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Anthropogenic drivers induced desertification under changing climate: Issues, policy interventions, and the way forward

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ABSTRACT

A study of the extended desertification due to anthropogenic causes under climate change (CC) associated with its impact is presented here. Desertification, the main environmental issue, severely impacts agricultural output, causing poverty and economic instability in a nation like India. The regional distribution of desertification was determined using the RF and MaxEnt models. The western, central, and southern portions of the nation are very high, high, and moderately susceptible to desertification, respectively, according to the RF model. The MaxEnt model indicates that the western, central, and southern parts of the country exhibit a significant susceptibility to desertification, with the eastern parts also showing a moderate level of vulnerability. The remaining portion of this region, mainly in the north, east, and northeast, is particularly resistant to desertification. The outcome demonstrated that the country's desertification process had expanded from the west to the south. However, there are some spatial differences associated with the mentioned part of the country. This relevant information is crucial for decision maker of this country to take suitable remedies in regard to the reduction of the intensity of desertification.

1. Overview of the study

Dryland and semi-arid regions, constituting approximately 40% of the Earth's land surface and hosting millions of inhabitants, face imminent peril due to the threat of desertification [1]. Desertification, also known as desertization, refer to the process wherein the biological productivity of drylands (semi-arid and arid regions) is diminishes as a result of either natural or human-induced factors [2–4]. Instead of the direct enlargement of existing deserts, the concept pertains to various processes influencing all arid ecosystems, encompassing deserts, grasslands, and scrublands [5,6]. Approximately 52 million square kilometers (equivalent to around 20 million square miles) of the Earth's land, excluding ice-covered areas, exist, incorporating some of the most economically disadvantaged nations globally. The United Nations Environmental Program reports that desertification has negatively impacted 36 million square kilometers (approximately 14 million square miles) of land, posing a significant international concern [7].

The Indian portion of the Thar Desert, located on the nation's northwest border, is around 28,600 km^2 large due to persistent drought and wind erosion [8]. The western scarp of the Aravalli range, extending from north to south-west, serves as both the geomorphic and climatic boundary between the eastern desert and the Pakistani desert to the west. This geographical feature reaches into the southern regions of the Gujarati states and the northern Indian states of Punjab and Haryana. As reported by Sinha et al. [9], Rajasthan alone harbors 91% of India's desert, covering an extensive 2.08 million square kilometers, which constitutes approximately 61% of the state's total geographical area. According to Kundu and Dutta [10], the western areas of the state are

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classified as part of the vast Great Indian Desert. However, desertification issues also pose a threat to districts such as Bikaner, Churu, and Nagaur. Desertification is a critical issue greatly threatened by increased population pressure and grazing stress on this delicate habitat. The usual causes of desertification in dryland regions include "climate change (CC) and unsustainable land-management practices". According to the "[11]", low or erratic rainfall is a characteristic of arid and semi-arid ecosystems by nature. Long-lasting droughts have the same fast effects on ecosystem production as CCs in such ecosystems [12].

Precipitation is a crucial climatic element that regulates primary production in semi-arid tropical desert and grassland ecosystems [13]. In arid environments, seasonal or yearly precipitation is directly correlated with vegetation productivity [14]. According to Huxman et al., and Knapp et al., [15,16], it is necessary to compute the link between precipitation and productivity to assess and anticipate the effects of CC on dryland ecosystems. Rainfall has been identified as one of the fundamental factors influencing the tropics' terrestrial ecosystems' net primary production (NPP).

Agriculture, animal grazing, and the harvesting of fuel wood are just a few of the activities humans engage in within the ecosystems of the dry plains [17]. There, various activities may have a detrimental effect on dryland ecosystems and exacerbate the desertification issue [18]. To gain a deeper comprehension of how climate change (CC) and human activities contribute to the progression of desertification, the impacts mentioned earlier can be categorized into four main groups: croplands irrigated with salt buildup often harm the soils, crops reliant on rain that are also subject to erratic rainfall and soil erosion brought on by the wind Overgrazing, soil compaction, and erosion affect grazing pastures, while excessive fuel wood use harms dry woodlands [19].

Imagine that fertile area turning into desert-like sand that has lost its moisture. On terrain with fewer than three inches of annual rainfall, it is practically difficult for plants and people like this farmer to exist and prosper. Unfortunately, this is not a fictional scenario. Deserts are growing at about twenty thousand square miles every year. Is that hard to envision? This means some twenty thousand square miles of land are becoming dried up and unusable every single year. This is a widely recognized problem since it is happening so rapidly around the world, not to mention it affects so many people. The numbers are astonishing. Worldwide, two billion people suffer the consequences of desertification. Not only that but according to Bogumil Terminski, "One of the primary causes of hunger in many parts of the world appears to be desertification of the land" (Current Dynamics). More deserts equals less land area to plant crops and tend animals. This creates a problem with food shortages in certain areas of the world.

In 1994, the United Nations instituted the UNCCD as the exclusive globally binding commitment that connects environmental and developmental aspects to the promotion of sustainable land management. Desertification debates were proposed at the "UN Earth Summit in Rio de Janeiro" in 1992, and the Convention was created in response to that request. In 1994, a treaty that was ratified by participating parties included a specific definition of desertification within the United Nations Convention to Combat Desertification (UNCCD). Desertification, therefore, refers to land degradation in regions with restricted water access is characterized more by the decline in land quality than the expansion of deserts per se. This decline has the potential to cause a lasting or temporary reduction in the quality of soil, vegetation, water sources, or wildlife. Additionally, it involves a decrease in the economic viability of the land, impacting its capacity to be cultivated for either commercial gain or sustenance. Drylands refers to all dry, semi-dry, and dry sub-humid regions. Predictably, these regions receive minimal annual precipitation in the form of snow or rain.

According to the United Nations, the nation's soil deterioration rate has increased, reaching 30 to 35 times the historical average. Desertification is a problem exacerbated by urbanisation, mining, farming, and ranching [20]. Drought danger is rising due to CC, which is important. All these elements contribute to soil erosion, preventing the ground from holding onto water and supporting plant growth [21]. The prospect of CC and rising average temperatures may intensify these effects. One study claims that if temperatures in the Mediterranean area climb by 2 degrees Celsius, southern Spain will ultimately transform into a desert. Recent research indicates that under similar temperature conditions, up to 30% of the Earth's land area could experience "aridification," leading to a drying out of those regions. A projected 50 million individuals might be displaced by desertification by 2030, where two billion people already reside. >100 nations are at risk of desertification, which will disproportionately affect the most vulnerable and underdeveloped areas. >90% of the Earth's surface may be impacted by 2050, up from >75% at now, according to the Desertification Atlas published by the European Commission. According to the reports from the Commission's Joint Research Centre, an area equivalent to half the size of the European Union, measuring 1.61 million square miles or 4.18 million square kilometers, undergoes annual degradation. Africa and Asia bear the most significant impact, being the continent's most severely affected by this phenomenon.

