exposure period P1_M is remarkable in comparison with the results of other periods. However, for relative humidity and wind speed, their effect is not clearly visible on the variation of the mass density in the graphs below. One of the main reasons for these observations could be the measurement period of dust accumulation relatively long, as weather conditions change continuously. In fact, this period was chosen to collect a significant and measurable amount of dust relative to the weight of the glass. The correlation between the meteorological variables and the mass density / transmittance loss will be detailed in section 3.

From Figure V-1, it can be observed as well that the difference in terms of mass density between the horizontal and inclined surfaces does not correspond to the same difference in terms of transmittance loss. For example, for S1_M (P1), S6_M (P3) and S7_M (P1), there was no difference between the horizontal and inclined samples in terms of mass density, but for transmittance loss, there was a difference which is not the same in all cases. Indeed, according to the study conducted by Figgis et al. [47] where they compared the methods for quantifying soiling losses, the mass density measurements were not perfectly representative of the transmittance losses due to soiling. The linear relationship between these two variables (mass density and transmittance loss) can be affected by the shape, composition and distribution (over the sample) of the deposited particles. For the same density, the effect of large and opaque particles against that of fine and transparent particles is not the same. In addition, particles can deposit on each other, which increases the mass density, but not the loss in transmittance. In order to explore further in this direction, section 4 will be dedicated to studying this correlation in depth.

By comparing the measurements on a horizontal surface with those on an inclined one, it can be seen that in terms of mass density, most horizontal surfaces have almost a density greater than that of inclined surfaces. Which is in perfect harmony with the study conducted by [32], [72], [129], [279] on the effect of the tilt angle. However, there are some cases where the density is the same for the two types of surfaces S1_M (P1 and P2), S2_M (P2), S5_M (P4), S3_M (P3) and S7_M (P1). For only two cases, S3_M (P1) and S5_M (P1), the inclined surface has accumulated more dust than the horizontal one. However, this difference is negligible for S5_M (P1), but considerable in the case of S3_M (P1). This can be explained by the results of the SEM / EDS analysis, which will be presented in chapter VI.

On the basis of the analysis of the results obtained in this section, it can be concluded that the effect of soiling is highly affected by location and depends on the tilt angle as well as the exposure period.

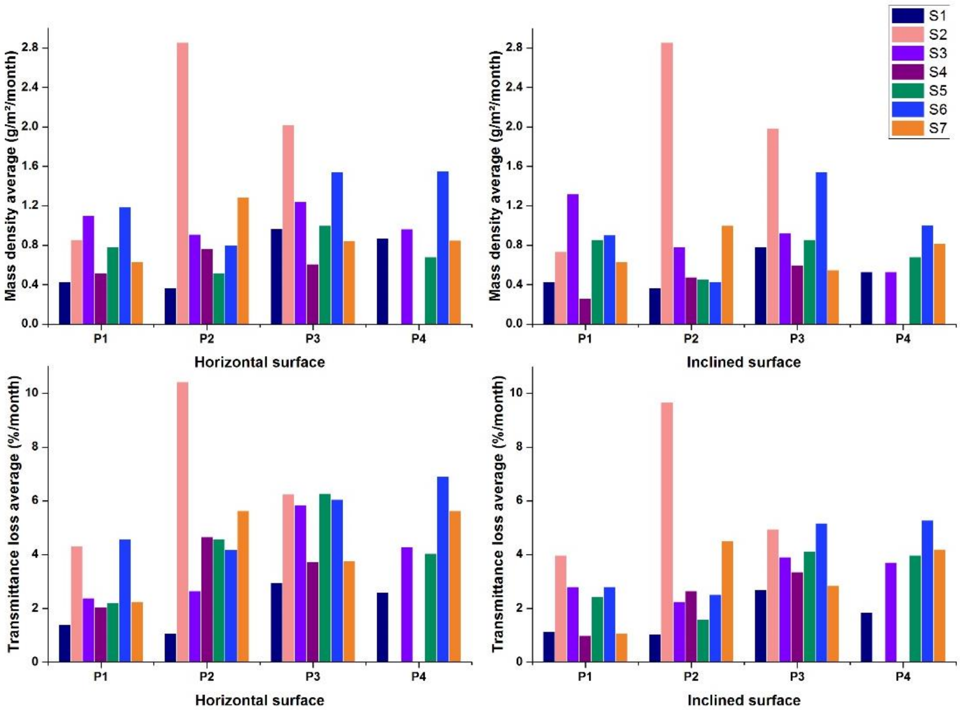


Figure V-1. Measurements conducted in Morocco for both (H) and (I) surfaces and during the four exposure periods (the average/month)

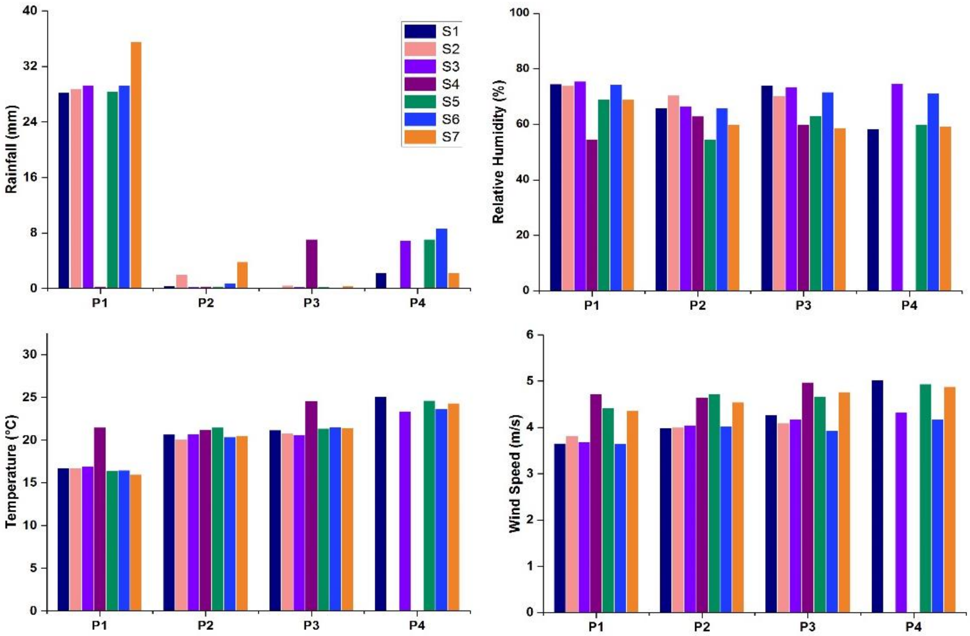


Figure V-2. Weather conditions (R, T, RH and WS) in the seven sites in Morocco and during the four exposure periods. Data recorded from https://power.larc.nasa.gov. Sum per period for rainfall and average per period for other variables

The measurements conducted in Morocco discussed above have been gathered with those of India and presented in the box plots in Figure V-3. From this figure, it can be seen that some measurements have been considered as outliers; since their values are very high than the majority. In the case of Morocco, these measurements represent the data of S2_M during the periods P2_M and P3_M. However, these values were considered as normal after considering the environmental characteristics of S2_M and the activities that know P2_M and P3_M periods. In the case of India, the two outliers concern the S2_In and S3_In during the period P4_In as it can be seen in Figure V-4. In fact, S2_In and S3_In experienced the highest dust deposition and loss in all periods but P4_In is the worst one. This can be explained by the content of Table IV-2, where we can see that the two sites are in the same location known mainly by less green spaces that will reduce the dust in the air. Moreover, the two sites S2_In and S3_In are giving almost similar values, meaning that they confirm each other. Furthermore, in their location, during the period P4_In a nearby road construction was happening and which generates much dust in the air. By looking at the weather conditions (sum per period for rainfall and average per period for other variables) presented in Figure V-5, it can be observed that for relative humidity and temperature, the sites are varying almost in the same way during the four periods. For wind speed, some variations are there, but in general the recorded wind speeds are not high and do not exceed 4.5 m/s. For rainfall, high values are observed and this is because the whole period of the study coincides with the monsoon period in Tamil Nadu state. This explains, on the one hand, the low soiling effect observed in this study. On the other hand, in almost all periods, S1_In knows much rainfall than the other sites, which is in perfect agreement with the low mass densities found on this site. The S2_In and S3_In experienced high mass densities; their rainfalls are in somewhat lower than the other sites. In general, the mass densities in the five sites in India are ranging from 0.03-1.42 g/m²/month while transmittance losses between 0.35-7.42 %/month and thicknesses between 0-9.21 µm/month.

By going back to Figure V-3 we can see that the boxes of India are shorter than the ones of Morocco, which means that the data in India are much closer while those of Morocco are more varied (0.37 – 2.86 g/m²/month and 1.05 – 10.04 % / month). This can be explained by the fact that data in Morocco belong to seven sites that have varied characteristics while in India they are only five sites. In addition, the four periods of Morocco belong to two seasons, spring and summer, while in India they belong all to the monsoon season. Furthermore, according to the Koeppen-Geiger classification [33], [34], the climate of the capital region of Morocco is Temperate-dry summer-hot summer (Csa), while that of Tamil Nadu state is characterized by a tropical-savannah climate (Aw) and a small portion belong to an arid-steppe-hot climate (BSh).

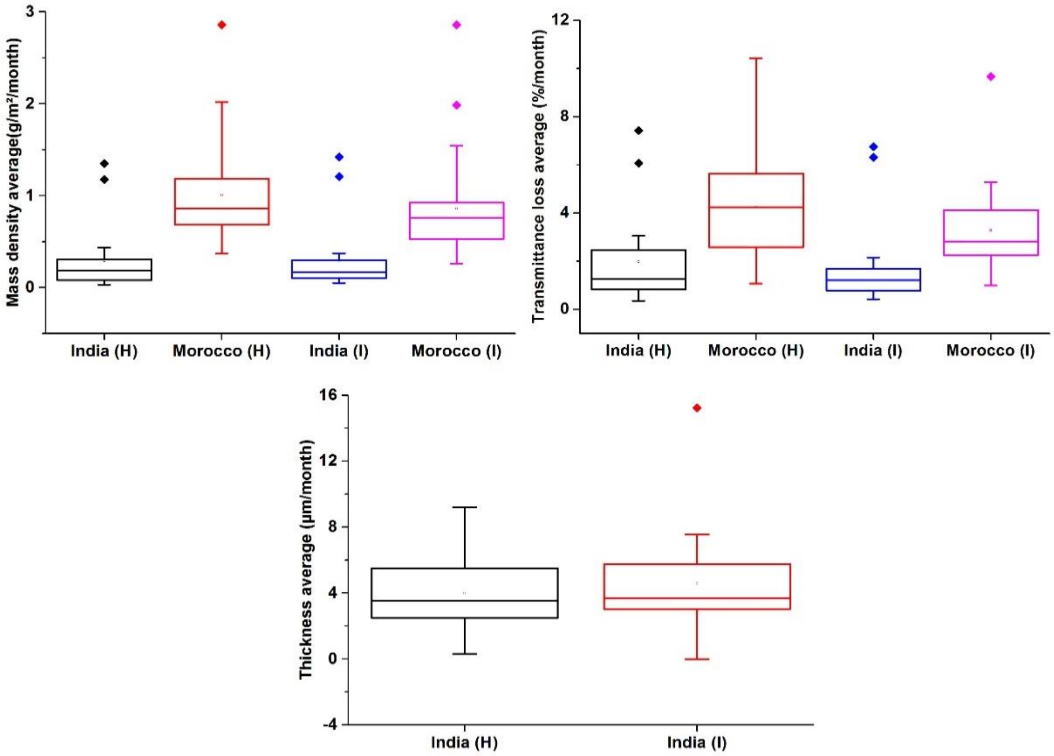


Figure V-3. Box plots of measurements conducted in India and in Morocco for (H) and (I) surfaces

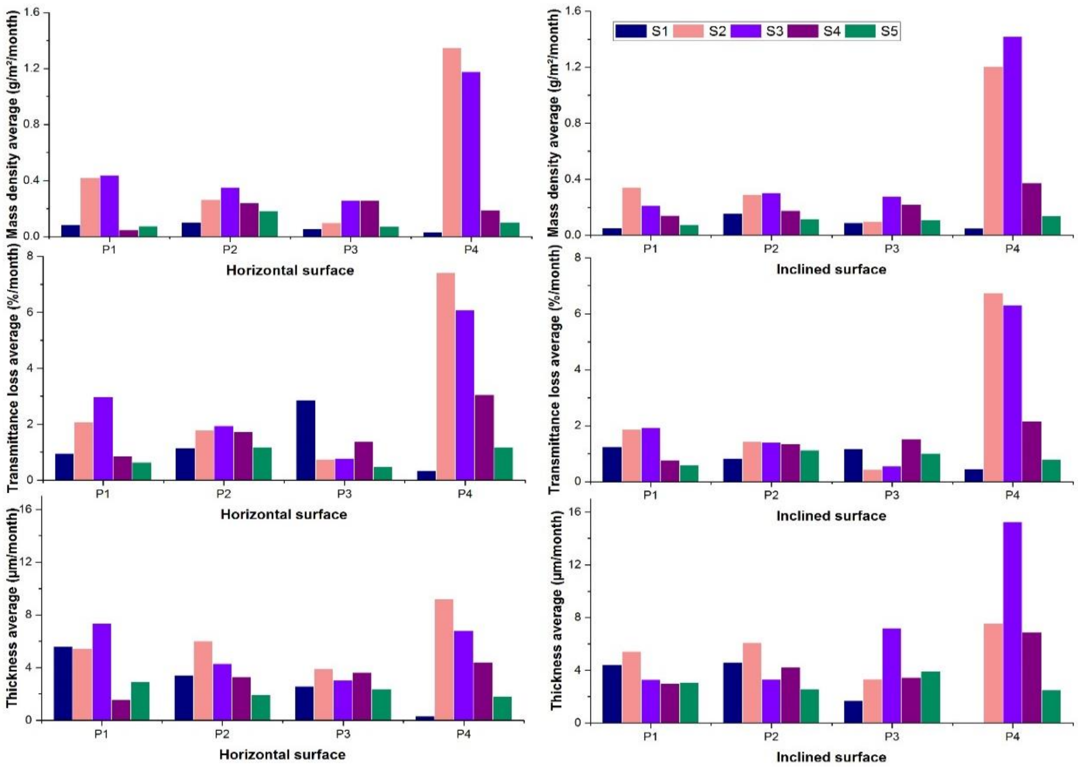


Figure V-4. Measurements conducted in India for both (H) and (I) surfaces and during the four exposure periods (the average/month)

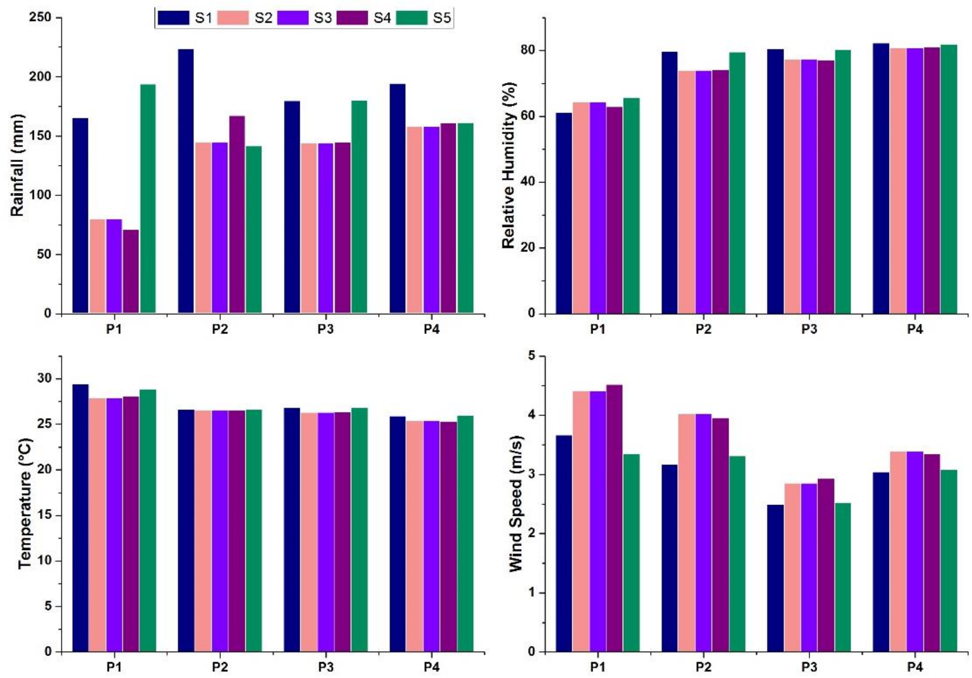


Figure V-5. Weather conditions (R, T, RH and WS) in the five sites in India and during the four exposure periods. Data recorded from https://power.larc.nasa.gov. Sum per period for rainfall and average per period for other variables

3. Effect of environmental and meteorological conditions on soiling effect

Many variables have been reported in the literature to have an effect on soiling of solar energy systems [271] (Figure II-9). In order to study the influence of climate and environmental variables on mass density and transmittance loss, the Pearson correlation coefficient analysis has been conducted using Python programming (Figure V-6, V-7 and V-8). In order to avoid numerical overflows because of very large or small weights [280], the working data have been normalized between 0.1 and 0.9. The following normalization equation was used before the analysis process:

$$Y = [(X_i - X_{min}) / (X_{max} - X_{min})] \text{ x } 0.8 + 0.1 \qquad \text{(V-1)}$$

where Y is the normalized value of X_i, X_{max} and X_{min} are respectively the maximum and minimum values of X_i.

Table V-2 presents the dependent and independent variables considered and their characteristics.

Table V-1. The characteristics of the independent and dependent variables considered in the correlation

Dependent variables		
Symbol	**Meaning**	**Unit**
MD	Mass density	[g/m²]
TL	Transmittance loss	[%]

Independent variables			
Symbol	**Meaning**	**Unit**	**Comments**
R	Rainfall	[mm]	Recorded from https://power.larc.nasa.gov. Sum per period for rainfall and average per period for other variables.
WS	Wind Speed	[m/s]	
T	Ambient Temperature	[°C]	
RH	Relative Humidity	[%]	
DO	Distance from the Ocean	[km]	Considered from Table IV-1.
TA	Tilt angle	[°]	
AL	Altitude	[m]	
TEG	Terrigenous	[Dimensionless]	According to Table IV-2, the symbol is encrypted with the numbers 1 to 3.
TP	Transport	[Dimensionless]	
GS	Green spaces	[Dimensionless]	
CS	Construction	[Dimensionless]	

Figure V-6, Figure V-7 and Figure V-8 represent respectively the results of correlation between mass density/transmittance loss and meteorological and environmental variables obtained for the data of Morocco, India and by gathering both. While Figure V-9 represents the mean and standard deviation of all the variables. By comparing Figure V-6, Figure V-7 and Figure V-8, it can be clearly seen that the amount, the value as well as the variance of data used have a great effect on the correlations obtained. Another remark can be observed from these figures is that almost all variables correlate in the same way with the mass density MD and transmittance loss TL except for WS in the case of Morocco (Figure V-6) and for TP in the case of all data (Figure V-8). Nevertheless, their effect level on them differs from one variable to another.

Regarding TA (tilt angle), the negative correlation confirms the observations made in section 2, when the tilt angle increases the mass density/transmittance loss decreases. For WS (wind speed), it can be seen that when it increases, the transmittance loss increases as well, and the same result found by [238]. However, for the mass density the effect is different, the increase of wind speed contributes to the decrease of mass density. This is because the wind can blow away the overlapping particles, which will not affect the transmittance, but will greatly affect the mass density [47]. In addition, wind speed may move particles from one place to another place on the sample, which will affect the transmittance but not the mass density. In Figure V-7, the increase of WS increases both mass density and transmittance loss. By looking at Figure V-9, we can see the variance of wind speed in both countries is almost same, which means that other factor is governing the effect of WS, and the wind direction and the orientation of the glass samples (or modules in general) is the expected one. Indeed, for the same wind speed, in one direction, the effect may be positive and on other direction, it may be negative. Also, when the panels face the wind, dust accumulation will be more affected than when they face the opposite direction [46], [48], [51], [62], [122].

In the case of Morocco, TP (transport) has a positive effect, however, for India, TP has a negative effect. Indeed, if the place is nearby roads known by frequent heavy traffic, this may have double effect, negative if the roads are not covered by asphalt which will increase dust in the atmosphere, and positive effect if the roads are covered. For both countries, GS and CS have great effect, by increasing green spaces the mass density as well as the transmittance loss decrease and the locations known by more construction activities are more likely to have more soiling effect. This confirms that PV modules installed in urban areas with covered roads and green spaces are less affected by soiling losses compared to those installed in non-covered areas. TEG impacts soiling negatively, large and empty fields near the location of measurements participate in the increase of dust and aerosols in the atmosphere as the case of Morocco. However, in India, TEG impact soiling positively, the mass density and the transmittance loss decrease when there is a nearby TEG source. The reason behind this can be the texture of the ground of these places, when it is loose then it is more likely to generate dust but if it is compact then the effect may be the inverse [105].

The effect of rain was not clearer while using only the data of Morocco or India but after merging them, rainfall effect ranks first (Figure V-8). Rainfall has always been considered as an important influencing factor, but when it is varying in the same way for all sites (in the case of the sites in India and Morocco), the effect will not be clearer. However, after merging the data, the variance becomes high (Figure V-9) and the effect becomes more visible. By merging data also, the highest effect, with a negative correlation, belongs to rainfall, temperature, distance from the ocean, and altitude while with a positive correlation it belongs to WS and TEG. Being far from the ocean (increasing DO) leads to an increase of soiling in both countries, however, after merging the data the effect of DO becomes the inverse.

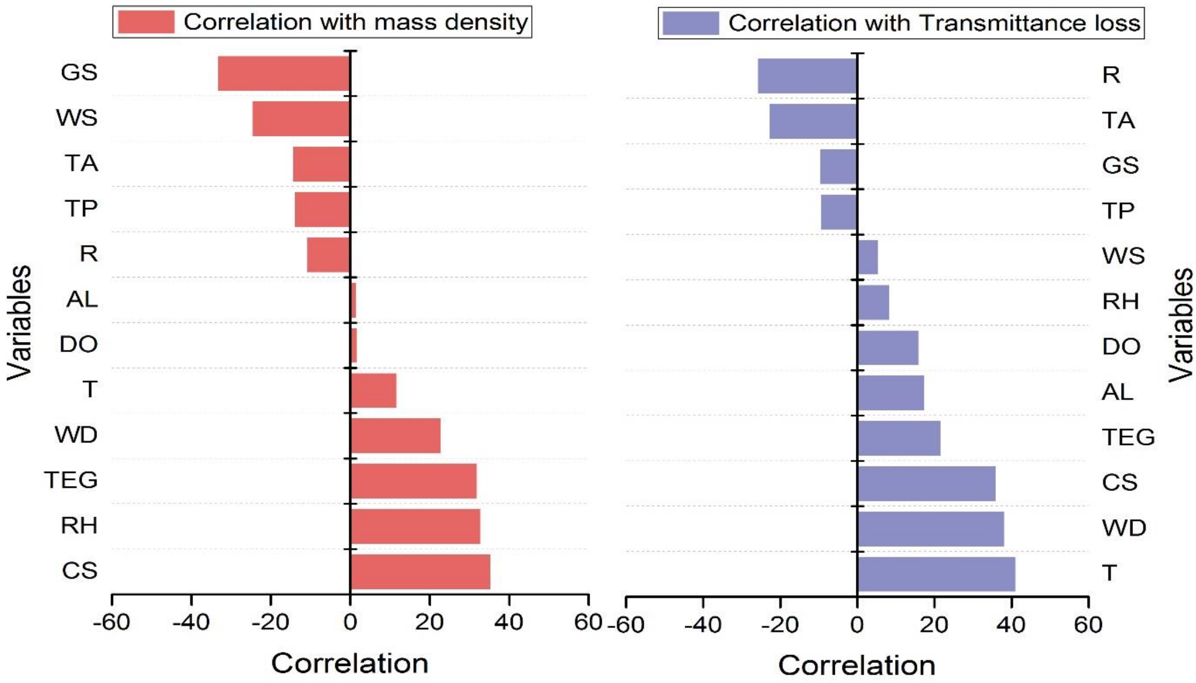


Figure V-6. Correlation between MD and TL with meteorological and environmental variables (Morocco data)

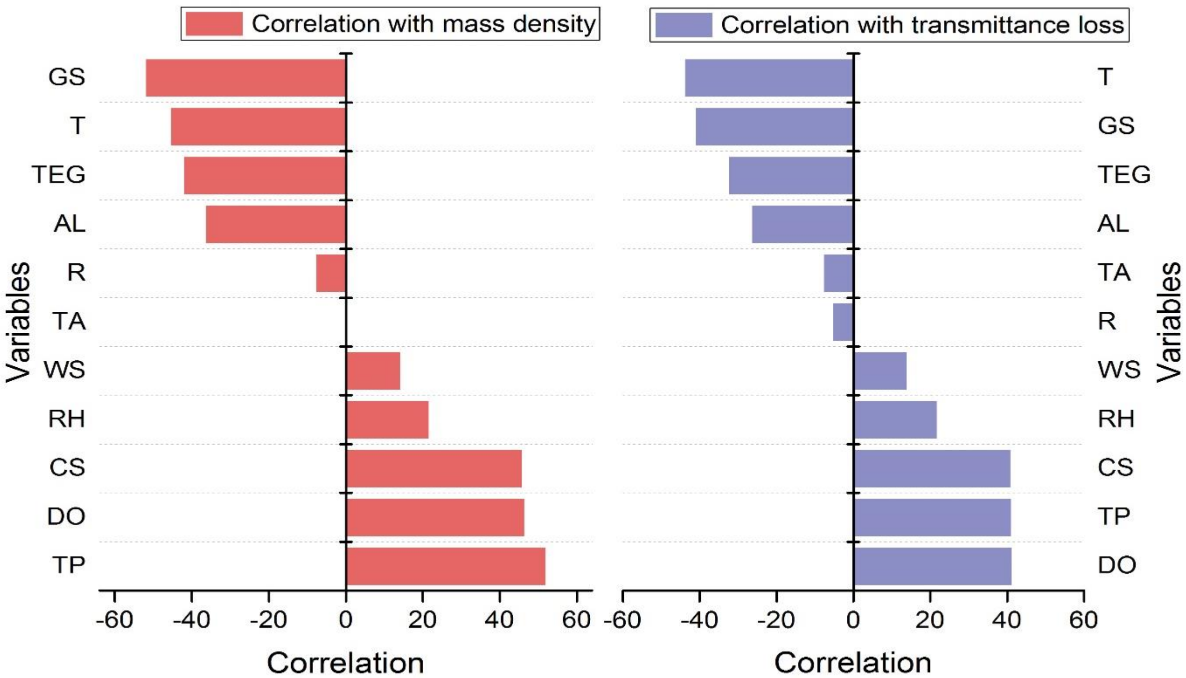


Figure V-7. Correlation between MD and TL with meteorological and environmental variables (India data)

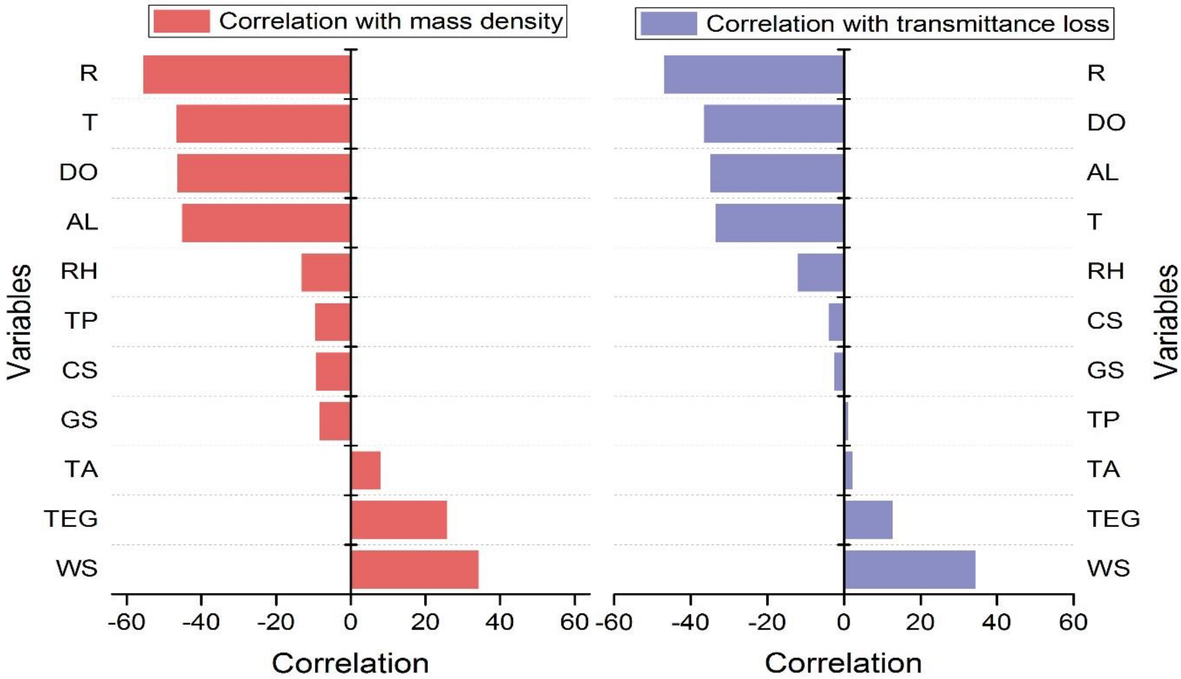


Figure V-8. Correlation between MD and TL with meteorological and environmental variables (all data)

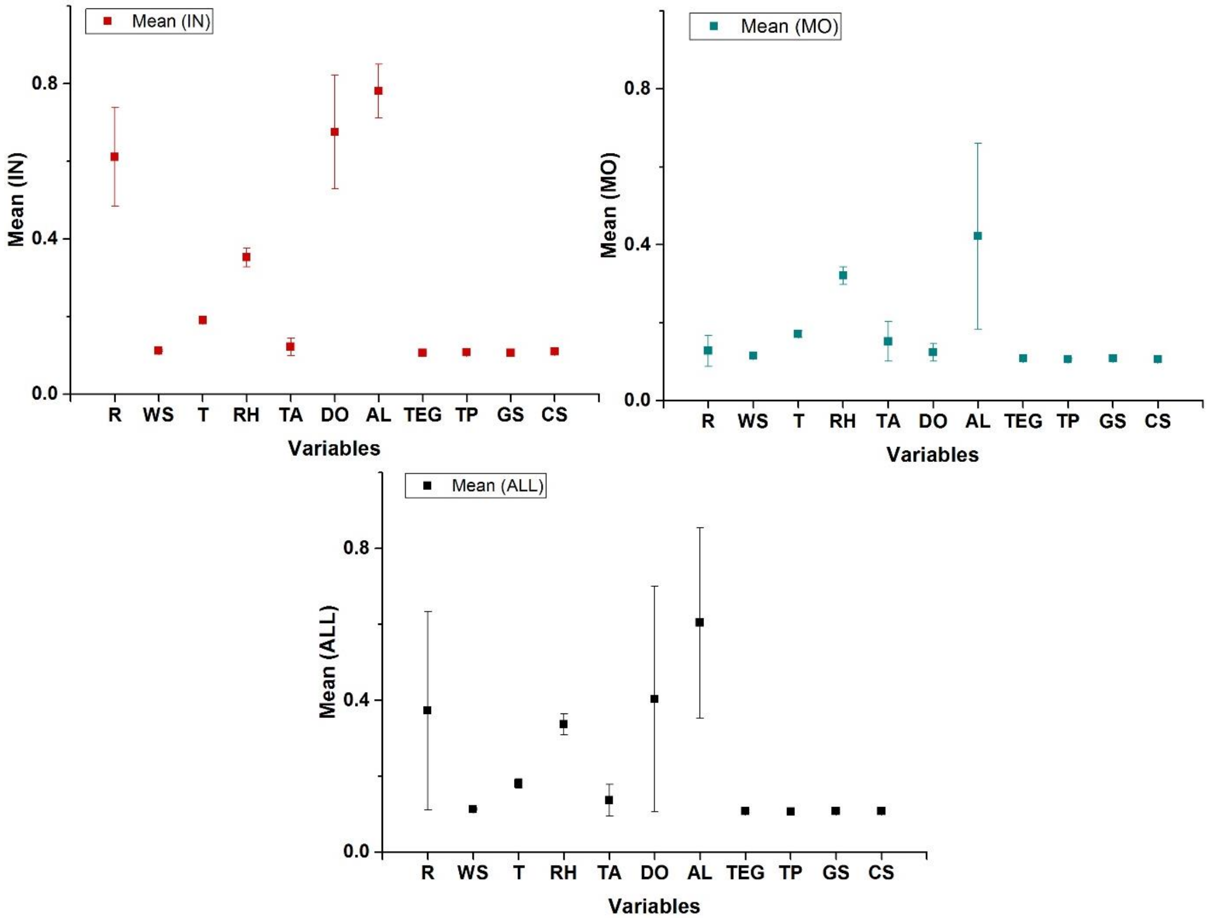


Figure V-9. Mean and standard deviation of data

The modeling of soiling on can be done based on the previous variables. However, not taking all factors that impact soiling detailed in Figure II-9 has been considered by many researchers as a cause that their models didn't perform well [4], [125], [219], [226], [235]. Nevertheless, in other studies, many variables have been chosen by the researchers, but based on a specified method they select the most influencing factors. These studies and the present one have been gathered in Table V-3. From this, it can be seen that the selected variable that have an important effect varied from one study to another. We can conclude that this depends on the method of selection applied on the dependent variable and on the independent variables initially chosen. For instance, in the two studies [281] and [172], the only difference is the method applied, and this leads to a difference in the selected variables. In the case of our study, we can observe that when the dependent variable changes, the selected variables change as well. We can conclude as well that the amount of data as well as the location impact the effect of the variables, this can be seen when we compare between the study in Morocco, that of India and after merging their data. This led to one major conclusion that the effect of the variables is very complex and depends on their each other effect. The effect of one factor in a place may affect positively because the location where it is not prevailing are dustier, and it may affect negatively in another place because the location where it is prevailing are more likely to have less dust. Furthermore, a factor can be the most affecting in one study but in another study another factor will be found as the most influencing and this only because the first factor is not considered in the independent variables in the other study. Creating a model that will predict soiling is not that much easier as it seems, it needs years of data where all factors that affect soiling are considered, highly varying, over different periods and on different sites.

Table V-2. Dependent, independent and selected variables as well as the method of selection applied to identify the most influencing factors

Ref.	Method of selection	Dependent variable	Independent variables	Selected variables
[238]	Boruta algorithm [269], [282]	Efficiency of the PV modules	Relative humidity, pressure, temperature, temperature min, temperature max, dew point temperature, wind speed range, clearness index, temperature range, max wind speed, rainfall, wind direction, PM10, wind speed.	Relative humidity, wind direction, PM10, wind speed.
[281]*	PAWN sensitivity analysis [262]	Transmittance loss	Irradiance, ambient temperature, humidity, rainfall, wind speed and wind direction.	Relative humidity, wind direction.
[172]*	Garson algorithm [261]	Transmittance loss	Irradiance, ambient temperature, humidity, rainfall, wind speed and wind direction.	Rainfall, wind direction.
This study (Morocco data)	Correlation factor	Mass density	Rainfall, wind Speed, wind direction, temperature, relative humidity, distance from the ocean, tilt angle, altitude, terrigenous, transport, green spaces, construction.	Construction, relative humidity, terrigenous, wind direction, wind speed, green spaces.
This study (Morocco data)		Transmittance loss	Rainfall, wind Speed, wind direction, temperature, relative humidity, distance from the ocean, tilt angle, altitude, terrigenous, transport, green spaces, construction.	Rainfall, tilt angle, construction, wind direction, terrigenous.
This study (Data of India)		Mass density	Rainfall, wind Speed, temperature, relative humidity, distance from the ocean, tilt angle, altitude, terrigenous, transport, green spaces, construction.	Transport, distance from the ocean, construction, relative humidity, altitude, terrigenous, green spaces.
This study (Data of India)		Transmittance loss	Rainfall, wind Speed, temperature, relative humidity, distance from the ocean, tilt angle, altitude, terrigenous, transport, green spaces, construction.	Transport, distance from the ocean, construction, relative humidity, altitude, terrigenous, green spaces.
This study		Mass density	Rainfall, wind Speed, temperature, relative humidity, distance from the ocean, tilt angle, altitude, terrigenous, transport, green spaces, construction.	Wind Speed, terrigenous, altitude, distance from the ocean, temperature, rainfall.
This study		Transmittance loss	Rainfall, wind Speed, temperature, relative humidity, distance from the ocean, tilt angle, altitude, terrigenous, transport, green spaces, construction.	Wind Speed, terrigenous, altitude, distance from the ocean, rainfall.
[104]	Coefficient of determination	Soiling ratio and soiling rate based on short circuit current	Average PM10 of best available stations, average PM2.5 of best available monitoring stations, average of PM2.5 of closest monitoring stations, average of PM10 of closest monitoring stations, number of PM10 sources within 10 km, number of PM2.5 sources within 10 km, number of PM10 sources within 30 km, number of PM2.5 sources within 30 km, number of PM10 sources within 50 km, number of PM2.5 sources within 50 km, average length of the dry period, max length of the dry period, average length of the dry period (only rain>0.3), max length of the dry period (only rain>0.3), number of rainy days per year (only rain>0.3), mean wind direction (angle of incidence at noon).	Average PM10 of best available stations, average PM2.5 of best available monitoring stations.

* refer to two works that we published in the framework of the present study. However, they have not been included in the content of the thesis report as they present preliminary studies.

4. Correlation between mass density and transmittance loss

4.1. Capital region of Morocco case

In order to better understand the observations presented in section 2, the correlation between the transmittance loss and the mass density of dust by linear regression is studied firstly for Morocco data. Figure V-10 presents this correlation taking into account the measurements carried out in all the Moroccan sites. According to it, the factor of determination is 91%. Indeed, according to [95], the mechanisms of adhesion of particles to the surface generally take place within 30 to 60 days. Beyond this period, the saturation of the surface can be reached. In addition, according to [76], the mass density threshold value causing saturation (which below a linear correlation between transmittance loss and mass density is observed) is around 6 g/m². In our study, these two conditions are verified (the deposit period is between 30 and 60 days and the maximum deposit value is approximately 3 g/m²). Therefore, a much better determination factor could have been found. In order to examine and check if the factor of determination could be improved, the effect of the tilt angle, exposure period and location on the correlation will be studied.