Factors contributed to the land degradation (LD) differ depending on the area, and they frequently cross over. The Aral Sea is surrounded by Uzbekistan and Kazakhstan; excessive irrigation for agriculture has been a major contributor to the sea's shrinkage, leaving behind a salty desert. Population growth has brought about transformations in the Sahel region of Africa, situated between the Sahara Desert lies to the north, while savannas stretch to the south. 96 million hectares, or over 29%, of India's total land area, are being degraded. India lost 31% of its grassland area over a ten-year period, or 5.65 million hectares (mha), according to information recently provided by the government to the UNCCD. It is estimated that around 105 million hectares, or 32% of India's land, is about to degraded. Between 2003 and 2005 and 2011–2013, India's desertification levels increased in 26 of its 29 states. According to data from the atlas, between 2011 and 13 and 2018–19, desertification increased in 28 of the country's 31 states and union territories.

The largest danger to desertification, according to a Down to Earth article from 2021, is coming from the main green revolution crops of wheat and rice. The farmed area in India has been overtaken by desertification. Countries with pockets of the green revolution are suffering from the greatest threat of desertification caused by the primary green revolution crops. India's cultivated fields are suffering from desertification. Particularly vulnerable to the issue are the nation's Green Revolution pockets. The two primary Green Revolution crops, paddy and wheat, are the biggest threat to desertification. The fertility of the land had been destroyed in a few years by the dwarf wheat harvests of the Green Revolution. Food security and desert resilience are two paradoxical benefits that the dwarf crop varieties created during the Green Revolution may provide for mankind. They are particularly high fertiliser, chemical, and water consumers. The land is so extensively worked during the green revolution's agronomic operations that erosion and mortality are unavoidable. Land deterioration, soil erosion, and desertification are all related. Natural systems suffer from desertification as a result of soil erosion and land deterioration.

By putting a stop to desertification, the world stands the best opportunity of stabilizing the effects of CC. Government and people sharing responsibilities for sustainable land use (LU) Alternative agricultural and industrial methods provide business prospects outside of drylands, Agriculture that is sustainably produced, The frequent use of eco-forestry, recycling of paper, and Increasing awareness of desertification can help safeguard animal species and our well-being. The core objective of this research is to assess India's susceptibility to desertification and its future vulnerability in respect to CC. In this perspective, various parameters related to desertification vulnerability have been selected.

2. Materials and methodologies

2.1. Profile of the study area

The study region, India, is located in between $8^0 4'$N to $37^0 6'$N latitude and from 6807′E to $97^0 25'$ E by, covering 32, 87,263.21 sq. km area (Fig. 1). The significant geographic features include the Indian Ocean to the south, the Arabian Sea to the southwest, the Bay of Bengal to the southeast, and the mountainous region along with the Thar Desert to the west in the northern portion [22]. Additionally, Andaman, Nicobar, and Lakshadweep are included in the political zone. The area is more active and important due to its climatic characteristics. The country's western part is characterized by an arid and semi-arid climate, whereas the northern and north-east regions have a chilly climate with snowfall. However, the majority of the nation has a humid tropical and sub-humid tropical climate. Temperature range between 10 °C during the winter and 40 °C during the summer, and within this range, the average temperature undergoes. LD and a rise in desertification have occurred in this nation as a consequence of the diverse environment, geographic setting, CC, and human influence [23]. Being the second-most populous country in the world, primary industries are the foundation of its economy, and the entire society is facing a dire food security situation.

2.2. Sources of data

Different researchers have recently examined various types of datasets to demonstrate the vulnerability of desertification in India . For better computational efficiency and quantifying the desertification vulnerability, all the datasets and those associated with raster have been converted into the same spatial resolution. In an obvious process, the mathematical GIS platform is used, which can affect the standard of methodology [24]. For better understanding, the parameter can be divided into various categories such as topographical, hydrological, pedological and environmental. The selection of the causal parameters has been made with the help of the recent literatures related to desertification vulnerability. The detail about the methodology of this study is shown in Fig. 2

As topographical parameters, slope and elevation have been considered, and DEM with 12.5 mt resolution enriched us by providing the output of this study region. On the other hand, drainage density, annual mean temperature (AMT), annual precipitation (AP), humidity and evaporation can be considered in the section of hydrology. The 'mean annual temperature' is calculated by averaging the temperatures of the warmest and coldest days throughout the year. This involves determining the mean averages for both the hottest and coldest months and then comparing these values to arrive at the overall mean annual temperature. The mean annual temperatures are a helpful climatology metric for determining how CC affect a particular place. The amount of precipitation that falls each year (AP) is a major factor in desertification. Rainfall in areas prone to drought ranges from 750 mm to 1150 mm. By emphasizing the abrasiveness of the network and the equilibrium between the erosional potentiality of surface movement and the friction of soils and rocks makes drainage density more crucial for erosion control (Table 2 and Fig. 3).