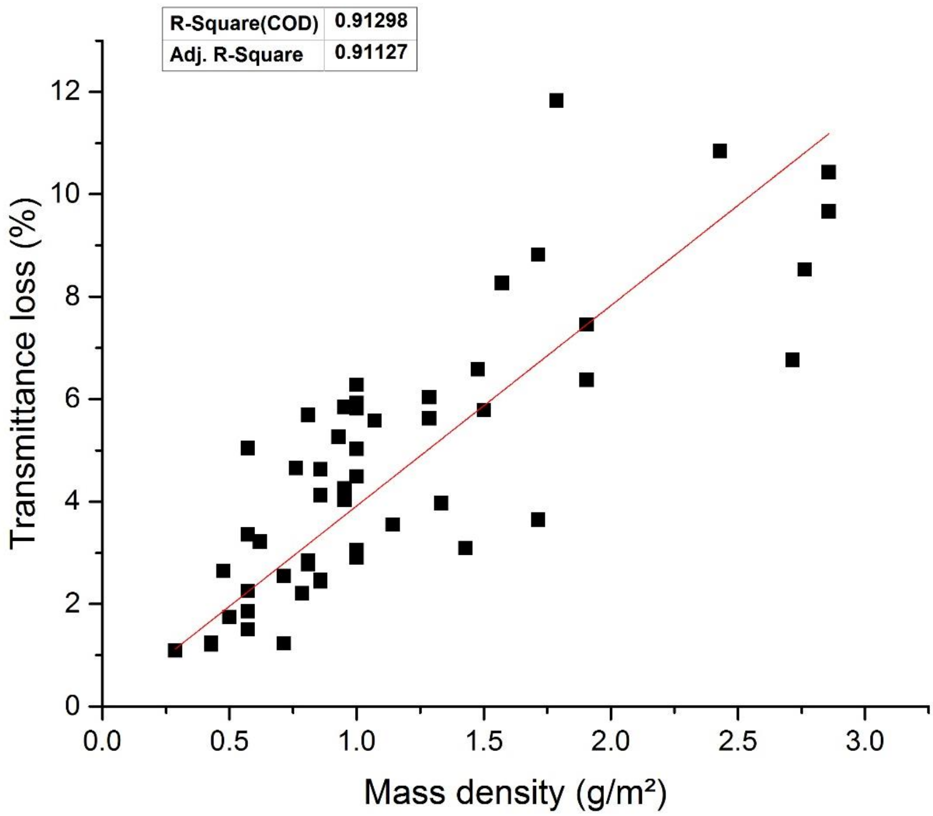


Figure V-10. Correlation between transmittance loss and mass density taking into account all the sites (Morocco data)

Effect of tilt angle

Figure V-11 shows the effect of tilt angle on the correlation between loss of transmittance and mass density. The determination factor for inclined and horizontal surfaces is 90% and 92% respectively. Practically, there is no difference between these two factors and the one found above. Then, in this case, it can be concluded that the correlation is not highly influenced by the tilt angle. Nevertheless, it can be said that the correlation is little bit better in the case of horizontal surface than in inclined one.

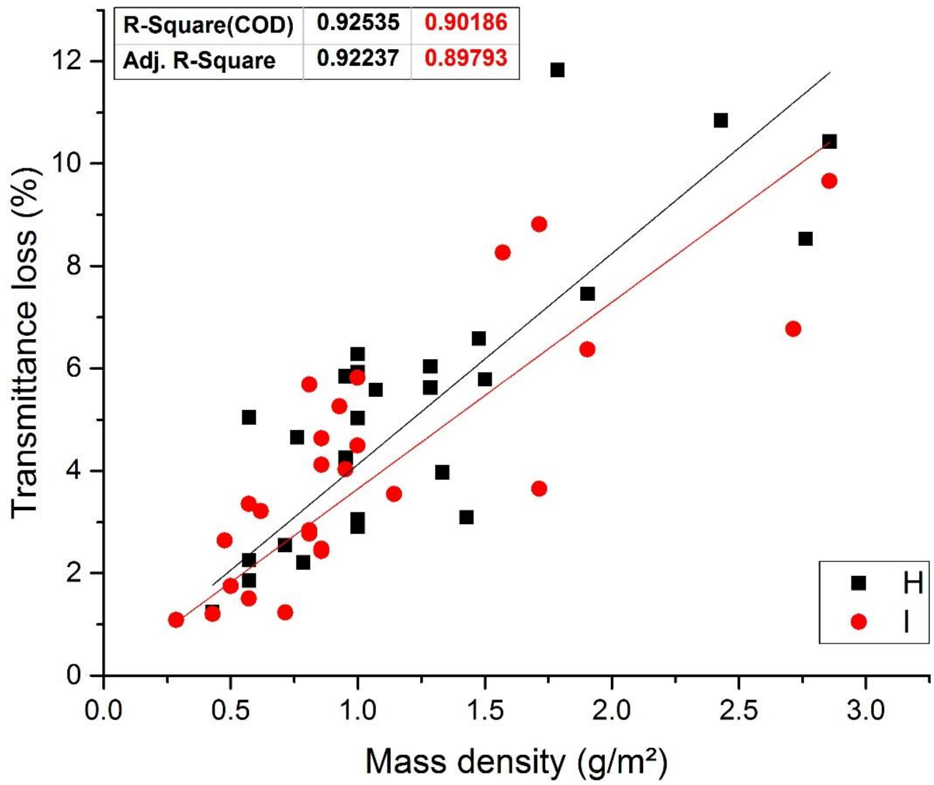


Figure V-11. Correlation between transmittance loss and mass density for horizontal and inclined surfaces (Morocco data)

Effect of exposure period

Figure V-12 shows the effect of the exposure period on the correlation between the loss in transmittance and the mass density. From this, it can be seen that there is a difference between the correlation factors for the different periods. Indeed, each period is characterized by different meteorological and environmental properties affecting the deposit in terms of size, shape, composition and density. However, the three periods P2_M, P3_M and P4_M have relatively high correlation factors compared to that of period P1_M. This can lead to two hypotheses: a) The correlation may be affected by the variation of the season, b) A problem with the measurements, in particular for S3_M and S5_M sites, which have already presented different results in terms of difference in deposition between inclined and horizontal surface (see section 2).

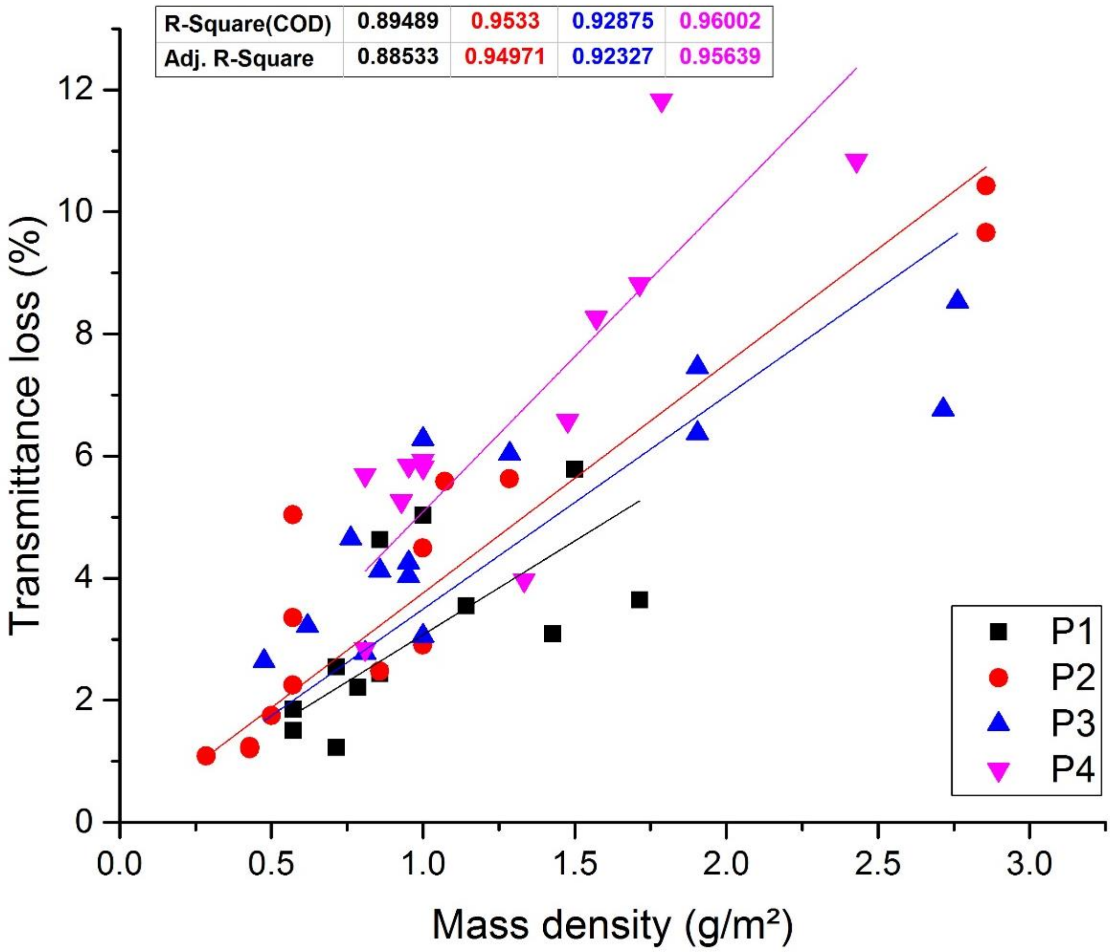


Figure V-12. Correlation between transmittance loss and mass density according to the different exposure periods (Morocco data)

Effect of location

Figure V-13 shows the correlation between the loss in transmittance and mass density of deposit for each site, taking into account the measurements made on a horizontal and inclined surfaces. The determination factor exceeds 94% for the case of S1_M, S2_M, S4_M, S6_M. and S7_M. S5_M site has a determination factor of almost 89% while that of S3_M is in the order of 84%.

In general, the various determination factors observed show the effect of the location on the variation thereof. Indeed, the sites have more or less different environmental characteristics (see chapter II, section 3). However, the correlation in the case of the sites:

S3_M and S5_M are abnormal, which affirm once again the hypotheses cited above concerning the results obtained from these two sites.

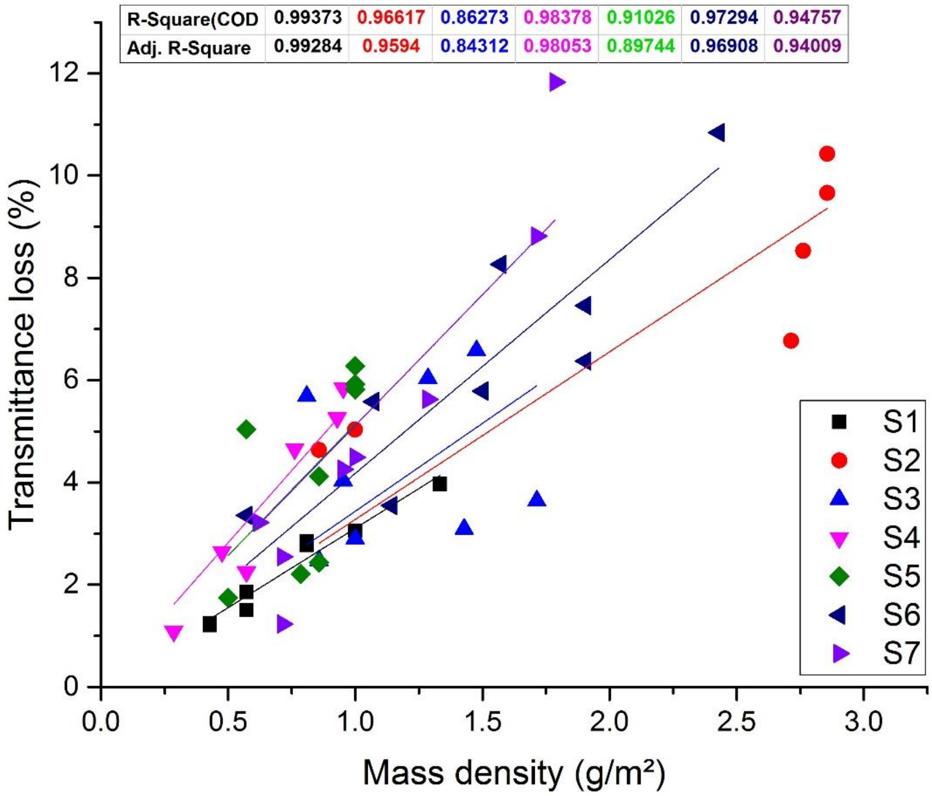


Figure V-13. Correlation between transmittance loss and mass density for each site (Morocco data)

Since the sites S4_M and S5_M are very close to each other, the correlation between the loss in transmittance and the mass density is conducted and illustrated in Figure V-14. (A) presents the correlation based on all the data of the two sites, while (B) presents the correlation by eliminating the data which prove to be outliers. These are the data of the site S5_M and more precisely those from the first period. After this treatment, it is visible that the correlation factor has increased. This justifies that there is a problem with the data of the first period for site S5_M, which is probably affected during the measurement or during the exposure by the accumulation of dust that was not entirely natural.

Regarding site S3_M, data for all periods are highly dispersed (see Figure V-13, S3_M). We think that this dispersion is due to the fact that this site is very close to the ocean (300 m).

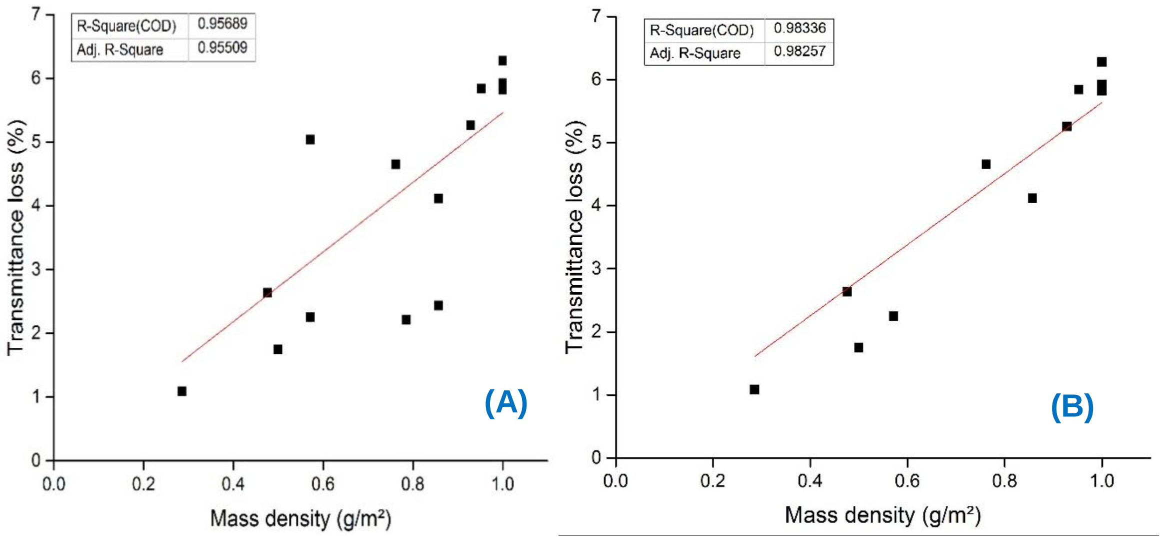


Figure V-14. Correlation between transmittance loss and mass density for site S4M and S5M, A (without processing); B (with processing)

Deduction

It can be concluded from this section that the correlation between the loss in transmittance and the mass density is influenced by the location and the period of exposure while it is not influenced by the inclination. Since the second hypothesis cited above is verified, we have eliminated the measurements of the site S3_M as well as those of S5_M considered to be outliers in the correlation presented below. From this one, it can be seen that the correlation factor has improved (see Figures V-10 and V-15).

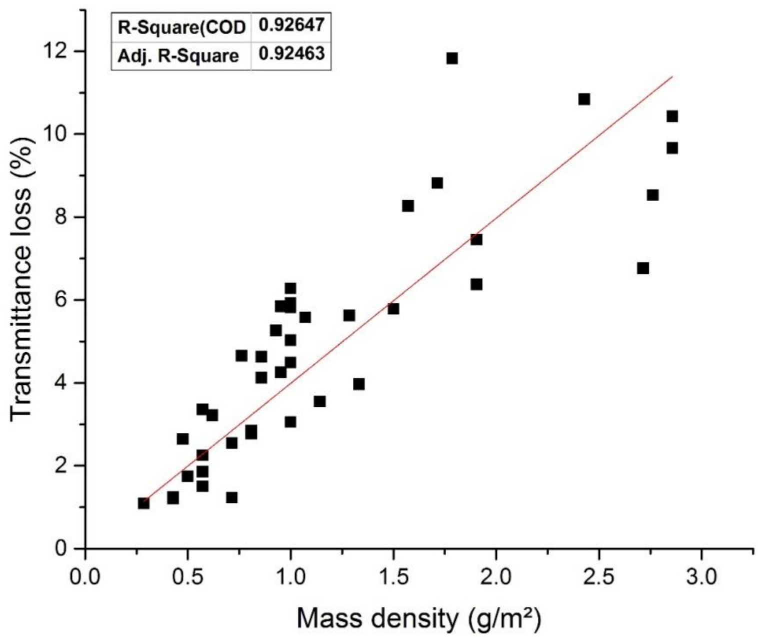


Figure V-15. Correlation between the loss in transmittance and the mass density taking into account all the sites (after processing)

4.2. Tamil Nadu state of India case

Unlike the site of Morocco, the correlation between transmittance loss and mass density here is higher, with a correlation coefficient of around 94%, as shown in Figure V-16. For thickness, its correlation with mass density and transmittance loss is low. As explained earlier regarding the factors that affect the correlation between mass density and loss of transmittance, there may also be some problems with thickness. The particles can be superimposed on each other, which will increase the thickness and mass, but may not increase the transmittance. For the same density, the composition in terms of the particle's size will affect the transmittance as well the thickness while in terms of color and distribution over the sample will have effect only on transmittance [47]. The low correlation with thickness would also be influenced by the uncertainty of the equipment used, which will affect more the small values.