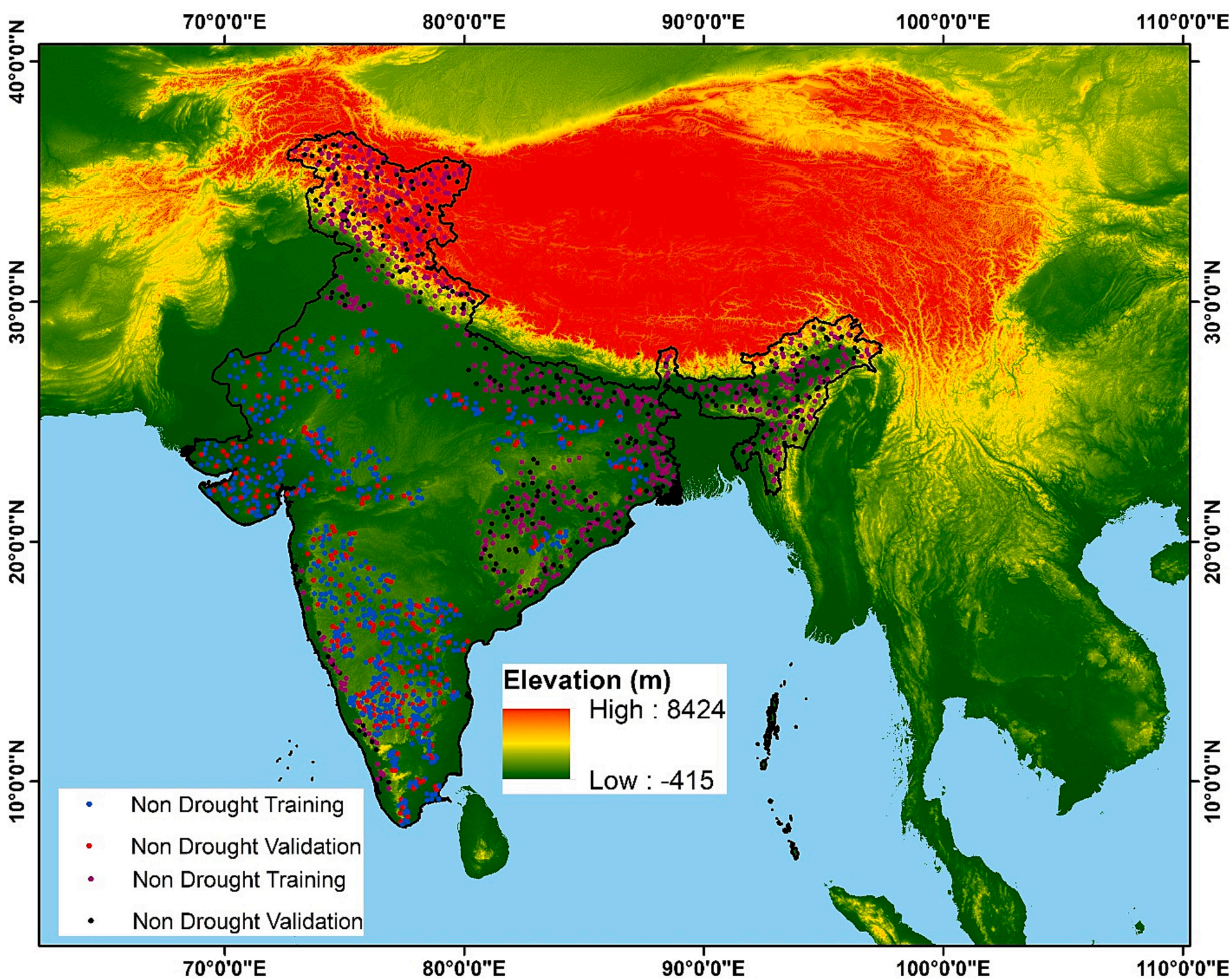

Fig. 1. Location of the study area.

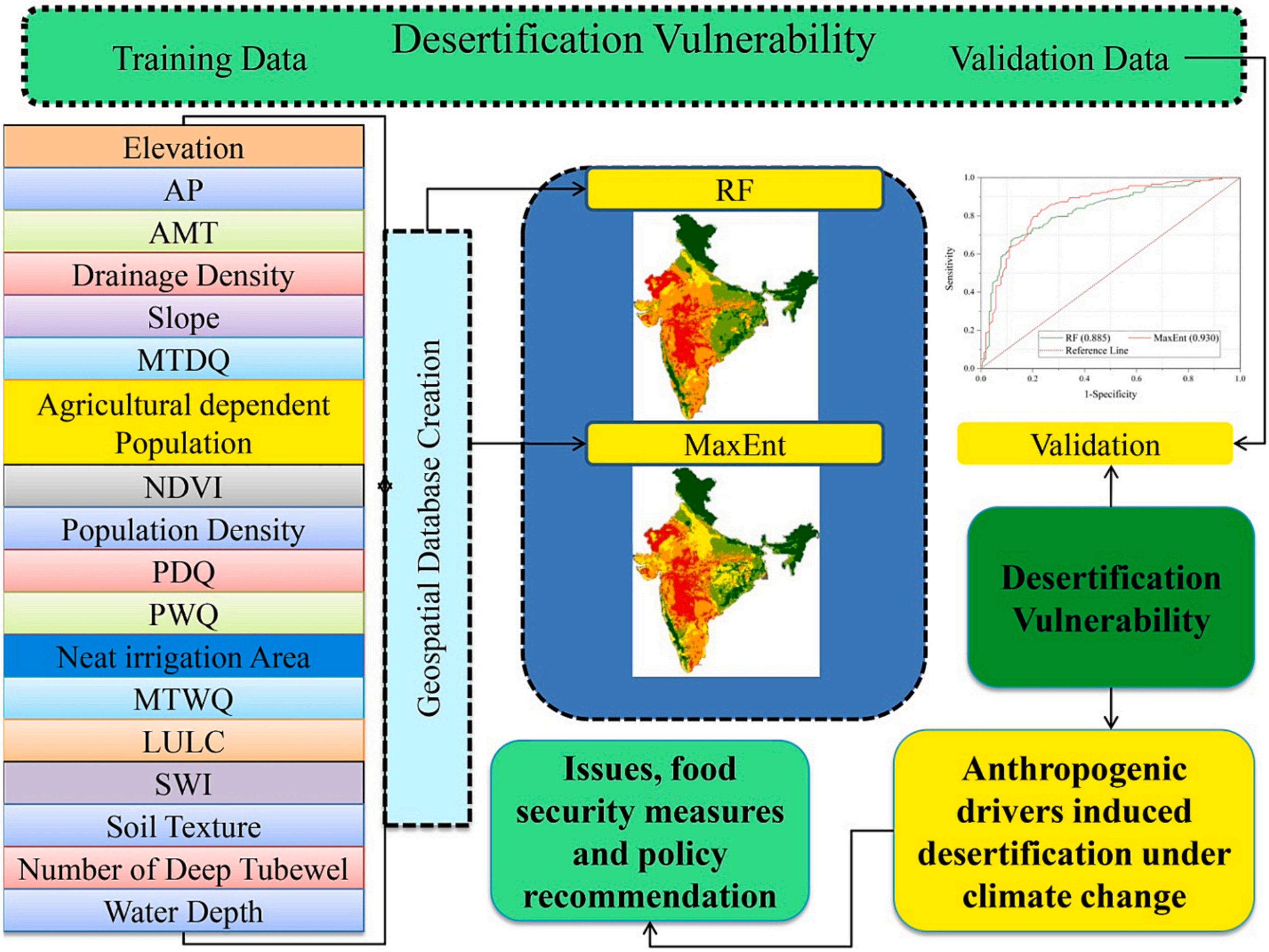

Fig. 2. Methodology flowchart.

The bio-climatic variables that also assisted in determining this region's susceptibility to desertification have been taken into consideration as another significant section: "MTDQ", "MTWM", "MTWQ", "PDM", "PDQ" and "PWQ" in addition, water depth showed the water-related issues. Water demands for people and the environment created the variance between the water condition and groundwater table. This drop condition would be a leader of desertification, which will differ geographically and individually. Droughts have occurred often over the past three to six years, and they can impact the net irrigation system, which is a significant contributor to desertification. Drought has been shown to have adverse effects on agricultural productivity and has resulted in a 20–40% yield reduction in rain-fed areas. Regarding science and commerce, the hydrological cycle's rainfall, with its temporal and spatial variation, is essential. In recent decades, there is evidence indicating that human activities can influence the circulation of weather patterns. The environment and society have been at risk due to catastrophic weather events linked to substantial changes in these patterns.

LULC is a significant contributor to CC on a micro-level, regional, and possibly global scale as well as over longer timescales (Jana et al., 2019; Varo et al., 2021; Sekac et al., 2022). LULC can be considered as representative environmental parameters, including both natural and anthropogenic factors. On the other side, increased water use is a result of population density, another social issue which eventually affects how dry the land is. This viewpoint can be determined in part by the growing population. Aquifers function as a better buffer during dry season than surface storage due to their enormous storage capacity and other factors, such as droughts and CCs, that impact them much a pace slower than the manner in which surface storage occurs. Due to the recent surge in groundwater demand in India, "groundwater consumption" will persist in upsurge due to CC, which will eventually lead to desertification.