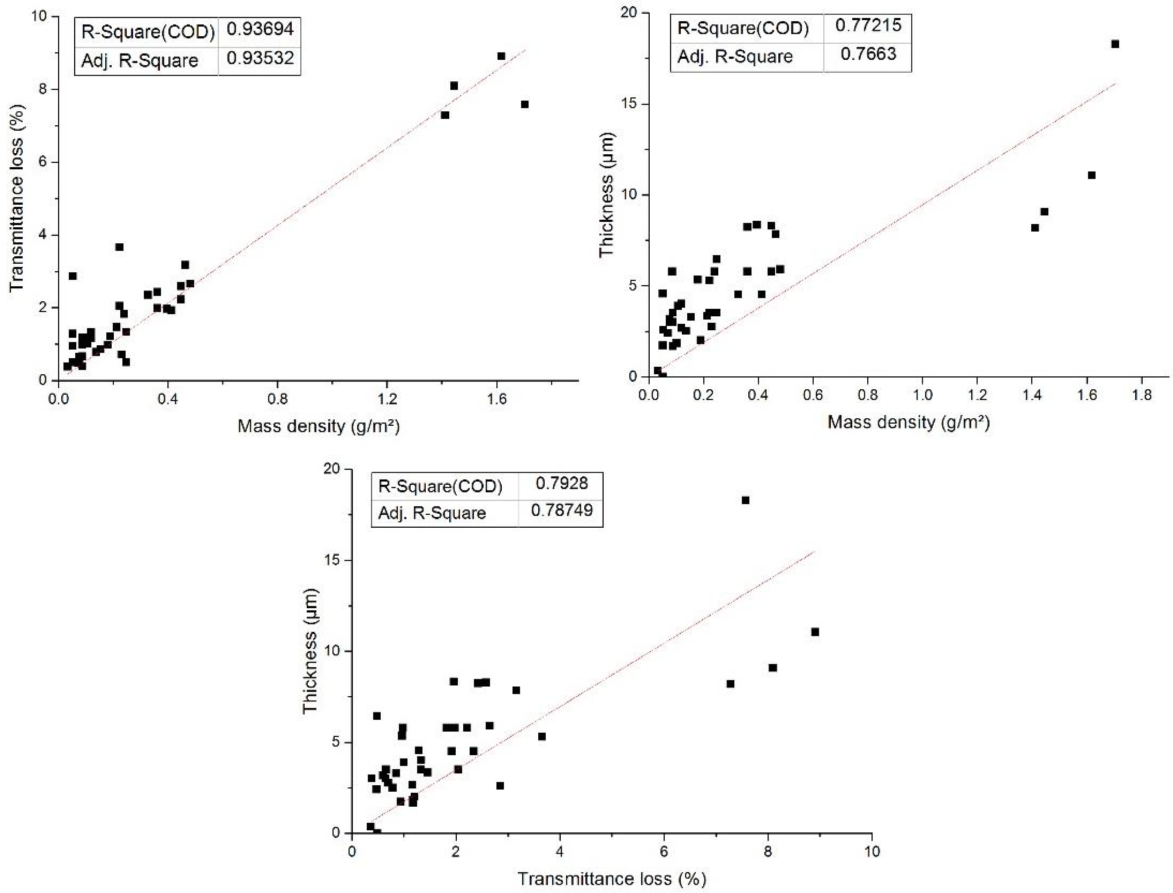


Figure V-16. Correlations between mass density, transmittance loss and thickness of dust layer. The data used here are raw data and not the average/month

4.3. Modeling of the correlation between mass density and transmittance loss

Few studies on the relationship between mass density and transmittance loss have been developed. For instance, A. Hegazy developed an empirical equation (Eq. V-2) with an accuracy of ±6% based on data of one year in Egypt , and on glass samples experienced cleaning per month [119]. While H. K. Elminir et al. developed the relationship represented by (Eq. V-3) [102]. Both studies of A. Hegazy and H. K. Elminir et al. have been conducted on samples with different orientations and tilt angles. Another linear relationship was developed by L. Boyle et al. (Eq. V-4) based on collected data from two sites in the front range of Colorado [221].

$$\left(1-\tau/\tau_{clean}\right)\% = 34.37 erf\left(0.17\omega^{0.8473}\right) \quad \text{(V-2)}$$

$$\left(\Delta\tau\right)\% = 0.0381\omega^{4} - 0.8626\omega^{3} + 6.4143\omega^{2} - 15.051\omega + 16.769 \quad \text{(V-3)}$$

$$\left(\Delta\tau\right)\% = 4.1\omega \quad \text{(V-4)}$$

where τ is the transmittance ($\Delta\tau$ is the transmittance loss) and ω is the deposited dust in g/m².

Based on these studies, the developed models have been plotted by taking into consideration the mass density intervals as described in the papers (Figure V-17). For the study of A. Hegazy [119], the mass densities are ranging from 0.2 and 10 g/m², from 1.5 and 9 g/m² for the study of H. K. Elminir et al. [102], while for the study of L. Boyle et al. [221] the mass densities range from 0 to 2 g/m². The royal blue color data present the data of the present study as well the data of our previous study conducted in the capital region of Morocco [283] and their mass densities are ranging between 0.0344 and 2.8571 g/m². From Figure V-17, we can see that there is a high correlation between our data and the model developed by L. Boyle et al. [221] up to 2g/m², a good correlation also with the one developed by A. Hegazy [119] for mass densities higher than 0.2 g/m². However, for the model developed by H. K. Elminir et al. [102], it can be seen that it covers only a part of the data starting from 1.5 g/m². According to [95], the mechanism of adhesion of the particles to the surface usually occurs within 30 to 60 days. During this period, surface saturation can be reached. This means that the linear relationship between mass density and transmittance loss is only valid under a certain mass density threshold, above which the transmittance loss will be somewhat stable. This means again that a linear model will not be enough to describe the real shape of this relationship. Based on this, the three models Gauss error function used by A. Hegazy [119], polynomial function used by H. K. Elminir et al. [102] and exponential model have been chosen to create three models that take into consideration almost all data (of this study as well as the three previous developed models) (Figure V-18). The three new developed models are as follows:

$$\Delta\tau_1(\%) = 32.111 erf(0.134\omega^{0.979}) \quad \text{(V-5)}$$

$$\Delta\tau_2(\%) = -0.208\omega^2 + 5.074\omega + 0.12 \quad \text{(V-6)}$$

$$\Delta\tau_3 = -43.156\exp(-0.125\omega) + 43.152 \quad \text{(V-7)}$$

In order to know the accuracy of these models in predicting our data, the simulated transmittance loss has been calculated based on our mass densities and the developed models (Figure V-19). From this figure it can be understood that all models follow the same trend except the one developed by H. K. Elminir et al. [102], which follows only for mass densities ≥ 1.5 g/m². For those under this value, the model shows a strange behavior.

In order to obtain more detailed information about which model is best for predicting transmittance loss, we chose three criteria: the coefficient of determination (R^2), which is used to evaluate the linear relationship between the measured data and the simulated data; the Root Mean Square Error (RMSE) that measures the difference between the model predicted respect to the experimental data; and the Mean Absolute Error (MAE) which measures the average error between the measured and the simulated data [281].

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(\hat{x}_i - x_i)^2}{\sum_{i=1}^{N}(x_i - \bar{x}_i)^2} \quad \text{(V-8)}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(\hat{x}_i - x_i)^2\right]^{1/2} \quad \text{(V-9)}$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}\left|\hat{x}_i - x_i\right| \quad \text{(V-10)}$$

The results of the evaluation are presented in Table V-4. As expected, the model that has shown the worst values is H. K. Elminir et al. [102]. The model developed by L. Boyle et al. [221] show good results, nevertheless it cannot be adopted since it is a linear model, and as has been explained before, the relationship between mass density and transmittance loss is not completely linear. The three new developed models show good results and almost similar and the best is New model 1 (Polynomial) that showed the highest R^2 and the smallest RMSE and MAE errors.

The three models have been developed based on:

- Our data which belong to 12 sites, 8 periods, 1 orientation, 3 tilt angles and mass densities range [0.03 and 2.86] g/m²;
- Data of H. K. Elminir et al. [102] model which belongs to 1 site, 8 orientations, 7 tilt angles and mass densities range [1.5-9] g/m²;
- Data of A. Hegazy [119] model which belongs to 1 site, 1 orientation, 8 tilt angles and mass densities range [0.2-10] g/m²,
- Data of L. Boyle et al. [221] model which belongs to 2 sites, 3 tilt angles and mass densities range [0-2] g/m².

The models have been tested on our data only which means that they perform well in the range of mass densities 0.03 and 2.86 g/m². For higher mass densities, the models have been adjusted based on the two models of A. Hegazy [119] and H. K. Elminir et al. [102]. The three developed models can be adopted as generalized models to predict the transmittance loss based on the mass density since they cover many sites, different tilt angles and orientations and different periods. However, to choose the best one, it would be more valuable if the models could be tested on higher mass densities.

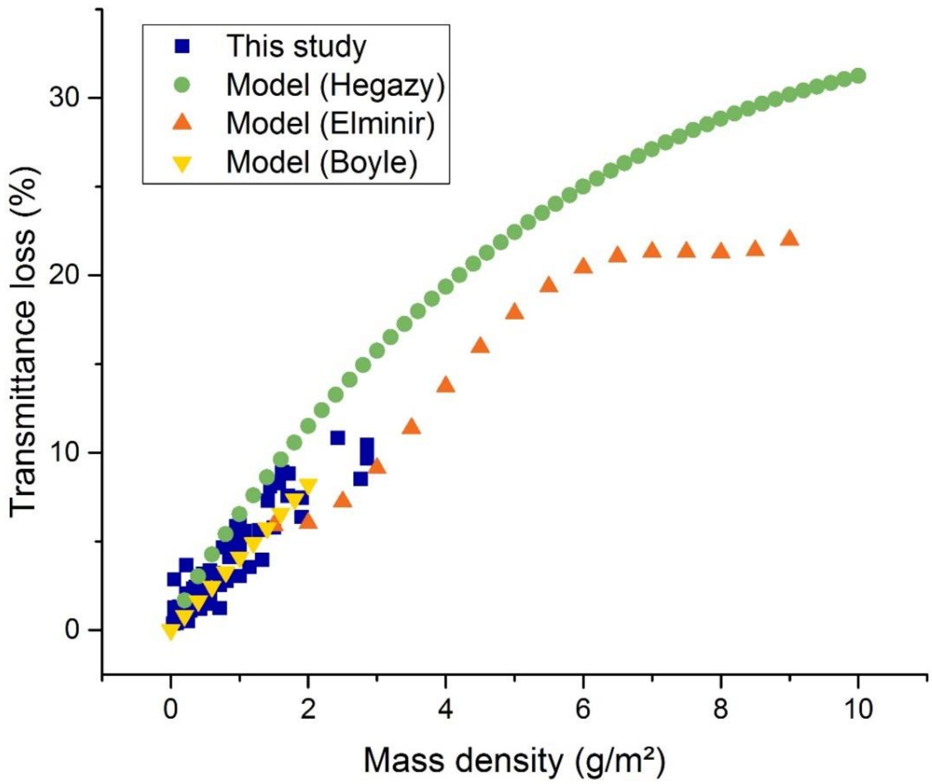


Figure V-17. Plot of the three developed models (A. Hegazy [119]***, L. Boyle et al.*** [221] ***and H. K. Elminir et al.*** [102]***) along with the data of the present study. The models are plotted based on the range of their mass densities as described in the papers. The data of India and Morocco used here are raw data not the average/month***

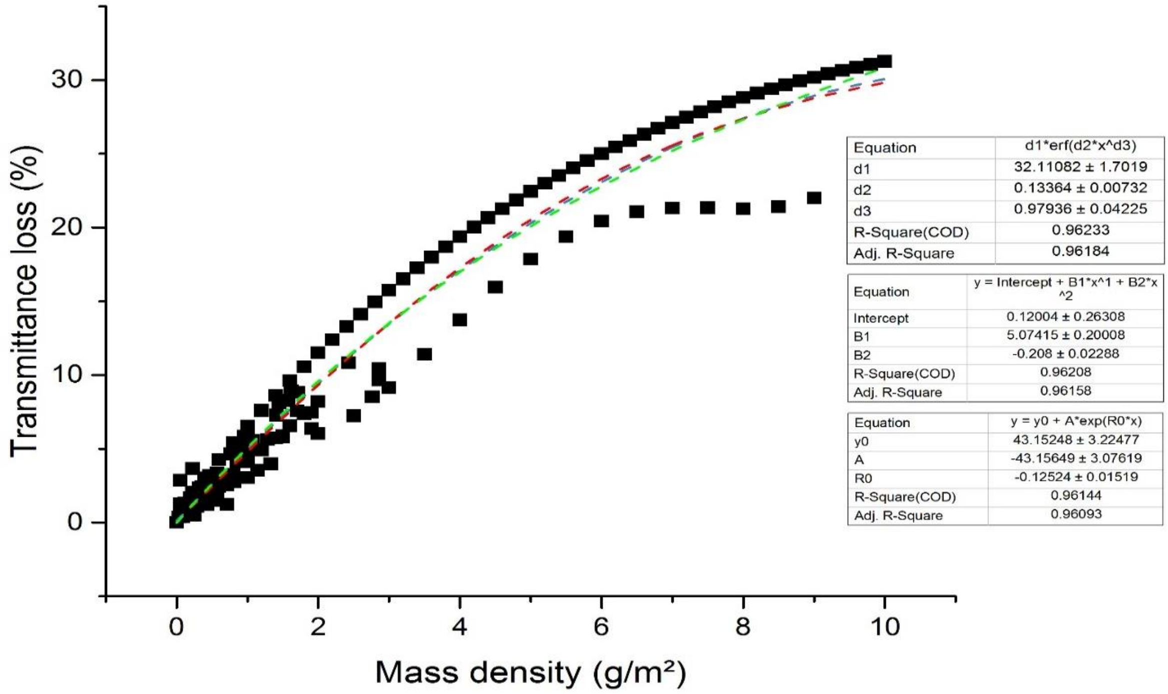


Figure V-18. Development of three models based on data of the three developed models (A. Hegazy** [119]**, L. Boyle et al.** [221] **and H. K. Elminir et al.** [102]**) and the data of the present study. The data of India and Morocco used here are raw data not the average/month

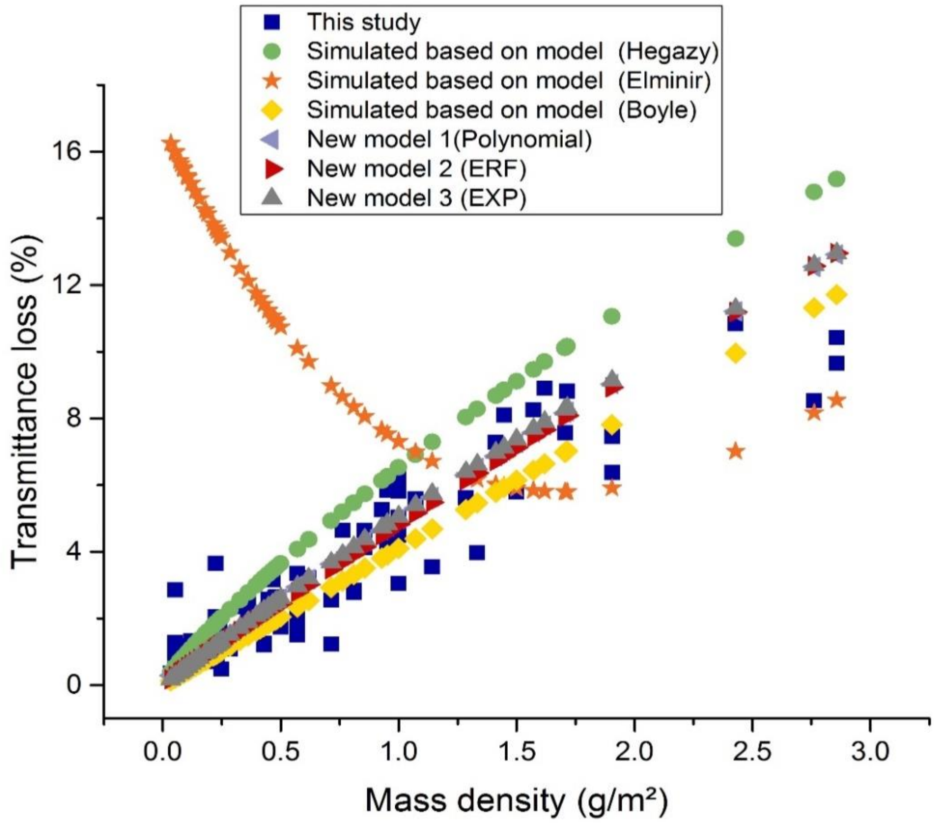


Figure V-19. Comparison between the three previously developed models and the three new developed models and the data of the present study. The data of India and Morocco used here are raw data not the average/month

Table V-3. Evaluation criteria results of the models

	R^2	RMSE	MAE
Simulated based on model (Hegazy)	0.46	1.99	1.44
Simulated based on model (Elminir)	-11.16	9.46	7.98
Simulated based on model (Boyle)	0.83	1.12	0.90
New model 1 (Polynomial)	0.82	1.15	0.81
New model 2 (ERF)	0.82	1.15	0.84
New model 3 (EXP)	0.81	1.18	0.84

In order to reply to the question raised above, and following the same methodology new measurements have been conducted in Morocco in three sites (Rabat, Errachidia and Ouled Teima) for a period of almost two months (June and July 2021). The data of this study include inclinations (0°, 15°, 30° and 45°) and has mass densities ranging from 1.38 g/m² and 17.72 g/m². The data collected have been gathered again with the first data and the evaluation criteria have been re-calculated. Since Elminir model performed in a strange way, it has not been considered in this test. From Table V-5, it can be clearly seen that the three models have higher coefficients of correlation and smaller RMSE and MAE. However, the best one is the exponential model (New model 3 (EXP)).

Table V-4. Evaluation criteria results of the models using the new data

	R^2	RMSE	MAE
Simulated based on model (Hegazy)	0.69	3.80	2.41
Simulated based on model (Boyle)	0.65	4.02	1.82
New model 1 (Polynomial)	0.73	3.54	1.65
New model 2 (ERF)	0.79	3.08	1.60
New model 3 (EXP)	0.84	2.74	1.52

5. Conclusion

In this chapter a comparison of soiling effect between the different chosen sites, an assessment of the impact of the environmental and meteorological conditions on soiling effect, and finally a correlation between the mass density and the transmittance loss and a deep investigation on its modeling are presented.

Based on the analysis of the results obtained, the conclusions drawn are as follows:

- Soiling is a much localized phenomenon.
- The deposition densities in the capital region of Morocco were observed in the range of 0.37 g/m²/month and 2.86 g/m²/month and the transmittance of the glass showed a reduction from 1.05% per month to 10.04% per month compared to the clean glass sample. These

quantities depend on the site of exposure, the inclination and the exposure period. Alkarya site (S2_M) experienced the highest mass density and transmittance loss in comparison to the other sites.

- The mass densities in Tamil Nadu state of India are ranging from 0.03-1.42 g/m^2/month while transmittance losses between 0.35-7.42 %/month and thicknesses between 0-9.2130 µm/month. Erode city (S2_In and S3_In) experienced high-soiling effect in comparison to Vellore (S1_In and S5_In) and Namakkal (S4_In).
- The capital region in Morocco experienced higher soiling effect than Tamil Nadu state, however, this is due to the difference in the climate type (Temperate-dry summer-hot summer (Csa) in Morocco and tropical-savannah climate (Aw) with a small portion of arid-steppe-hot climate (BSh) in India), the periods of exposure (spring and summer in Morocco and monsoon period in India) and the environmental characteristics of the sites.
- The effect of the factors that influence soiling is very complex and highly depend on their each other effect, the amount of data used as well as on the location. This makes it highly difficult to predict soiling losses based on the variables that affect it.
- For mass densities less than 3g/m^2, a positive and linear correlation between the mass density and the loss in transmittance was observed. However, this depends on the period and the location of the exposure.
- By correlating the mass density and the transmittance loss, three new generalized models have been developed and which can predict the transmittance loss based on the mass density more accurately since they cover many sites, different tilt angles and orientations, and various periods. However, the best one which has the highest R^2 and the smallest RMSE and MAE is the exponential model (New model 3 (EXP)).