The most crucial deciding factors for drought-like conditions across the globe are soil moisture and water-holding capacity, which are shown by soil texture under soil characteristics.

2.3. Methods

With the help of RF and MaxEnt model, along with various causative parameters, the vulnerability of desertification has been estimated. In this paper, potential effects on the nation's food security have been explored. Over the last several years, there has been a global increase in concern about how to mitigate the negative consequences that droughts have on the "environment, the society, and the economy". More precise assessments, the identification of, and the (spatial) development of focused alternatives are needed to minimize the danger of desertification. Currently, it is crucial to spread awareness about the elements contributing to desertification and its specific course. The results of a thorough evaluation of the literature on people-centred desertification vulnerability and risk ideas and assessment impacts have been given. After finding recurring gaps, we developed a thorough flowchart to standardize the process for assessing the region's susceptibility to desertification. In doing so, we acknowledged the variety or variety of methods used in exploration and application of learning, along with the

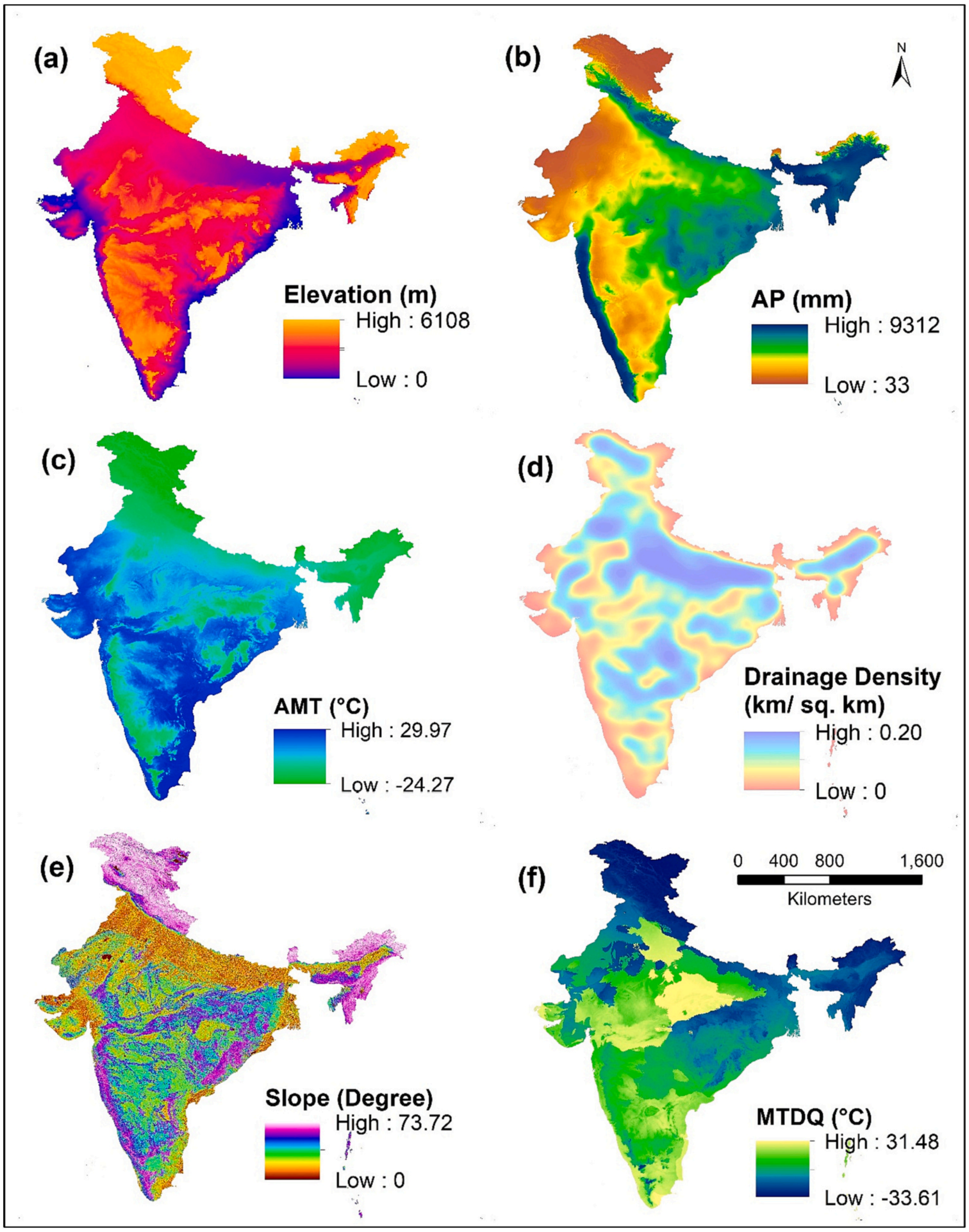

Fig. 3. Conditioning parameters.

challenges and possibilities they present in the context of India.

2.3.1. Maximum entropy model

According to Charrua et al., [25], Utility software that is written in Java. By combining existing information ("species presence/occurrence data with predictor parameters" that may be "continuous and/or categorical"), MaxEnt provides a framework of "habitat suitability" with the maximum entropy. Csiszár [26] explained that the theoretical principles of information theory and statistical ideas serve as the groundwork for MaxEnt. According to a number of studies and pieces of evidence, Shannon is the one who initially introduced the concept of entropy.

$$H(X) = E[1(X)] = E[-In(\widehat{\pi}(x))], \quad (1)$$

where, "I is the data content, and E is the expected amount of the representative components. The equation employs the negative natural logarithm to represent the probability allocation of the components."

According to the findings of Geyer and Thompson [27], entropy is subject to two constraints, akin to other probability functions. Initially, in accordance with a statistical principle, it is required to assign a "positive probability" for the occurrence of each x across all observable events. Nevertheless, the total sum of probabilities assigned to x must equal one. Two criteria have been modified and implemented in this context. Two criteria are changed and applied:

$$H(X) = -\sum_{x \in X} \widehat{\pi}(x) In\left(\widehat{\pi}(x).\right. \quad (2)$$

In reality, "The response variable (Y) for this research is given as a set of randomly selected locations (x) within a wider set (X), with the relevant qanat in each location. When certain qanats are present, Y = 1, but when they are not, Y = 0. MaxEnt uses a probability distribution P (x, y) or a conditional probability P (x | y) to produce data, while discriminative models learn using a probability distribution P (y | x)".

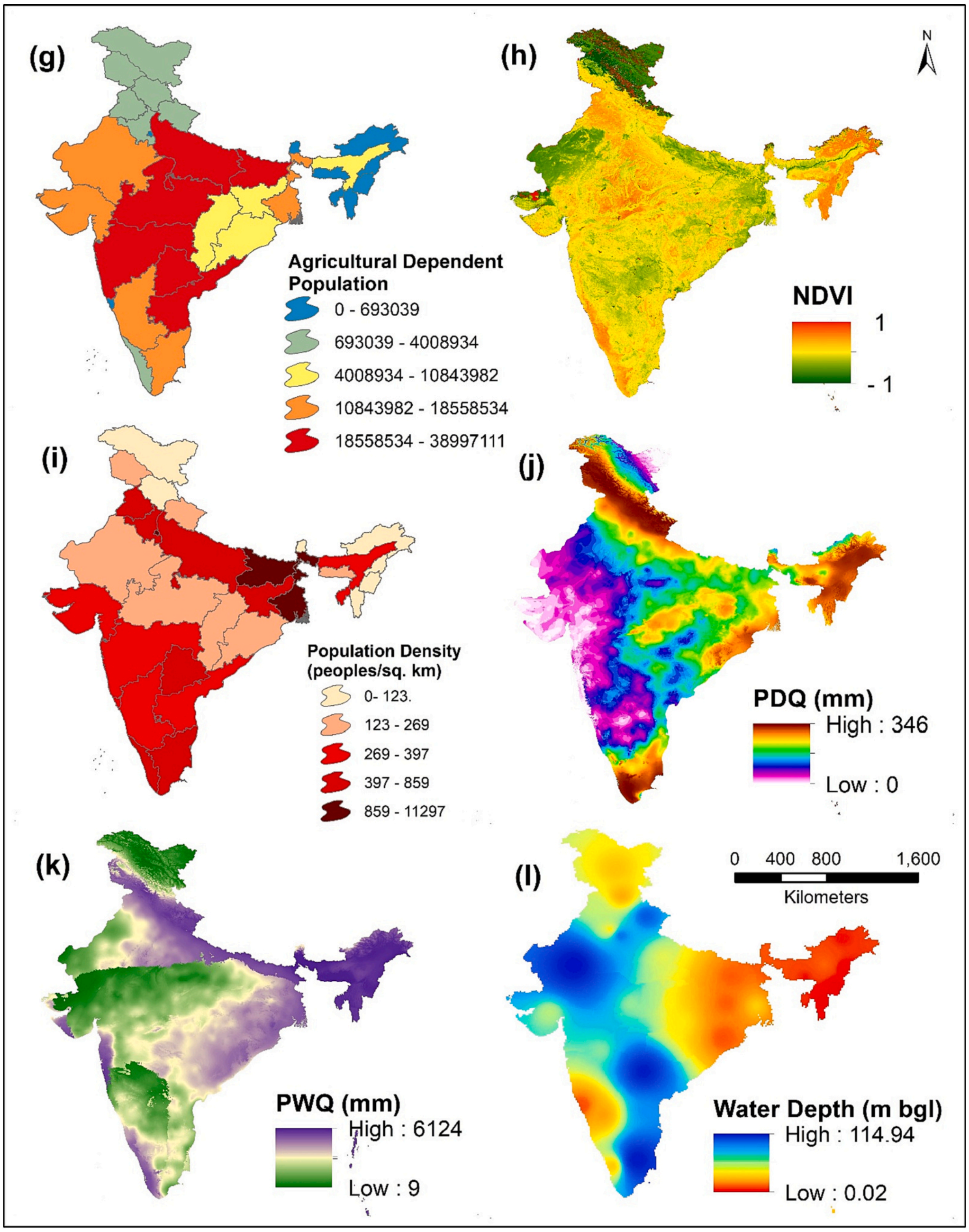

Fig. 3. (*continued*).

$$P(y = x \mid y) = \frac{P(1 \mid y = 1)P(y = 1)}{P(x)} \tag{3}$$

$P(x)$ represent the probability that site x will be selected, which is equivalent to (x) in the context of Maximum Entropy (MaxEnt). The probability $P(x)$ is defined as $1|X|$, where $|X|$ represents the total number of possible sites.

An alternative expression for this equation could be:

$$P(y = 1 \mid x) = \pi(x)P(y = 1)|\ X| \tag{4}$$

"By leveraging the probability distribution observed in generative models, we can redefine $P(x)$ using the following expression:

$$P(x) = \sum_y P(x \mid y) = P(x|y = 1)P(y = 1) + P(x|y = 0)P(y = 0). \tag{5}$$

If the "If both the probability the probability of absence and presence are equal (P (y =0) = P (y =1) = 0.5), then the equation may be used".

$$P(y = 1 \mid x) = \frac{P(x \mid y = 1)}{P(x \mid y = 1) + P(x \mid y = 0)} \tag{6}$$

2.3.2. RF (Random Forest)

According to Breiman et al., (1984), The term "RF" refers to an ensemble of CART that has been trained on datasets of equivalent size to the training set. By randomly resampling the training set, these datasets—recognized as bootstraps—are produced. After the tree has been constructed and evaluated, a set of bootstraps is used, eliminating any specific trace from the initial dataset ["out-of-bag (OOB) samples"]. The classification error rate across all test sets serves as the out-of-bag assessment of the generalization error. Applying a test set of a similar size as the training set yields the same OOB error for bagged classifiers, according to empirical evidence. Thus, employing the "OOB estimate" eliminates the necessity for a independent test set, as shown by Breiman