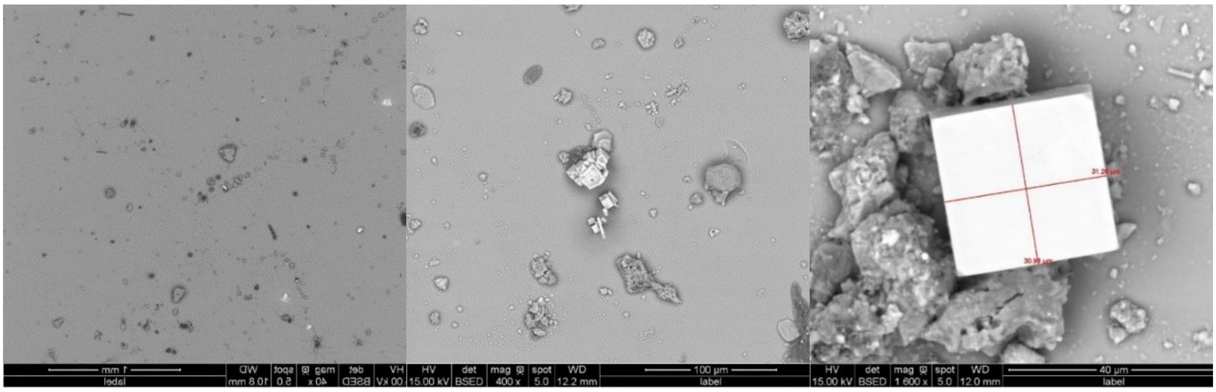
CHAPTER VI : CHARACTERIZATION OF DUST PARTICLES AND INVESTIGATION OF THE INFLUENCING FACTORS ON SOILING IMAGES ANALYSIS

1. Introduction

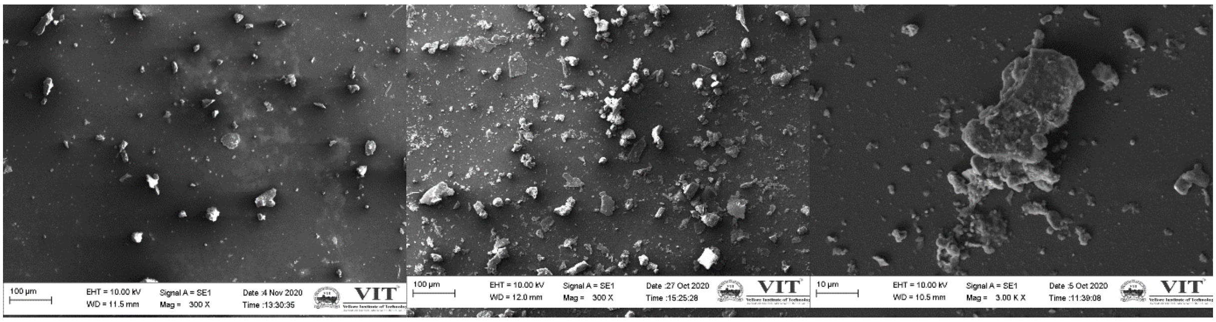
In this chapter, we present the second section of the results obtained. It revolves around the characterization of dust particles and an investigation on the influencing factors on soiling images analysis. These mainly include shape, size, composition analyses, and an investigation on transmittance loss and coverage area relationship.

2. Shape Analysis

Figure VI-1 presents examples of SEM images of the dust particles collected on some sites of the present study. Preliminary examination of these observations shows that the particles deposited have different sizes and morphologies. The shapes tend to be geometrically spherical or elliptical, even cubic in the case of a coastal site (P1S3I_Morocco_1600 x) or elongated. In fact, the morphology of each particle is linked to the deposit on the surface of the glass. When the glass is still clean, the first layer of dust particles can be deposited randomly, having any shape. As the space available will be limited, fine particles of dust of spherical geometry can fill the small spaces between the deposited particles [284].



P1S1H_Morocco_40x **P1S5H_Morocco_400 x** **P1S3I_Morocco_1600 x**



P1S2H_India_300x **P1S3I_ India_300x** **P2S5H_India_3000x**

Figure VI-1. Samples of SEM images of dust particles in some sites of the study with different magnifications

In order to analyze the shape of the dust particles, the circularity factor noted Circ. given by ImageJ is used. A value of 0 refers to a particle which is not circular while 1 refers to a perfect circle [278]. The formula used is shown in Eq. VI-1. The shape factor (Eq. VI-2) is the inverse of the circularity and it varies from 1 to infinity [149]. In general, increasing the form factor indicates a higher probability that the particles are aggregates [149].

$$Circ. = 4\pi \times \frac{Area}{(Perimeter)^2} \tag{VI-1}$$

$$ShapeFactor = \frac{1}{Circ.} \tag{VI-2}$$

Figures VI-2 and VI-3 represent the shape factor analysis of the data of the present study for Morocco and India sites respectively. (P1, P2, P3 and P4) correspond to the four periods of the study, (S1, S2, S3, S4 and S5) to the sites while H and I to horizontal and inclined surfaces respectively. Based on this, it can be seen that more than 50% of the particles in all sites, periods and for both horizontal and inclined surfaces have a regular shape. Furthermore, in the Moroccan sites (Figure VI-2), it can be observed that the regular shapes are more important in the case of the inclined surface, while the irregular or elongated shapes are more important in the case of the horizontal surfaces. This can be explained by the fact that on horizontal surfaces, the probability of particles being aggregates is higher than inclined surfaces due to the gravity effect [149]. This can be clearly visible as well in the Indian sites (Figure VI-3), where it can be observed that in inclined surfaces, particles are more likely to have shape factor of 1. Nevertheless, the difference is not that much high and can be due to the tilt angle of the inclined surface used which is equal to 13°. We expect that if the inclination is high, due to gravity, the difference in shape factor between horizontal and inclined surfaces can be much clearer.

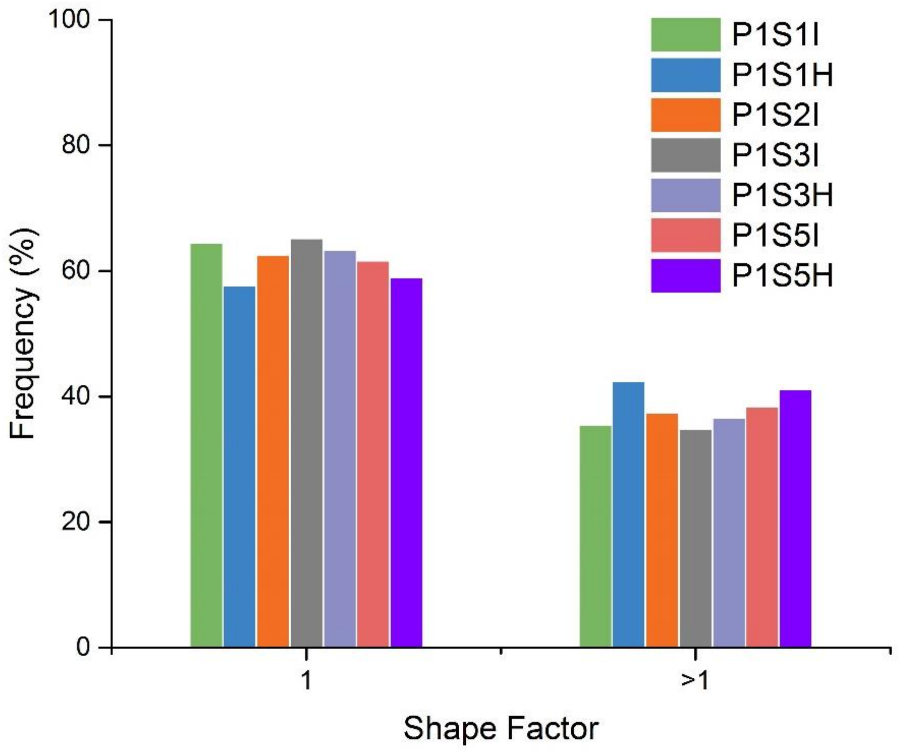


Figure VI-2. Shape factor analysis; (P1) correspond to the period of the study, (S1, S2, S3 and S5) to the sites while H and I to horizontal and inclined surface respectively. Analyzed from SEM images 40x. (Capital region of Morocco)

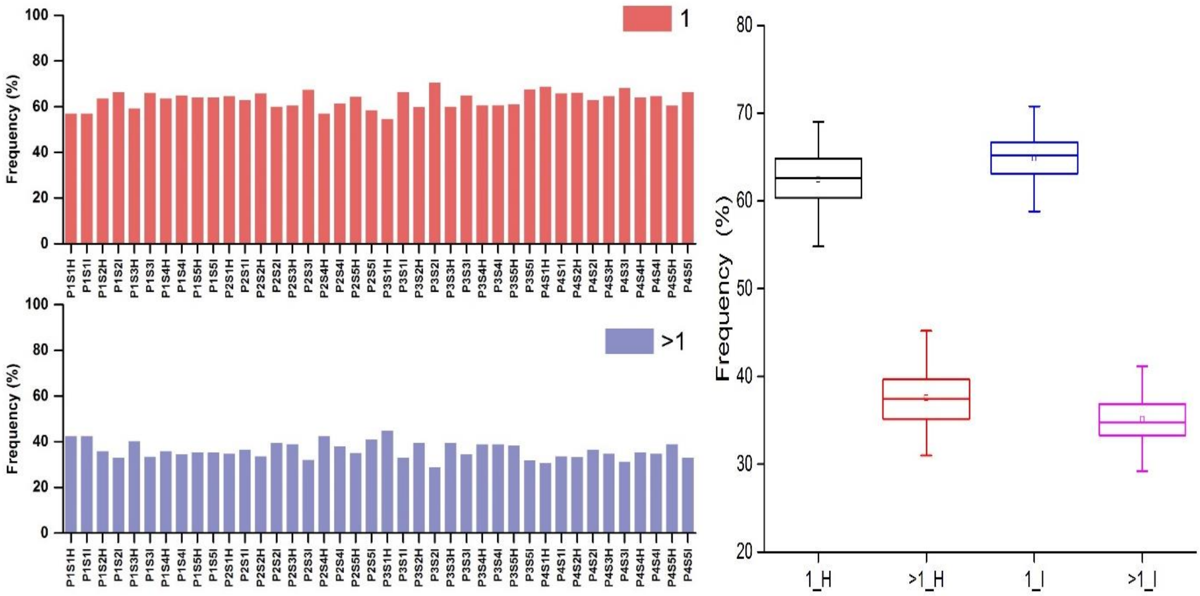


Figure VI-3. Shape factor analysis; (P1, P2, P3 and P4) correspond to the four periods of the study, (S1, S2, S3, S4 and S5) to the sites while H and I to horizontal and inclined surface respectively. Analyzed from microscope images 20x. (Tamil Nadu state of India)

For the period P4_India, we tried to have microscope images as well with magnification 10x and compare the results obtained. Figure VI-4 shows the shape factor with both magnifications 10x and 20x. From this, it can be clearly seen that more regular shapes are detected when the magnification is 20x. However, the tendency remains same in both magnifications.

It has been stated in literature that when particle size increases, the shape factor increases as well [285][286]. To check this, a sample of data has been chosen randomly and plotted in Figure VI-5. This latter shows that the median of size particle increased from 0.1 µm to 0.4 µm when the shape factor increased. This has been explained by the fact that large particles tend to have more complex shapes and forms especially that are generally aggregates.

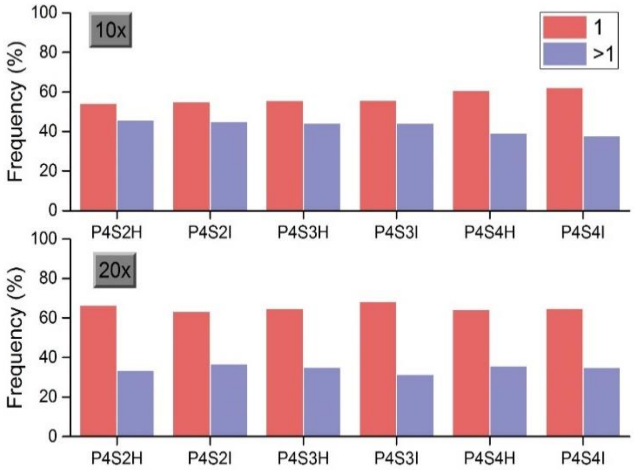


Figure VI-4. Comparison of shape factor results using 10x magnification with 20x

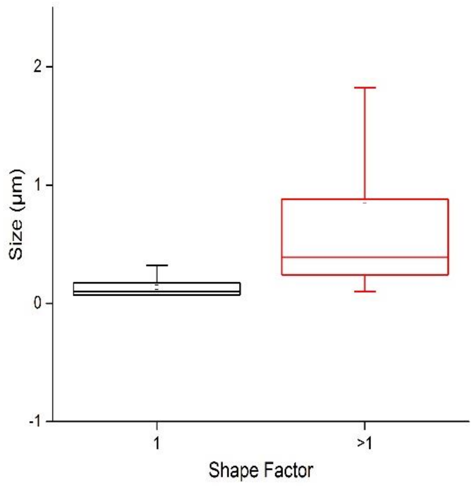


Figure VI-5. Particles size vs. shape factor

3. Size analysis

In order to analyze the particle size, the assumption that all particles have a spherical shape is adopted since the percentage of particles that have a Shape Factor equal to 1 exceeds 50% for all sites. Figure VI-6 and Figure VI-7 show the frequency of the particles in function with the equivalent diameters for Moroccan and Indian sites respectively.

The particle size distribution was found to be larger in the range of (3-14) µm but more concentrated in the range (3-4) µm in the capital region of Morocco. However, large particles of the order of a few tens or even hundreds of µm in diameter are also observed. According to the studies already carried out on the particle size distribution of particles naturally deposited on glass (PV modules), it has been found that in arid and semi-arid climates, the main proportion of particle size is attributed to dust particles in the silt range (particle diameter between 2 and 63 µm), because large particles with a diameter > 63 µm are too heavy to be lifted high enough to settle on the glass, except in the case of strong desert storms [88]. This is consistent with the results found in the capital region of Morocco in terms of size, as it is an area characterized by a semi-arid climate.

Unlike the particle size distribution in the capital region in Morocco, the distribution in Tamil Nadu state of India covers sizes in the range of (0-6) µm but more concentrated in the range of (0-1) µm. According to the Köppen-Geiger climate classification, the five sites selected in India fall within the tropical savanna climate (Aw) while that of the capital region of Rabat-Morocco is dry-summer subtropical climate which often referred to as "Mediterranean" [287]. Moreover, the climate type of the capital region of Morocco is semi-arid, while that of Tamil Nadu state is ranging from wet rainforest to semi-arid. Thus, this would be the reason behind the difference in term of particle diameters prevailing in each location.

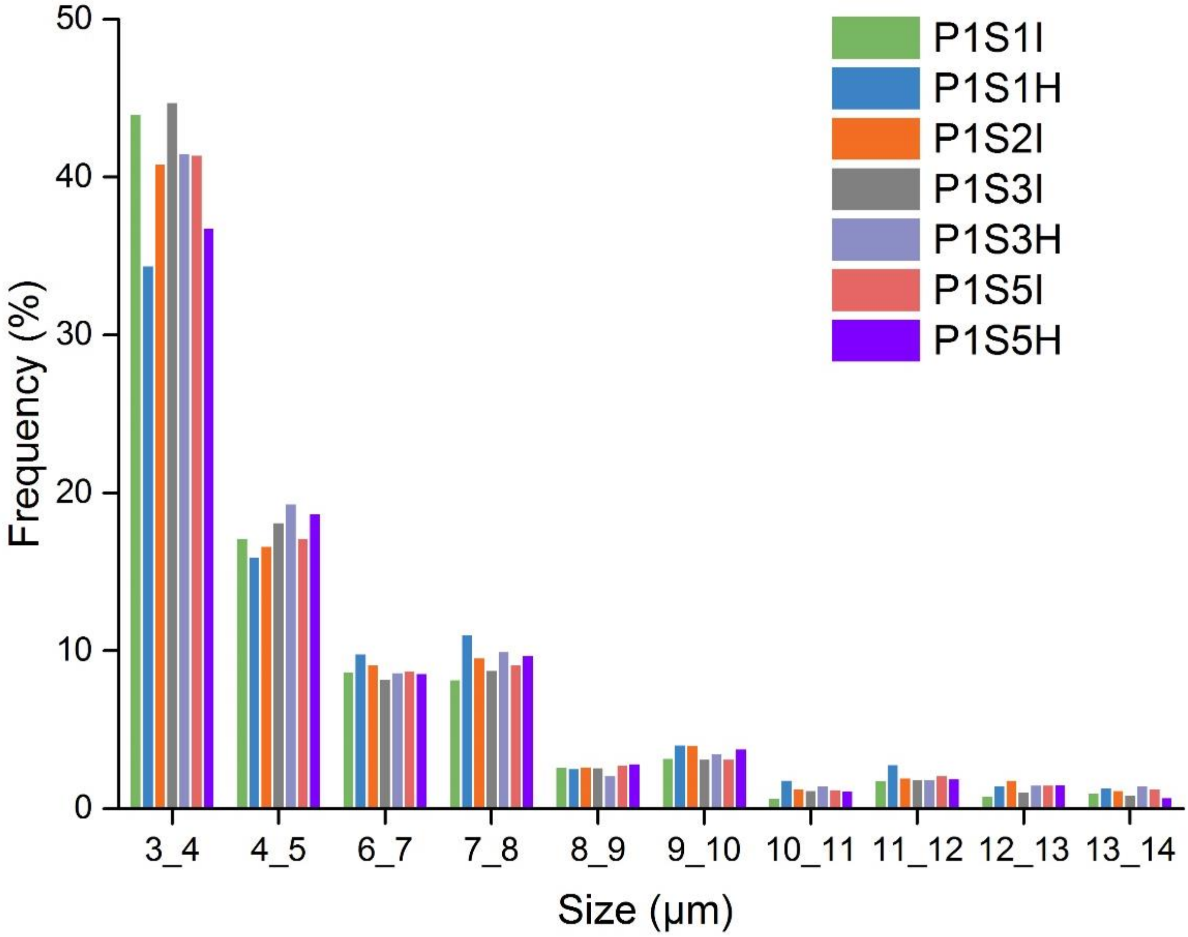


Figure VI-6. Particles size analysis; (P1) correspond to the period of the study, (S1, S2, S3 and S5) to the sites while H and I to horizontal and inclined surface respectively. Analyzed from SEM images 40x. (Capital region of Morocco)