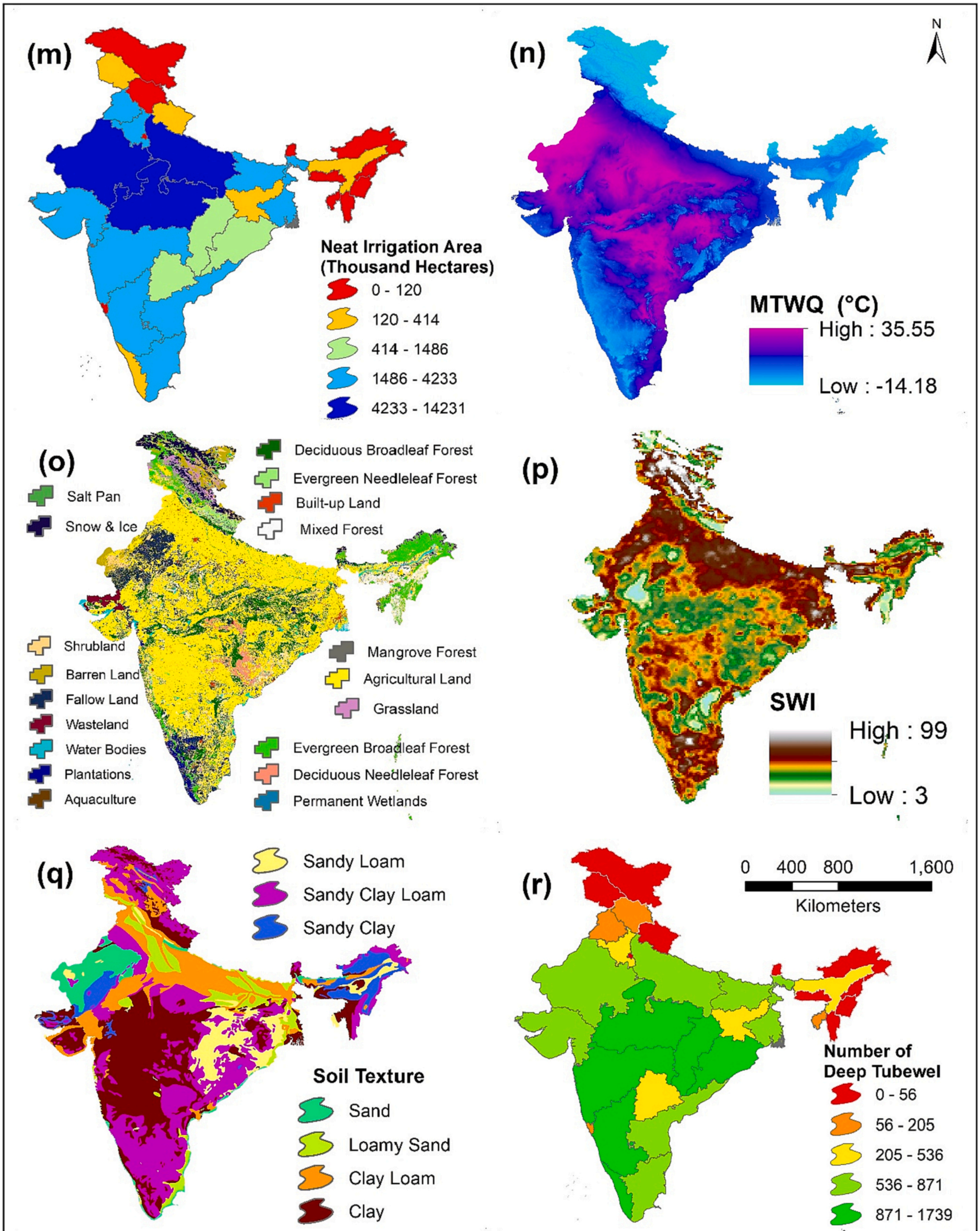

Fig. 3. (*continued*).

[29]. When comparing RF to other machine learning algorithms, it is clear that RF adheres to more stringent guidelines for "constructing trees, combining trees, self-testing, and post-processing". The expectation is that it will be more robust to overfitting and constant in the face of outliers in exceptionally "high-dimensional parameter" [30,31]. The "Gini impurity criteria index" is used in RF with a random

subspace approach to give the idea of variable relevance with implicit feature selection [32].

By apparently accommodating the level of forecast variability arising from bagged data for the components, the Random Forest (RF) seemed to anticipate the values of the components, whereas other methods have tended to be more predictable [33]. The RF requires two elements for updating: the number of trees and another unspecified element [34]:

$$GE = P_{x,y}(mg(x,y) < 0) \tag{7}$$

$$mg(x,y) = a_{vk}I(h_k(x) = y) - max_{j \neq k}av_kI(h_k(x) = j)) \tag{8}$$

The edge component of the indicator is mg and I, where x and y are flood causal parameters indicating the likelihood of x and y. [35].

2.3.3. Validation of the models

The “receiver operational characteristics-area under the curve (ROC-AUC)” test was used to examine and measure the learning outcomes of overall desertification. This statistical method is often applied to evaluate the validity of the susceptibility and risk model and is more effective at evaluating deterministic and probabilistic reasoning. The X and Y axes, also known as 1-specificity and sensitivity, are where the ROC is shown. AUC values close to or equal to 1 in the study of drought prediction show flawless model performance, whereas AUC values below 0.5 show subpar results. The AUC index, which is often used in numerous geospatial fields to evaluate model performance, describes the AUC-ROC curve. It is suggested that current machine learning applications of the AUC will improve the comprehension of interested readers. The following indicators were used to evaluate how well the results were predicted:

$$Sensitivity = \frac{TP}{TP + FN} \tag{9}$$

where “FN stands for a false negative and TP for a true positive”.

$$Specificity = \frac{TN}{FP + TN} \tag{10}$$

where “FP stands for a false positive and TN for a true negative”.

$$PPV = \frac{TP}{FP + TP} \tag{11}$$

where; “TP stands for true positive, FP for false positive, and PPV for positive predictive value”.

$$NPV = \frac{TN}{TN + FN} \tag{12}$$

where “TN stands for the true negative, FN for the false negative, and NPV for the negative predictive value”.

$$AUC = \frac{(\sum TP + \sum TN)}{(P + N)} \tag{3}$$

Where “P denotes the positive, N denotes the negative, TP denotes the true positive, TN denotes the true negative, and AUC is the area under the curve”.

$$F - Score = 2*\frac{Sensitivity*Specificity}{Sensitivity + Specificity} \tag{14}$$

“The F measure, or F score, is commonly employed to assess the effectiveness of a test. It represents the weighted harmonic mean of the test’s accuracy and recall.”

3. Desertification monitoring

3.1. Spatial distribution of desertification

The RF and MaxEnt models were used to determine the desertification’s geographical spread. According to the RF model, the country’s western, middle, and southern regions have very high, high, and moderate susceptibility to desertification. The remaining portion, primarily in this region’s northern, eastern, and north-eastern parts, is associated with minimal and reduced susceptibility to desertification (Fig. 4). The MaxEnt model indicates that the susceptibility to desertification is significantly elevated in the western, middle, and southern portions of the nation, with the eastern regions also displaying a relatively lower degree of susceptibility. The remainder of this area, mostly in the north, east, and northeast, has a very low sensitivity to desertification despite significant regional differences in the susceptibility of the two models to desertification.

In the RF model, the Area Under the Curve (AUC) values for the training and validation datasets are 0.885 and 0.870, respectively. In contrast, the Maximum Entropy model yields AUC values of 0.930 for the training set and 0.908 for the validation set (Fig. 5).

The predicted models were validated using various indices. The value of all statistical data considering training and validation datasets is shown in Table 1.

3.2. Changes in desertification intensity

According to Gibbs and Salmon, (2015), there are wide variations in current estimates of the severity and breadth of desertification because of missing and incorrect data. It is getting harder and harder to quantify desertification because of how diverse and complicated the processes are [37]. According to UNEP (1992), The widely accepted interpretation of “drylands” is constructed using the aridity index. Feng and Fu, 2013; Huang et al., 2016, pp. 1960–2013; Ji et al., 2015; Spinoni et al., 2015; Zarch et al., 2015 found that aridity has grown over the past several decades in many parts of the world, extending the size of certain drylands in the process. While not entirely in agreement with the aridity index, other classifications of climate types uses different ratios involving “temperature and precipitation,” such as Köppen-Trewartha and Köppen-Geiger, have been utilized to examine historical shifts in climatic zones. These ratios have also been employed to investigate alterations in past climatic zones. They also noticed a propensity towards drier climate types [41,43]. The increase of drylands does not necessarily signify desertification in the absence of sustained decline in biological production, ecological complexity, or human values of the “drylands”. There are still wide differences in the degree and severity of desertification both worldwide and regionally. Depending on the definitions used and the assessment methods utilized [44]. Professional judgement, satellite observations of “net primary production (NPP)”, the use of “biophysical models”, and an “inventory of abandoned land” were the four methodological tools utilized to assess the degree of desertification. Together they provide a reasonably thorough analysis, but none of them can adequately describe the issue on their own [36,45].

3.3. Factors influencing desertification

The primary causes of this worldwide threat have been recognized by several scholars throughout the world as the decline in natural vegetation (NV), climate conditions, and anthropogenic involvement [46,47]. According to [48,49] the most direct measures of desertification are the “normalised difference vegetation index (NDVI)”, albedo, and “net primary productivity (NPP)”. Under consideration, few aspects have contributed merely when the area under desertification is identified; it is understood that the graver situation for combining the process of the direct and indirect indicators of desertification [8]. Today’s academics are primarily focused on learning more about the different significant aspects (alike natural and artificial) and investigating their combined impact on soil erosion and desertification. Environmental sensitivity was used as a significant component of the “MEDALUS (Mediterranean Desertification and Land Use) Project”, which was launched in 1999 by Europeans engaged in environmental and climatic research to show how

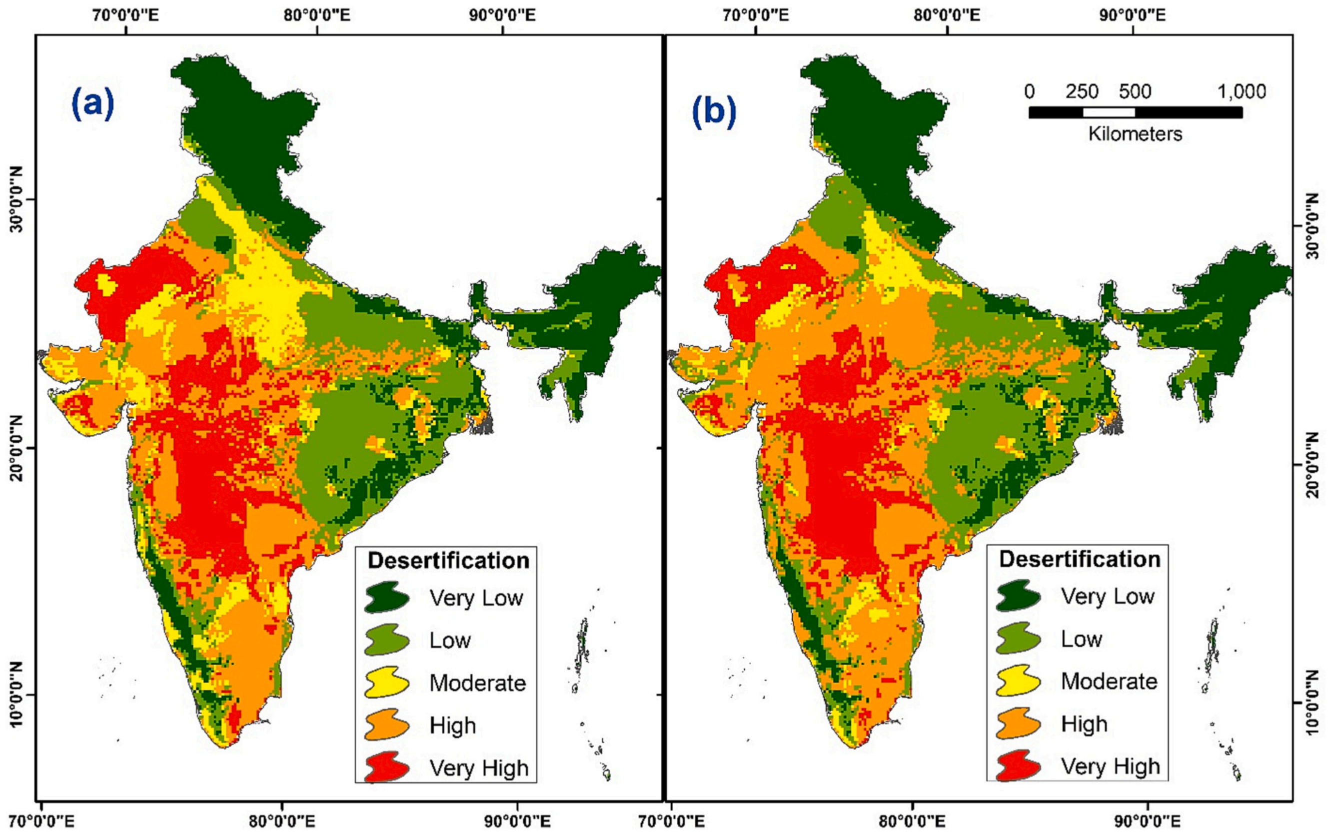

Fig. 4. Desertification vulnerability using RF (a) and MaxEnt (b) model.

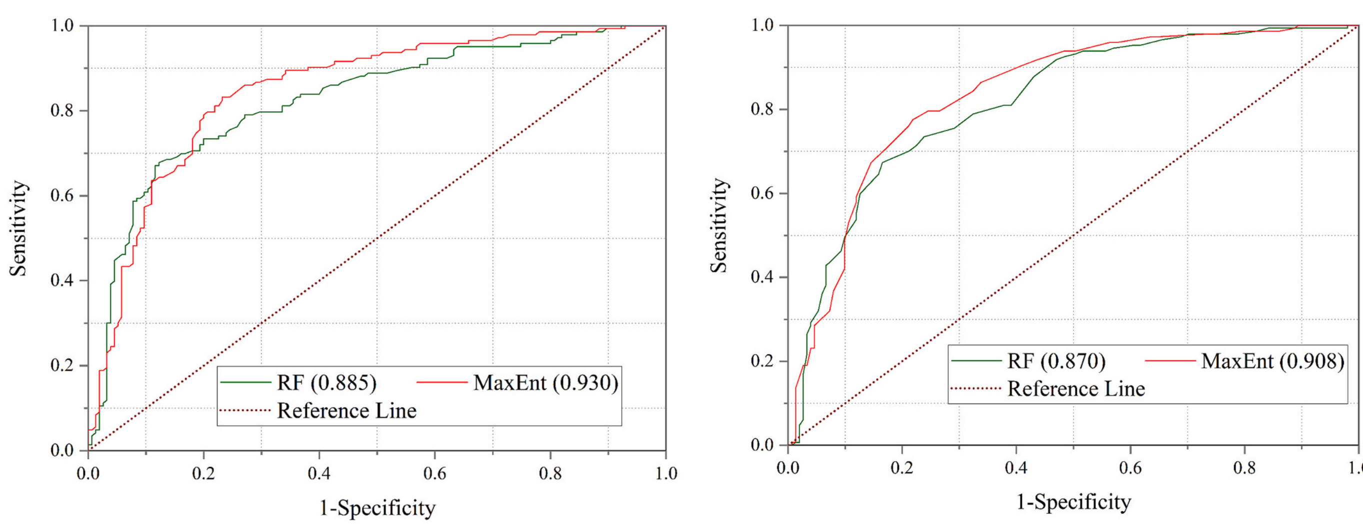

Fig. 5. Validation of the models using training (a) and validation (b) datasets.

the land is impacted by the appearance of these factors [50–52]. A thorough method of assessing desertification is made possible by the MEDALUS model's capacity to take into consideration a variety of meteorological, vegetal, and soil indicators in addition to human ones [53–57].