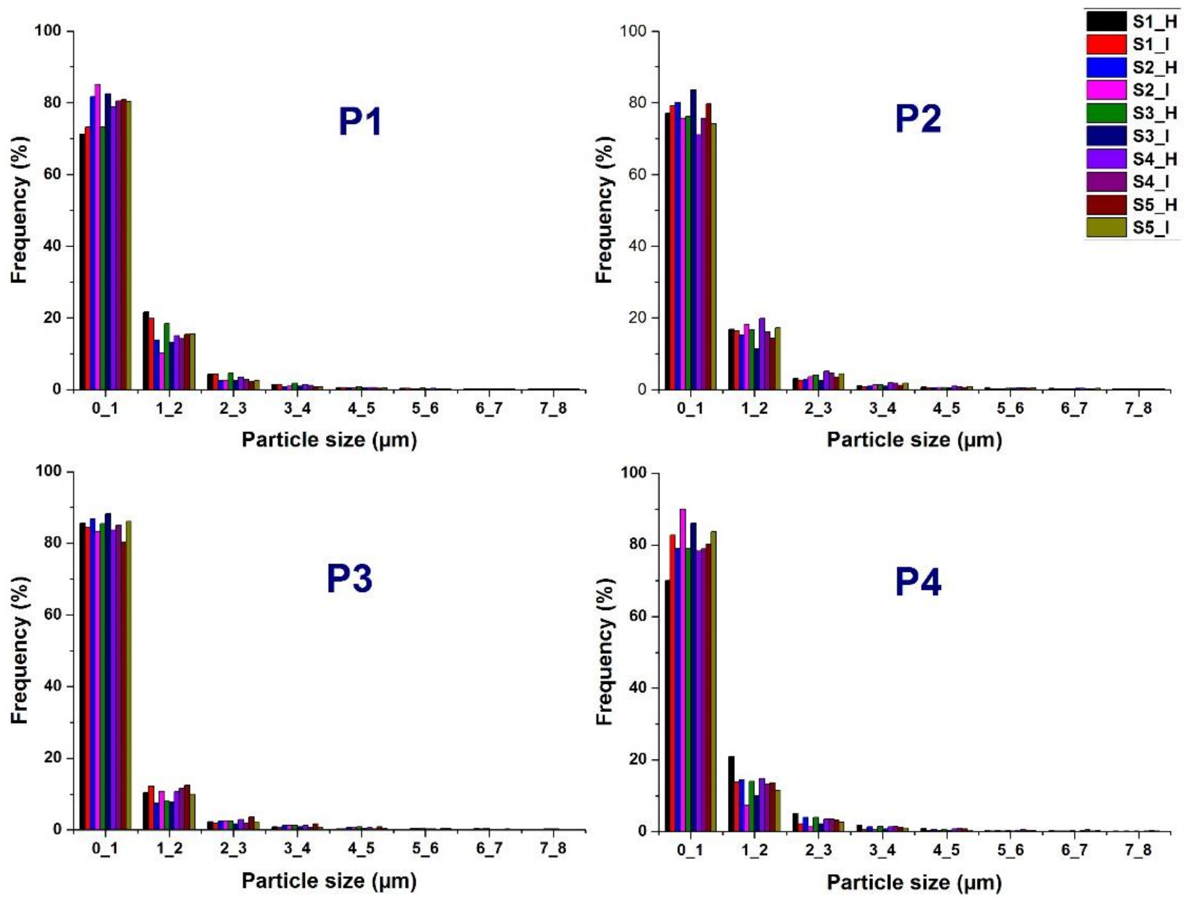


Figure VI-7. Particles size analysis; (P1, P2, P3 and P4) correspond to the four periods of the study, (S1, S2, S3, S4 and S5) to the sites while H and I to horizontal and inclined surface respectively. Analyzed from microscope images 20x. (Tamil Nadu state of India)

As for the shape factor, we tried to see the effect of the magnification on the results. Figure VI-8 displays the diameters of particles obtained for period P4 for sites S2, S3 and S4 and for magnifications 10x and 20x (Indian sites). From this, we can see that the particle size is highly affected by the magnification. With 20x magnification, more than 75% of particles detected are in the range of (0-1) µm, however for 10x it is completely different. Larger particles are detected as well. This result is completely normal because when the magnification increased, small particles tend to be detected more and vice versa. Similar result has been found by [31] where they found that with magnification of 500x, particles with diameter less than 1 µm are the abundant ones in comparison to 100x magnification where larger particles are detected.

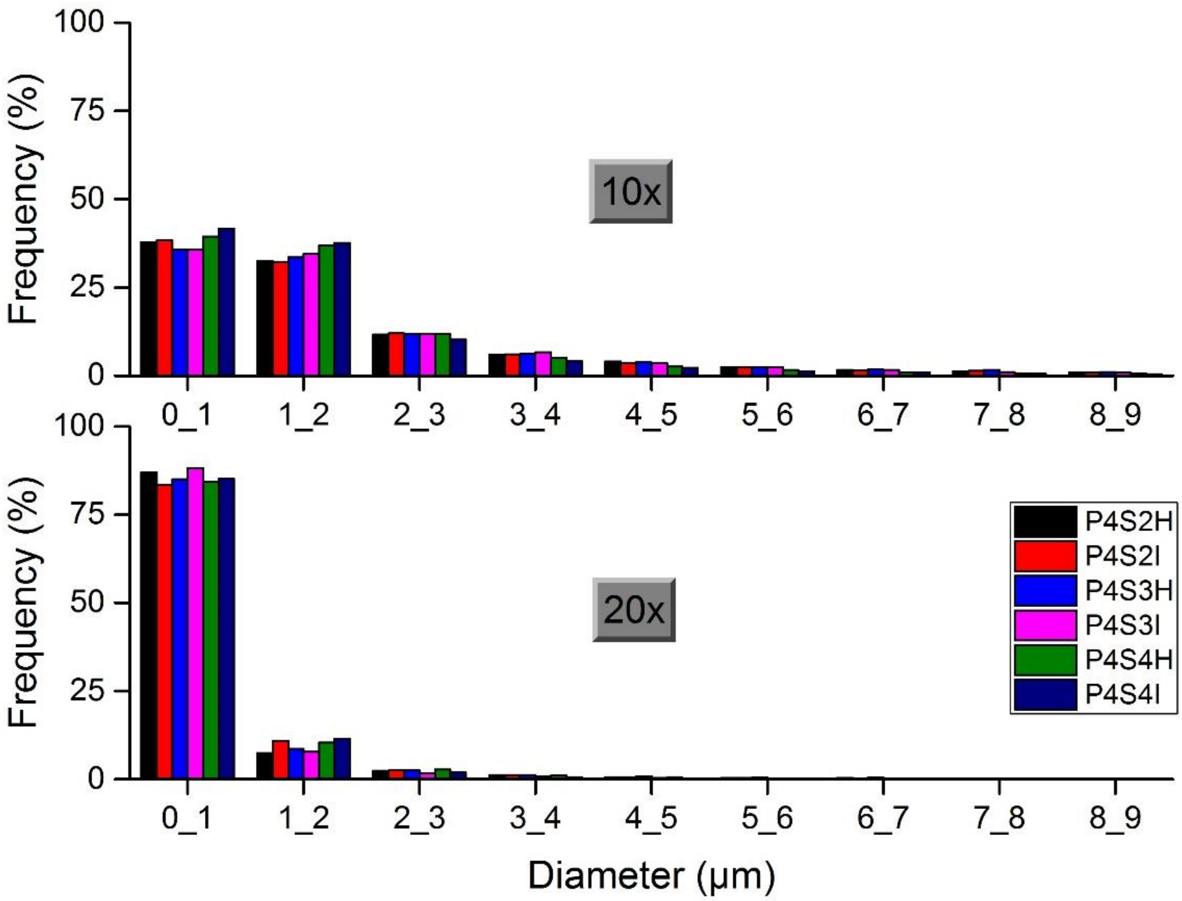


Figure VI-8. Comparison of particle size results using 10x magnification with 20x

Another analysis that has been conducted where we checked: how much it is representative when two images or three images are taken for one sample? Does the inclination of the sample while exposure impact this result? Which particle size range is more affected?

In order to answer these questions, the standard deviations have been calculated based on the frequencies of particle's size obtained from two and three images of periods P3 and P4 (Indian sites). Only (0-1) µm and (1-2) µm ranges have been considered since they represent the prevailing sizes. Table VI-1 shows the median of the standard deviations for each case. From this, independently on the size or the number of images, it can be seen that going from horizontal to inclined surface the median decreases. This means that soiling on the inclined (13°) surface is more homogenous than on the horizontal one. This can be confirmed as well based on the results of the shape factor discussed above that in inclined surface the particles shape is more regular. It has been expected the inverse since on inclined surface, the bottom of the surface will accumulate more dust than the top. However, the result obtained maybe due to the low inclination and heavy rainfalls. It can be noticed also from Table VI-1 that by increasing the size of particles, the median of the standard deviation decreases. This means that small particles are more affected and their distributions are changing over the sample.

By comparing the medians when two or three images are considered, it is clearly visible that they increase. This means that the size average when three images are taken is highly changing and one spot on the sample may not represent the size trend on the whole sample. Increasing the number of images and average their results may assimilate the whole sample. However, how much is the number of images required to do that? This need to be further investigated by taking into account different samples exposed on different inclinations and sites and the reference should be the whole scanning of the sample.

Table VI-1. Effect on size distribution of capturing two or three images of the sample

		Horizontal	***Inclined***
2 images	**Size (0-1) µm**	3.31	1.07
	Size (1-2) µm	1.90	0.90
3 images	**Size (0-1) µm**	3.38	2.29
	Size (1-2) µm	2.28	1.88

4. Transmittance loss vs. fractional coverage area

In few studies, they tried to relate the transmittance with the fractional coverage area as has been done in [31], [200]. However, the number of data that has been used is very limited. In this section, we tried to test how much these two variables are correlated and is there any possibility to get information on the transmittance loss just based on the image analysis of the sample? We intend to test also, how much the fractional coverage area will be affected if two or three images are captured.

ImageJ has been used to calculate the total analyzed area A_a as well as the projected area of each particle on the surface A_c. These latter have been summed in order to obtain the total area covered by all particles. The total covered area by the particles is then divided by the total analyzed area to obtain the fractional coverage area f_{ca}. For the period P1 and P2, two images have been captured on the sample; while for the periods P3 and P4, three images have been captured (Indian sites). For each site, the results obtained were averaged.

$$f_{ca} = \frac{1}{A_a} \sum_i A_C(i) \qquad \text{(VI-3)}$$

The correlation between the transmittance loss and the fractional coverage area is plotted in Figures VI-9 and VI-10. In Figure VI-9, the data of all periods have been gathered while in Figure VI-10, periods P1 and P2 have been plotted separately than P3 and P4. The coefficient of determination including all periods reaches 53 % which is a good sign that the two variables are related. As expected, when three images are taken into consideration the coefficient of determination becomes much better. This is explained by the fact that the distribution over the sample is not the same. Furthermore, with the magnification of the microscope the area that will be analyzed is very small which may not represent the whole sample. Another factor that may affect the results obtained is the magnification. In Figure VI-11, results of the fractional coverage area are displayed for both magnifications 10x and 20x. From this we observe that the difference between the results when magnification change is not that much higher, it can be even neglected. In the study [31], different results are obtained. In this latter magnification has an effect on the results. One reason can be behind is the level of magnification which was high in this study than our study.

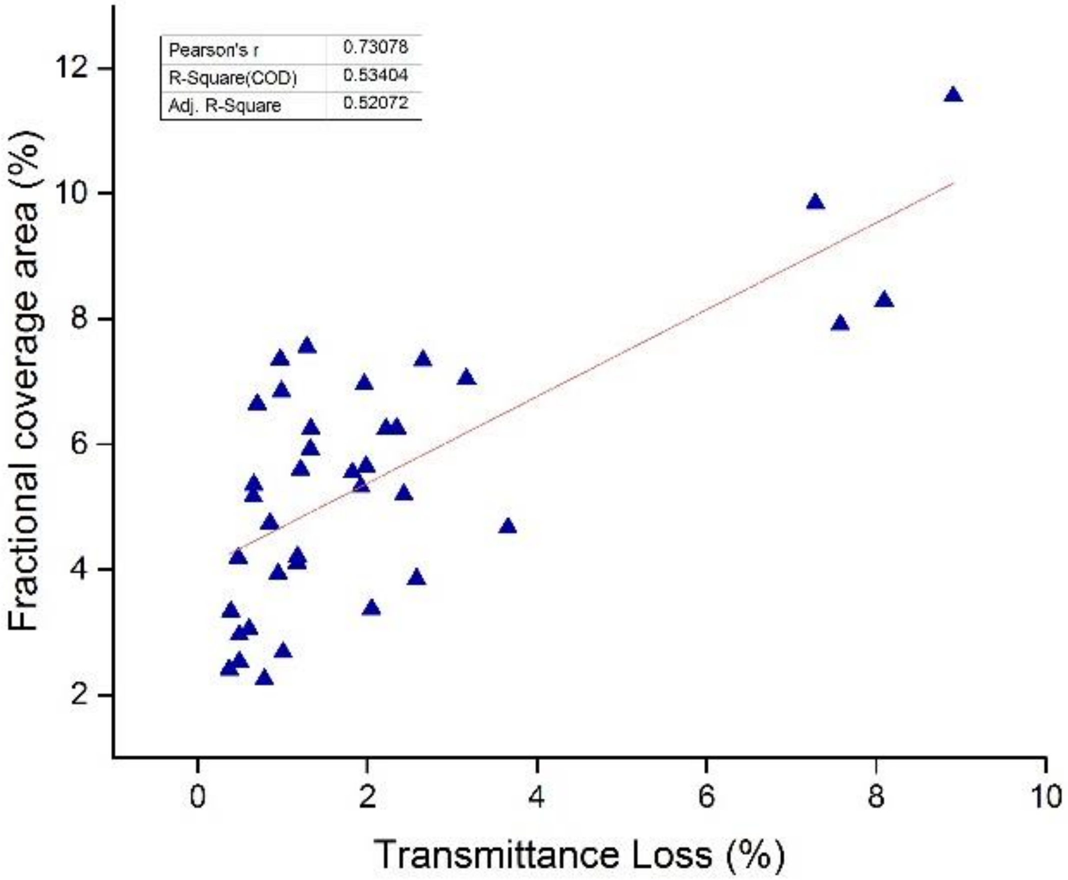


Figure VI-9. Fractional coverage area vs. transmittance loss using data of all Indian sites

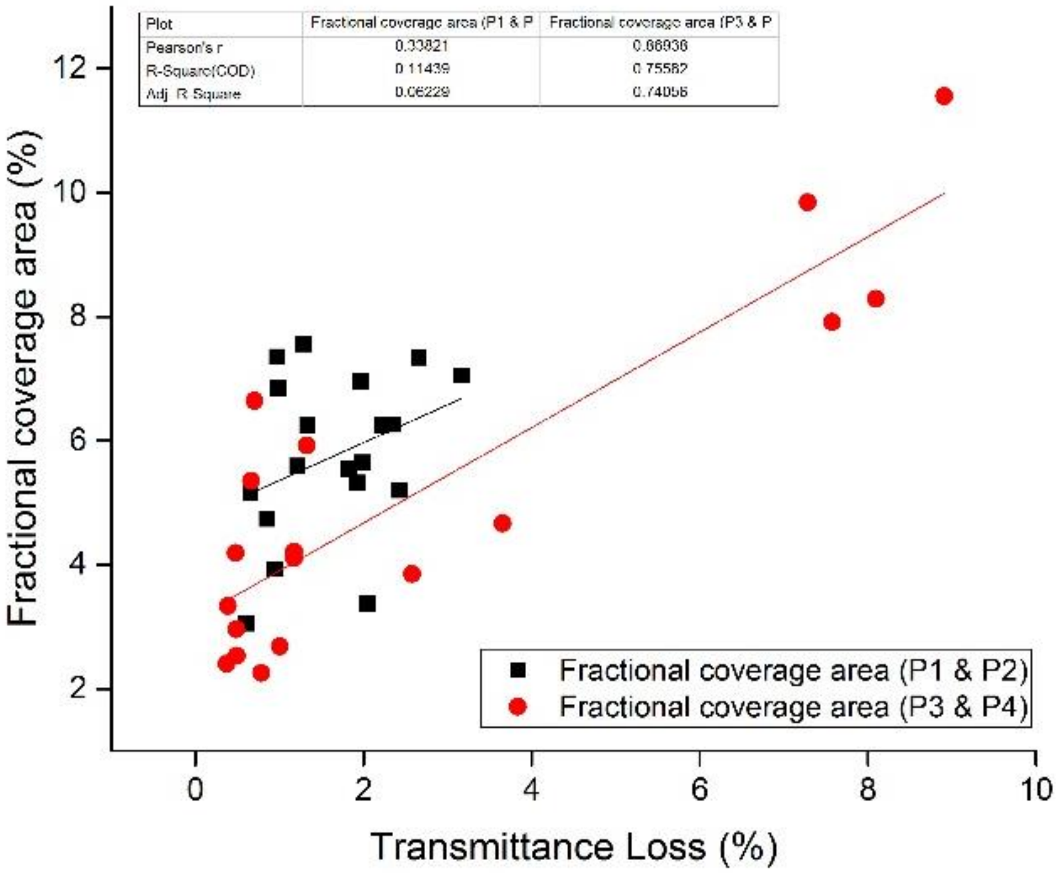


Figure VI-10. Fractional coverage area vs. transmittance loss using data of all Indian sites, separated periods

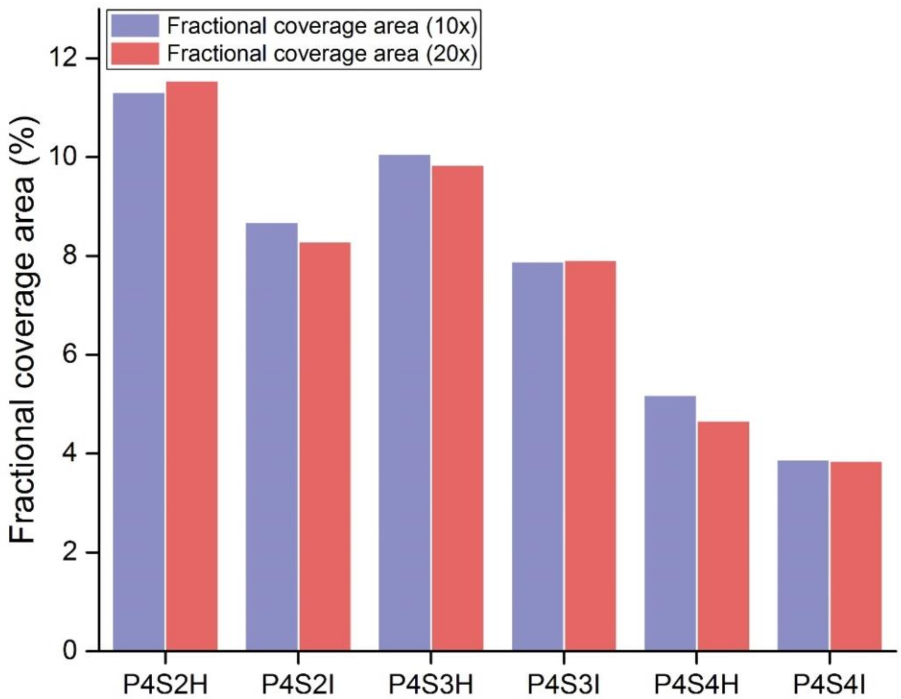


Figure VI-11. Effect on fractional coverage area of capturing two or three images of the sample

5. Chemical composition analysis

5.1. Moroccan sites case

Atmospheric dust contains a distribution of inorganic and organic particles. The inorganic particles in turn contain a distribution of water soluble and insoluble salts. At high humidity, the water-soluble dust particles formed on the surface formed microscopic droplets of saline solutions also retaining the insoluble particles. As the relative humidity decreases, the drops of saline solution dry out, allowing the precipitated salt to act as a cement to anchor insoluble particles on the surface (see Figure VI-12) [56], [111]. This process is clearly demonstrated by the results of the SEM/EDS for the samples installed in the site closest to the ocean, therefore closest to the source of the salt, more particularly the site S3_M (Figure VI-13). The spectrum of elementary analysis (Figure VI-14) by the SEM / EDS of the samples installed at site S3_M clearly confirms that the main elements present in the dust deposited on these samples are Chlorine (Cl) and Sodium (Na). As a result, several aggregates formed from NaCl crystals and other particles are observed. These crystals from seawater have been cemented forming strong bridges between the particles and the surface of the glass.

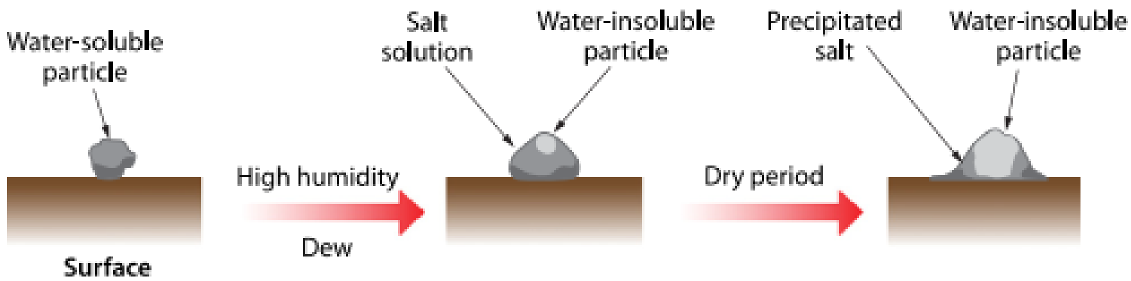


Figure VI-12. Cementation process

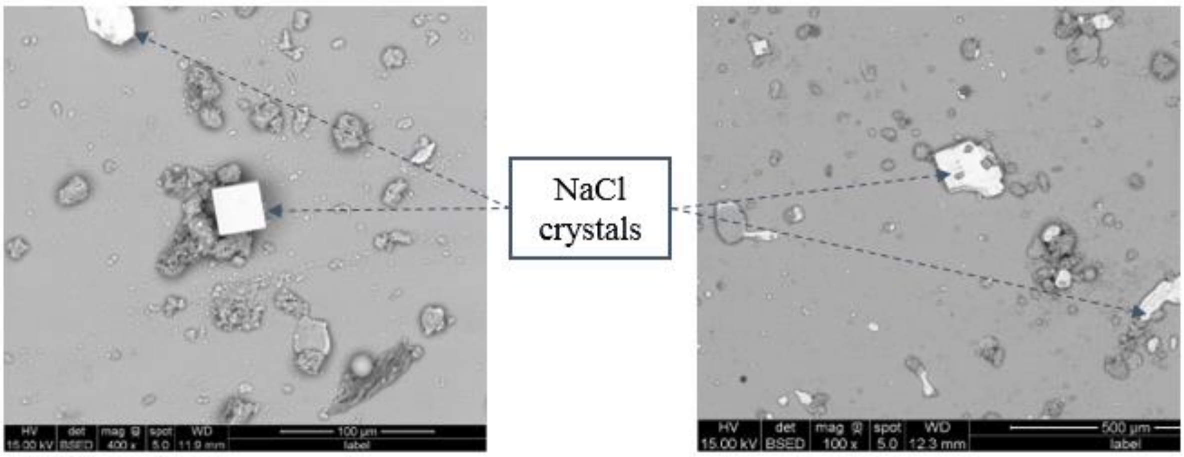


Figure VI-13. SEM images of S3_M sample (P1_M)

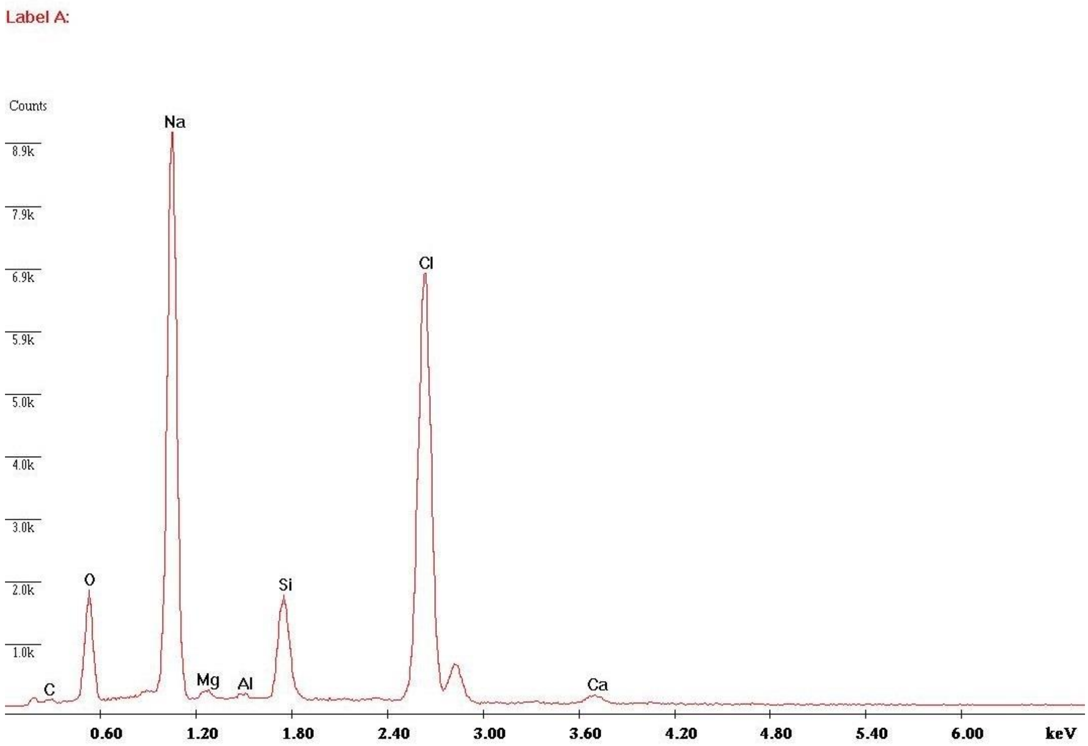


Figure VI-14. Spectrum of elementary analysis from SEM/EDS of particles deposited on the inclined surface at the site S3_M during the first exposure period P1_M

The obtained results in this section can be used to justify the fact that the inclined surface has accumulated more dirt than the horizontal one in the case of S3_M (P1) (see Chapter IV section 2). Indeed, the dominant wind directions in the P1_M period at this site were: W (West), WSW (West-South-West) and NNW (North-North-West). The latter is facing the samples-holder which is exposed to the south direction (see Figure VI-15). Under the effect of the higher humidity in this area (68% of the values in the range of [70 - 80] % and 20% in the range of [80 - 90] %) a significant rate of salt particles transported by the wind are cemented on the inclined surface and favoring the deposition of particles on this surface.

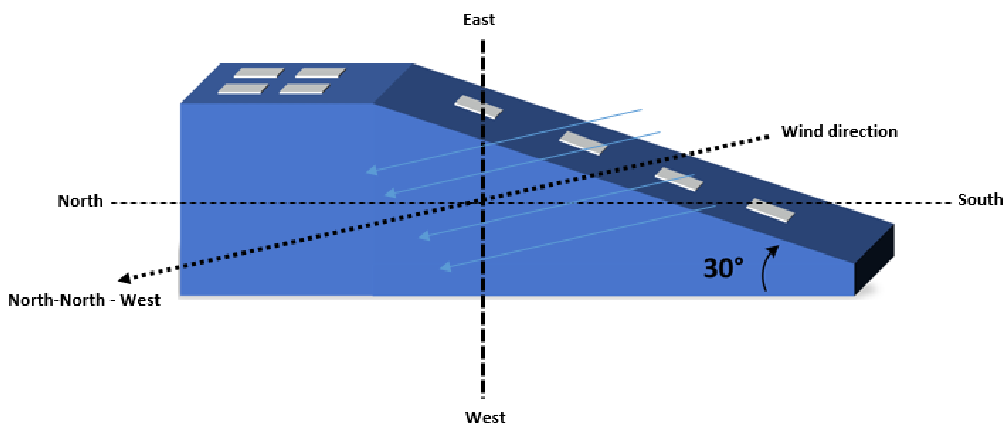


Figure VI-15. Dominant wind direction in the site S3_M during the first period of exposure P1_M

For more investigation of the dust composition, five soil samples, collected in five cities (Rabat, Agadir, Oujda, Ifrane and Errachidia) from different climates, were prepared and analyzed. The identification of the components from the results of the XRD and FTIR analyzes is performed, respectively, based on ASTM files from the database and from [151], [288]–[290]. The results of the analysis are summarized in Tables VI-2 and VI-3 and in Figures VI-16 and VI-17. For XRD and FTIR analyzes, the presence of quartz, calcite and kaolinite can be seen at all collection sites.

Compared to Rabat and Agadir, the soil sample collected in Errachidia City, which has the whitest color (Table IV-6), shows a high quantity of calcite. This must be explained by the nature of the Errachidia region which has a lot of limestone sedimentary rocks, along the High Atlas Mountains, where calcite is the main mineral constituent [291]. In terms of oxides, the composition of Errachidia's soiling sample (41.8 % SiO_2, 17.4 % CaO, 9.56 % AL_2O_3) is similar to that from Sharjah City in the United Arab Emirates (45.53 % SiO_2, 24.62 % CaO, 10.83 % Al_2O_3) as published by Darwish et al. [143]. This is can be explained by the fact both sites belong to zones with almost the same climate conditions.

Table VI-2. XRD analyzes qualitative results of soiling samples

Rabat (XRD)	**Errachidia (XRD)**	**Agadir (XRD)**	**Ifrane (XRD)**	**Oujda (XRD)**
Quartz Calcite Dolomite Kaolinite	Quartz Calcite Dolomite Kaolinite Muscovite	Quartz Calcite Dolomite Kaolinite Muscovite Albite	Quartz Calcite Dolomite Kaolinite Muscovite	Quartz Calcite Dolomite Kaolinite Muscovite

Table VI-3. FTIR analyzes results of soiling samples

Rabat (FTIR)	**Errachidia (FTIR)**	**Agadir (FTIR)**	**Ifrane (FTIR)**	**Oujda (FTIR)**
Quartz Calcite Kaolinite Muscovite	Quartz Calcite Kaolinite Muscovite	Quartz Calcite Kaolinite Muscovite	Quartz Calcite Kaolinite Muscovite Dolomite	Quartz Calcite Kaolinite Muscovite

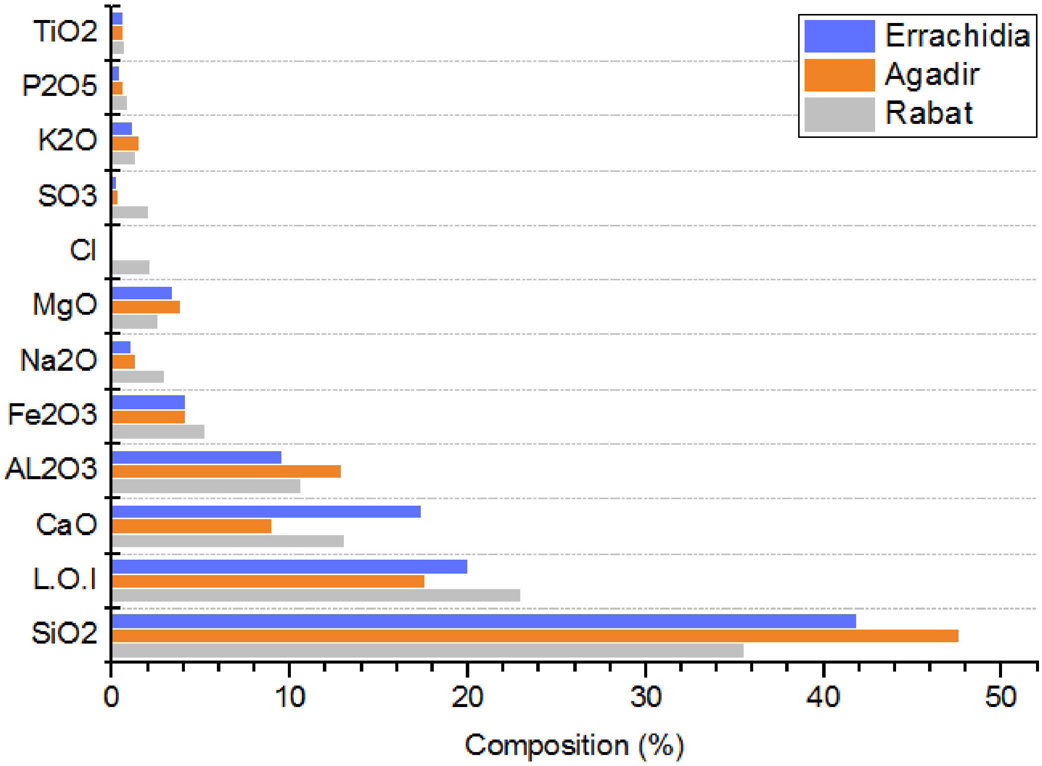


Figure VI-16. X-ray fluorescence results of the samples (the major oxides). L.O.I refers to the loss on ignition which gives an indication of the organic matter content and the organic carbon (Corg) content of the soil

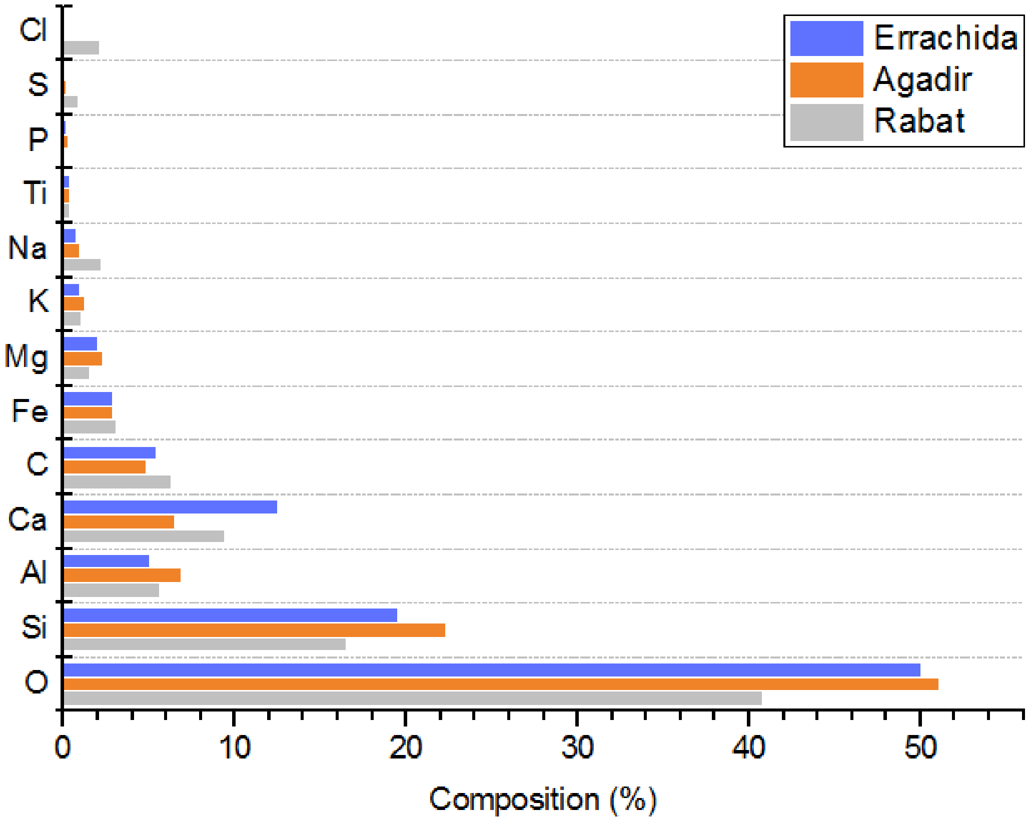


Figure VI-17. X-ray fluorescence results of the samples (the major chemical elements)

For the three cities Rabat, Agadir and Errachidia, whose XRF analysis results are available, the impact of soiling on the optical transmittance of the glass has been studied. Each soil sample was homogeneously distributed to form a thin film in a Petri dish and analyzed by spectrometry. This analysis consists in sending a white light beam on the soiling thin film and analyzing the transmitted spectrum using an integrated optical fiber. The results obtained are summarized in Figure VI-18. We can easily note that the soiling sample from Rabat leads to the highest light attenuation, followed by those of Agadir and Errachidia. This can be explained by the fact that Rabat's soiling sample was more dark/black color compared to those from Agadir or most particularly Errachidia whose soiling color was the clearest (Table IV-6). The color of soiling can be directly connected to the carbon (or even the L.O.I) which is present with higher quantity in Rabat's sample. This confirms on the one hand the results published by El-Shobokshy and Hussein [70] where they found that at the same density, carbon of 5 μm average diameter had a more significant effect on the degradation of P_{max} and I_{sc}, followed by the cement of 10 μm average diameter and the three types of limestone particles with an average diameter of 60 μm, 70 μm and 80 μm. On the other hand, as explained above, Errachidia's sample, which has the whitest color, is rich in calcium oxide in comparison to Rabat and Agadir samples (FigureVI-16). Although Rabat's soiling affects more the glass transmittance, the soiling effect in Errachidia is more pronounced due to the desert climate of this city known by rare rain and dusty winds [29].

As has been previously detailed in chapter IV, section 4, a good correlation between transmittance loss and mass density has been found. However, as has been stated, this correlation is affected by many factors which prevent it from being very strong such as the particles' shape, size, composition and their distribution over the sample. Regarding the composition, the results obtained in this section confirm this hypothesis. For the same mass density, the transmittance loss of dark and opaque particles (case of Rabat's sample) is different (and precisely high) than that of white and transparent particles. Nevertheless, soiling phenomenon is more evident in Errachidia than in Rabat as has been found by [29].

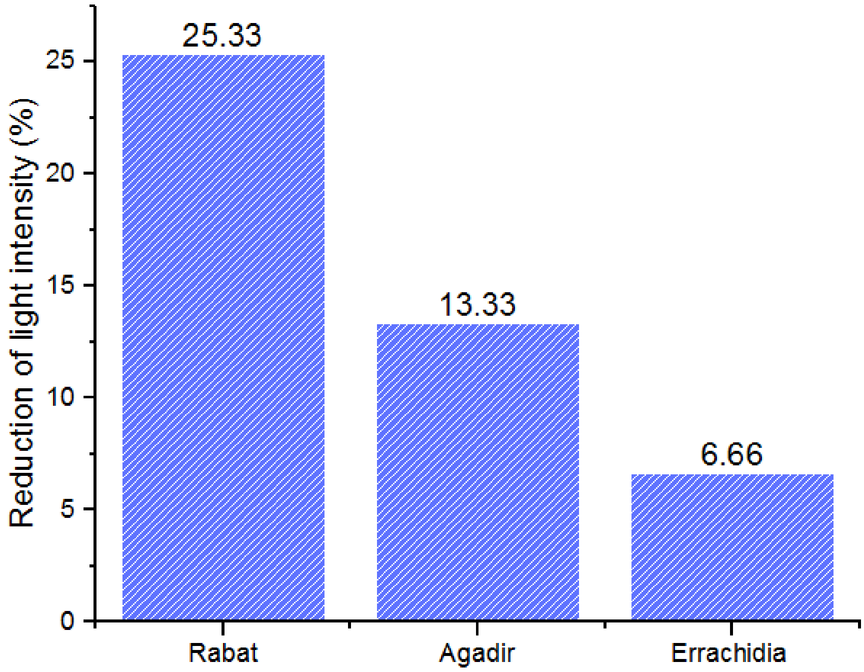


Figure VI-18. Attenuation of white light intensity according to the soiling samples origin

5.2. Indian sites case

Figure VI-19 shows the results of the EDS analysis of the chemical composition of soiling particles for the two periods P1_In and P2_In of the sample installed in Tamil Nadu state of India. The results show that the main elements are Si, Na, Ca, and Mg. R. S. Kumar and P. Rajkumar, in their study [292], analyzed dust air particles in multiple sites over Tamil Nadu state and found that the main constituent is the quartz SiO_2 which confirm the result obtained in the our analyses. In the sample P2S3I, it can be observed the presence of a considerable quantity of carbon which we expected to be due to high traffic that knows the site (see Table IV-2 of description of sites) as it has been found in [123]. However, P2S3H, P2S2H and P2S2I samples are almost in the same location, hence, the carbon element should be present in them as well. Furthermore, the sample is not carbon coated but gold and palladium coated. For this reason, the presence of carbon can be due to the carbon tape on which the samples are stuck. Generally EDS analysis is not accurate for light elements, hence the result obtained for oxygen and Carbon concentrations will not be discussed [286], [293]. Table VI-4 summarizes some studies on the chemical composition of dust deposited on the solar energy systems. It shows that the composition varies from a climate to another but more or less same components. From this it can be seen that these components are mainly coming from earth's crust, soil erosion, rocks and from construction sites.

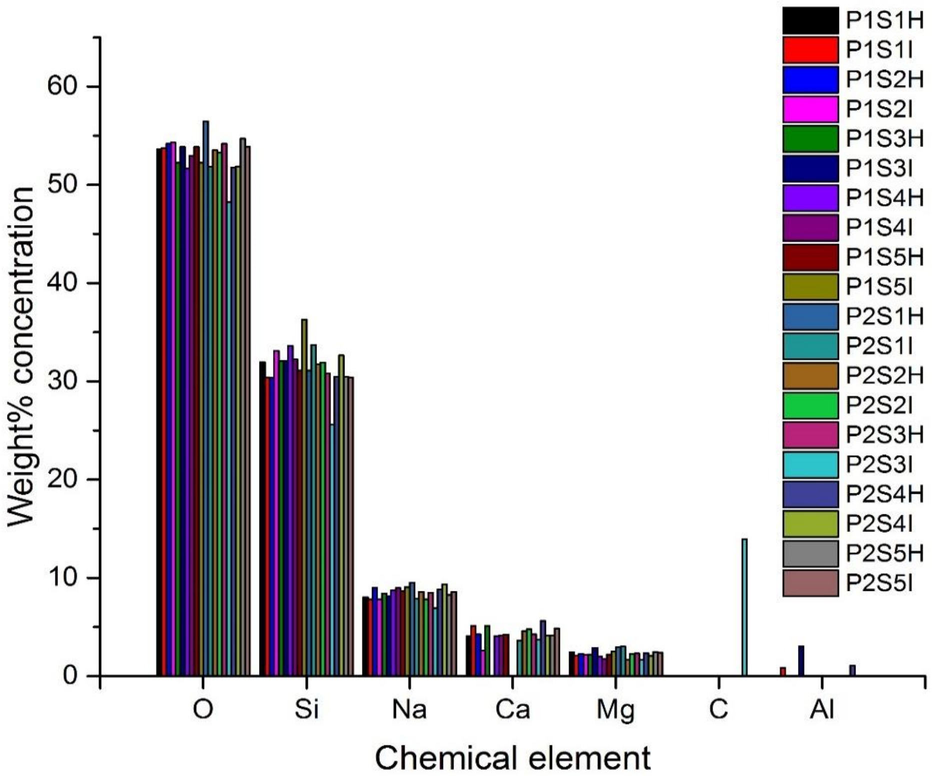


Figure VI-19. SEM/EDS results of the chemical composition of dust particles in Tamil Nadu state of India

Table VI-4. Summary of some studies on the chemical composition of dust particles according to the climate type and their origins

Ref.	Location	Climate type	Composition	Expected origin of particles
[294]	Gdansk, Poland	Temperate oceanic	Si, Al, Mg, Fe	Si is from silica (SiO_2) coming from earth's crust and sand. Al is from di-aluminum trioxide (Al_2O_3) and Mg from magnesium oxide (MgO) present in nature. Fe from anthropogenic origin from the wear of frictional elements of mechanical components of machines, for example automotive brakes.
[286]	Doha, Qatar	Arid climate, hot desert	Ca, Si, Mg, Al	-
[295]	Ben Guerir, Morocco	Hot semi-arid (steppe)	Ca, Si, Fe, Na, Mg, Al	Si is from soil erosion and anthropogenic activities, Ca is from building related emissions while Fe, Na, and Al are from rocks surrounding the site as it happens on a mining area.
[296]	Sharjah, UAE	Arid climate, hot desert	Ca, Si, Mg, Al	-
[84]	Ben Guerir, Morocco	Hot semi-arid (steppe)	Si, Al, Fe, K, Mg, Ca, P	Si, Al, Ca, Fe are from nearby construction site while K, Mg and P are from a nearby phosphate mine.
[297]	Sharjah, UAE	Arid climate, hot desert	Ca, Si, Mg, Al, Fe, Na	Ca and Si are from sands, and the content is affected by the nearby industrial areas.
[298]	Doha, Qatar	Arid climate, hot desert	Ca, Si, Fe, Mg, Al, Na, Cl	Ca and Si are from Arabian desert while Na and Cl are from sea.

6. Conclusion

In this chapter, the characterization of dust particles and an investigation on the influencing factors of soiling images analysis are presented. The main conclusions that can be drawn are as follow:

- Although some particles have irregular shapes, the majority of dust particles have a regular shape. However, regular shapes were observed more in the inclined surfaces than in the horizontal ones. Furthermore, shape factor is affected by the magnification, the more the magnification increased, the more regular shapes are detected
- Particles size distribution was concentrated in the range (3-4) µm in the capital region of Morocco and in the range of (0-1) µm in Tamil Nadu state of India. It is affected by the magnification, the inclination, and the number of images captured on the sample. Higher magnification leads to higher detection of small particles. In addition, homogeneity in term of particle size is observed on horizontal surfaces than on inclined ones. Furthermore, capturing three images on the surface of the sample is more representative of the distribution of soiling on it.
- The transmittance loss and the fractional coverage area are related and this latter can be used to estimate the transmittance loss. However, this estimation is more precise when three images on the sample are captured.
- Cementation at the level of the samples installed in the closest site to the ocean is observed to be enhanced by the presence of salt crystals on the surface.
- Soiling samples have almost the same chemical and mineralogical composition but with different percentages in the components. The abundant constituents in the samples collected from the capital region of Morocco are mainly quartz, calcite and kaolinite. Rabat’s soiling sample, which is darker and richer in carbon, has shown to have the worst deterioration effect compared to those from Agadir or Errachidia which is the whitest and the rich in calcium oxide. Nevertheless, soiling phenomenon is more pronounced in Errachidia than in Rabat. The results obtained confirm as well the effect of chemical composition on the correlation between mass density and transmittance. In Tamil Nadu state of India, the main constituents that were found are Si, Na, Ca, and Mg.

CHAPTER VII : GENERAL CONCLUSION

1. Summary and conclusions

Soiling is acknowledged as the third parameter determining the productivity of solar energy systems after irradiance and temperature. Its considerable effect has made it a hot topic during the last years. Understanding and mastering this phenomenon or predicting it will significantly help to save many investments from losses, especially since it has a big impact in areas known to be the most investment-attractive regions of solar energy exploitation. It will also save the precious natural resource "water" by determining the mitigation techniques wisely.

The present thesis evolves around the investigation of the effect of soiling on solar energy systems in Morocco and India and insights on its modeling and prediction. It includes mainly: A first review focusing on the presentation of the soiling process, the methods of quantification, the factors which influencing it, the methods to handle it and a literature survey on studies conducted in both countries Morocco and India. A second review of the different studies conducted to model soiling phenomenon has been presented. A summary of the most important information about each model has been described. The papers summarized have been analyzed and gathered into groups to better present the trend that research on this phenomenon follows. Then, a comparison of soiling effect between the different chosen sites, an assessment of the impact of the environmental and meteorological conditions on soiling effect, a correlation between the mass density and the transmittance loss and a deep investigation on its modeling are presented. Finally, the characterization of soiling particles and an investigation of the influencing factors of soiling images analysis are discussed.

From the reviews and the studies, the following conclusions can be drawn:

- Dust deposits on the front surface of the module can significantly decrease the solar energy amount received by the panel. The accuracy of mass measurements is a limiting factor in determining the level of loss due to the accumulation of dust. While the reflection and transmittance measurements seem to be sufficient to detect optical changes. However, these two methods do not represent the actual effect of soiling on the reduction of the electrical performance of the photovoltaic module. To more accurately quantify the effects of soiling, researchers often use the method based on the electrical characteristics of a real PV system.
- The effect of factors influencing soiling phenomenon is very complex to understand and in most cases each factor has double effect, positive and negative impact. The effects of these

factors are interrelated, which make it highly difficult to isolate and study each factor alone since it will be different than that of the real outdoor conditions.

- Many cleaning techniques and methods have been developed to reduce the impact of soiling. However, a clear map on the usage of each technique is still needed since the efficiency of these methods depends strongly on site/installation characteristics and weather conditions.
- In Morocco as well as in India, soiling phenomenon has an increased interest. Nevertheless, since this phenomenon is highly localized, more studies are still needed in order to reach generalized conclusions.
- A variety of the applied models and methods to model soiling phenomenon are discussed. Each model has its own strengths and weaknesses. According to the objective desired from the modeling, five groups were identified. These, describe the different parts of the cycle of soiling, from weather conditions to end up in the losses. The parts are complementary to each other and they will be useful for researchers to identify on which they will focus on.
- The analysis of the applied models has shown that statistical modeling has been applied more than theoretical modeling. The analysis of the latter has revealed that studies conducted have taken into consideration hypotheses that were, in most cases, far from reality. The results have shown as well that in the statistical modeling itself, although regression analysis has been used more frequently, neural network approaches performed better in prediction of soiling phenomenon.
- Two kinds of modeling have taken part in the works performed. The first one concerns the prediction of soiling effects based on factors affecting it and the second one is concluding soiling losses from the data of existing solar plants. These models can be very valuable respectively when a station with the necessary sensors is available and only when a solar plant exists.
- The investigation on soiling effect has shown this phenomenon is a much-localized.
- The deposition densities in the capital region of Morocco were observed in the range of 0.37 g/m²/month and 2.86 g/m²/month and the transmittance of the glass showed a reduction from 1.05% per month to 10.04% per month compared to the clean glass sample. These quantities depend on the site of exposure, the inclination and the exposure period. Alkarya site (S2_M) experienced the highest mass density and transmittance loss in comparison to the other sites.

- The mass densities in Tamil Nadu state of India are ranging from 0.03-1.42 g/m^2/month while transmittance losses between 0.35-7.42 %/month and thicknesses between 0-9.21 µm/month. Erode city (S2_In and S3_In) experienced high-soiling effect in comparison to Vellore (S1_In and S5_In) and Namakkal (S4_In).
- The capital region in Morocco experienced higher soiling effect than Tamil Nadu state, however, this is due to the difference in the climate type (Temperate-dry summer-hot summer (Csa) in Morocco and tropical-savannah climate (Aw) with a small portion of arid-steppe-hot climate (BSh) in India), the periods of exposure (spring and summer in Morocco and monsoon period in India) and the environmental characteristics of the sites.
- The effect of the factors that influence soiling is very complex and highly depend on their each other effect, the amount of data used as well as on the location. In the absence of a huge database of the influencing factor along with the soiling effect data, it will be highly difficult to predict soiling losses based on the variables that affect it.
- For mass densities less than 3g/m^2, a positive and linear correlation between the mass density and the loss in transmittance was observed. However, this depends on the period and the location of the exposure.
- By correlating the mass density and the transmittance loss, three new generalized models have been developed and which can predict the transmittance loss based on the mass density more accurately since they cover many sites, different tilt angles and orientations, and various periods. However, the best one which has the highest R^2 and the smallest RMSE and MAE is the exponential model (New model 3 (EXP)).
- Although some particles have irregular shapes, the majority of dust particles have a regular shape. However, regular shapes were observed more in the inclined surfaces than in the horizontal ones. Furthermore, shape factor is affected by the magnification, the more the magnification increased, the more regular shapes are detected
- Particles size distribution was concentrated in the range (3-4) µm in the capital region of Morocco and in the range of (0-1) µm in Tamil Nadu State of India. It is affected by the magnification, the inclination, and the number of images captured on the sample. Higher magnification leads to higher detection of small particles. In addition, homogeneity in term of particle size is observed on horizontal surfaces than on inclined ones. Furthermore, capturing three images on the surface of the sample is more representative of the distribution of soiling on it.

- The transmittance loss and the fractional coverage area are related and this latter can be used to estimate the transmittance loss. However, this estimation is more precise when three images on the sample are captured.
- Cementation at the level of the samples installed in the closest site to the ocean is observed to be enhanced by the presence of salt crystals on the surface.
- Soiling samples have almost the same chemical and mineralogical composition but with different percentages in the components. The abundant constituents in the samples collected from the capital region of Morocco are mainly quartz, calcite and kaolinite. Rabat's soiling sample, which is darker and richer in carbon, has shown to have the worst deterioration effect compared to those from Agadir or Errachidia which is the whitest and the rich in calcium oxide. Nevertheless, soiling phenomenon is more pronounced in Errachidia than in Rabat. The results obtained confirm as well the effect of chemical composition on the correlation between mass density and transmittance. In Tamil Nadu state of India, the main constituents that were found are Si, Na, Ca, and Mg.

2. Usefulness and practicality

We believe that the results obtained in the present work will be useful since:

- The first review gathered mostly all-important aspects that a new researcher looks for in the topic of solar photovoltaic soiling. It will be as a paved guide to help readers to better understand soiling phenomenon and to get a clear idea about the trend of research on this subject in both countries Morocco and India.
- The second review will help to gain an overview of the models applied. It will also help to better choose the right direction in modeling and predicting soiling phenomenon. It aims at serving as a reference for future studies.
- The assessment of soiling effect in different sites and on different inclinations and its interaction with environmental and meteorological conditions will be very advantageous to get an approximate idea on how soiling is in the different selected sites in Morocco and India and to know how soiling change according to location and its characteristics. This will be valuable as well in predicting soiling losses more accurately.
- The results obtained on soiling images analysis are very useful for the development of highly precise soiling sensors camera-based and the outdoor soiling microscopes, which are the main component for an efficient and economic cleaning.

- The identification of soiling composition will be helpful for researchers working on PV modules surface degradation, especially those who are trying to develop efficient anti-soiling coating materials for glass surfaces. It will be useful as well to better choose the appropriate cleaning solutions.

3. Perspectives

In order to approach the complex behavior of the soiling phenomenon and to predict it over time accurately, more data for long periods are still needed. Furthermore, all parameters affecting soiling should be taken into consideration. Additionally, it is highly recommended that the same model should be tested in different climates and on different technologies to validate its usefulness. Furthermore, as it has been proved that the dust concentration ranks first in predicting soiling losses, the use of existing databases of soiling potential adjusted using weather conditions from existing databases (or from meteorological stations) seems to be a low cost and valuable method to predict soiling losses. This will be achieved, however, only after finding the accurate relationships between the parameters and validating them on the site. Finally, it is highly recommended as well that instead of suggesting new models, it will be wiser to test the published models that have proved good results in different sites and technologies to overcome their limits and to achieve the accurate and well-tested model. Based on these recommendations, a new study is launched and it is in the framework of a PhD in order to achieve this model.

The representativeness of the result obtained on a spot on a glass sample remains a questionable issue. In the present work, we made the comparison between the results of capturing two and three images on the glass sample and found that capturing three images is more accurate. However, what would happen if we increased the number of images? Does the accuracy will increase? This need to be further investigated by taking into account different samples exposed on different inclinations and sites and the reference should be the whole scanning of the sample. This work has been started already in the framework of master degree project and may be continue in the framework of a PhD.

In section 5 of the review detailed in Chapter II, the effect of ambient temperature and the temperature of the module on soiling has been discussed. For this latter, what if the effect is mutual and soiling in his turn is affecting the temperature of the module? What if the effect of soiling not only provoking optical losses but also participates in the increase or the decrease of the module temperature? This inversed effect was rarely investigated and if ever discussed, it is not deeply. To check this relationship, a study has been started but due to the insufficient of data to get concrete conclusions, it has not been included. For this reason, this relationship will be investigated more in future works.

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ROYAUME DU MAROC
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Abstract

This thesis investigates the effects of soiling on solar energy systems in Morocco and abroad (India), and presents various and important insights on their modeling and prediction. The investigation on soiling effect has shown this phenomenon is a much-localized. The exploration of the effect of the factors that influence soiling has revealed that their effect is very complex and highly depend on their each other effect, the amount of data used as well as on the location. This makes it highly difficult to predict soiling losses based on the variables that affect it. By correlating the mass density and the transmittance loss, the best generalized model which has the highest R^2 and the smallest RMSE and MAE is the exponential model (New model 3 (EXP)). Regarding the physical characterization of dust particles, the majority of dust particles have a regular shape and the shape factor is affected by the magnification. Particles size distribution was concentrated in the range (3-4) µm in the capital region of Morocco and in the range of (0-1) µm in Tamil Nadu State of India. It is affected by the magnification, the inclination, and the number of images captured on the sample. Furthermore, capturing three images on the surface of the sample is more representative of the distribution of soiling on it. The transmittance loss and the fractional coverage area found to be correlated and this latter can be used to estimate the transmittance loss. On the subject of the chemical characterization of dust particles, soiling samples have almost the same chemical and mineralogical composition but with different percentages in the components.

Key Words: Solar energy; PV modules; Soiling; Morocco; India; Transmittance; Mass density; Modeling; Prediction; Shape Factor; Chemical-physical analyses.

Résumé

Cette thèse étudie les effets de l'encrassement sur les systèmes d'énergie solaire au Maroc et à l'étranger (Inde), et présente un aperçu et de diverses réflexions importantes sur leur modélisation et leur prédiction. L'évaluation de l'effet de l'encrassement a montré que ce phénomène est très localisé. L'exploration de l'effet des facteurs qui influencent l'encrassement a révélé que leur effet est très complexe et dépend fortement de leur effet réciproque, de la quantité de données utilisées ainsi que l'emplacement. Il est donc très difficile de prédire les pertes les effets de l'encrassement à partir des variables qui les affectent. En corrélant la masse du dépôt et la perte en transmittance, le meilleur modèle généralisé qui a le R^2 le plus élevé et les RMSE et MAE les plus faibles est le modèle exponentiel (Nouveau modèle 3 (EXP)). En ce qui concerne la caractérisation physique des particules des salissures, la majorité des particules ont une forme régulière et le facteur de forme est affecté par le grossissement. La distribution granulométrique des particules était concentrée dans la gamme (3-4) µm dans la région capitale du Maroc et dans la gamme de (0-1) µm dans l'État du Tamil Nadu en Inde. Elle est affectée par le grossissement, l'inclinaison et le nombre d'images capturées sur l'échantillon. De plus, la capture de trois images à la surface de l'échantillon est plus représentative de la répartition des salissures sur celui-ci. La perte en transmittance et le pourcentage de surface couverte sont corrélées et cette dernière peut être utilisée pour estimer la perte en transmittance. En ce qui concerne la caractérisation chimique des particules de salissures, les échantillons de salissures ont presque la même composition chimique et minéralogique mais avec des pourcentages différents.

Mots-clefs: Énergie solaire ; modules photovoltaïques ; Encrassement ; Maroc ; Inde ; Transmittance ; Densité de masse ; Modélisation ; Prédiction ; Facteur de forme ; Analyses physiques-chimiques.

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