Changes in "vegetation, LULC contribute to both desertification and land degradation". The intricate interplay of the atmosphere, the thermodynamic process, and the land-earth surface determines the climate's equilibrium condition [58]. The LULCC offers a variety of coverage options. Natural catastrophes (like "floods, droughts, and landslides lead to soil erosion and the displacement of fertile soil"), "Wind erosion" (sand invasion by wind diminishes soil fertility, rendering the area prone to desertification), but man-made causes are also taken into consideration. Badland Topography is caused by water erosion and is itself an early stage of desertification. Between 2005 and 2015, India lost 31% of its grasslands to overgrazing and deforestation, which prevents trees from serving as carbon sinks and reduces land usage, productivity, and biodiversity. Deforestation adds to the greenhouse effect by releasing carbon dioxide into the atmosphere.

The vegetation exerts substantial influence on Earth's climate, hydrology, soils, and biota [59]. Any evaluation of the processes relating to CC must take into account LULC, which involves the conversion of land

Table 1
Multi-collinearity test.

Parameters	Multi-Collinearity	
	TOL	VIF
AMT	0.61	1.64
AP	0.26	3.85
Elevation	1.32	0.76
Slope	1.01	0.99
Drainage Density	0.37	2.70
MTDQ	0.61	1.64
MTWQ	0.41	2.44
PDQ	0.53	1.89
PWQ	0.19	5.26
Water Depth	0.28	3.57
Neat Irrigation Area	0.39	2.56
LULC	0.89	1.12
Soil Texture	0.99	1.01
Population Density	0.17	5.88
Number of Deep Tube Well	0.32	3.13
Agricultural Dependent Population	0.95	1.05
NDVI	0.28	3.57
Soil Water Index	0.77	1.30

surface. Cloud cover, numerous elements of the weather at both local and regional levels, and modifications to the structure of the planet's boundary layers are all impacted from the ground up [60]. The study of LULC instances is made possible by the use of land surface variables, such as soil moisture, as the atmosphere's lower boundary condition in numerical weather and "climate models". In this context, we thoroughly examined the effects of continuous desertification and LD in the Indian monsoon climatic region in this study.

3.4. Spatial distribution of desertification across various types of vegetation

Indian desertification is a harmful phenomenon that is presently in progress. Desertification has a negative influence on food production, in addition to the loss of biodiversity. Local LU habits and practices, as well as the topography in the area, have an impact on how much desertification is occurring. Karnataka is the state with the greatest terrain impacted by desertification, followed by Telangana and Andhra Pradesh. While desertification appears to have decreased by roughly 0.52% in Telangana due to land reclamation, it appears to have grown by 0.19% and 0.05% in Andhra Pradesh and Karnataka, respectively. In Andhra Pradesh, water erosion, vegetation degradation, and water logging are the main contributors to desertification, whereas in Karnataka, water erosion, vegetation degradation, and salinization are the main contributors. Excessive evaporation and minimal rainfall are the primary contributors to desertification in Karnataka. Mining activities and deforestation exacerbate the issue by leading to water erosion and an upsurge in soil salinity due to the absence of trees. There is a significant amount of desertification in the districts of Belgaum, Gulbarga, Tumkur, and Bijapur. The Bellary area has significant vegetative degradation as a result of increasing mining and wood exploitation.

3.5. Role of climate change in desertification process

Understanding that desertification is primarily a man-made problem that is worsened by CC is crucial. This is due to the fact that a rise in CC-related weather extremes, such as droughts and severe rains, would induce more soil degradation. Any event that modifies the climate system—from a volcanic eruption to a cycle in solar activity—is called a "climate system perturbed". This whole phrase is frequently viewed as the same as anthropogenic CC, where human activity causes the CC. The release of heat-trapping greenhouse gases into the air is a principal way to affect climate conditions.

Desertification is the deterioration of dry land caused by a variety of reasons, together with CC and "human activity". Following prolonged drought conditions and dry periods, drylands have recently tended to lose their biological and economic output. On all continents, drylands are now being harmed by inadequate irrigation, excessive grazing, overcultivation, and deforestation. Social, environmental, and economic reasons are often responsible for these sorts of overexploitation. Resource overexploitation is pushed by economic, environmental, and soil processes. On the other side, poverty is a direct or indirect result of desertification since the first resources to vanish in the face of desertification are healthy crops, greenery, and fertile soils. The lowest GDP per capita and the highest infant mortality rates may be found in dry regions all over the globe. In addition to causing environmental damage, poverty, migration, and warfare, LD also feeds a vicious cycle that often endangers the political stability of the affected countries and regions.

Although rainfall may have decreased over time due to CC, rain has been heavier. According to the IPCC assessment, the number of intense rain events in central India increased threefold between 1950 and 2015. This has affected a number of processes that lead to land deterioration, such as soil erosion. Desertification and CC interact strongly. Desertification damages rich soil and vegetation, which has an effect on CC. There is a lot of carbon in soils, and some of it might be released into the atmosphere due to desertification, which would have a big impact on the climate system of the world. The IPCC and its Impact published a 1500-page study in response to the UN Convention's findings on desertification. The IPCC has cautioned all nations to adopt a sustainable land management procedure to mitigate the effects of land degradation, CC, and desertification, according to a warning issued to countries.

In "Sub-Saharan Africa, South East Asia, Eastern Europe, and Latin America", agricultural land has replaced roughly 50 million hectares (ha) of forest since 2000. The volume of "greenhouse gases (GHG)" in the environment has reached a record level as wetlands are dried up, forests are used for agriculture, and natural grasslands are replaced with pastures. From 2007 to 2016, human actions led to a 13% increase in atmospheric carbon dioxide (CO_2), a 44% rise in methane, and an 82% elevation in nitrous oxide levels. In most places, desertification and land degradation are accelerated by global warming brought on by GHGs. Additionally, it is anticipated that when temperatures rise, agricultural yields will decrease in tropical and semi-tropical regions. Because dryland temperatures are twice the world average, some temperate dry land may soon become permanently dry.

The soil was more easily eroded by water when it was broken up. Changes in rainfall patterns can alter the composition and cover of the vegetation. This may very well be a significant factor in land deterioration on its own. Sea levels are rising everywhere due to CC, notably in tropical and subtropical areas. High salinity saltwater has been injected inland as a result of this procedure and the lack of water in rivers.

Table 2
Validation of the models.

Models	Stage	Parameters					
		Sensitivity	Specificity	PPV	NPV	F Score	AUC
RF	Training	0.92	0.87	0.87	0.95	0.89	0.885
	Validation	0.89	0.85	0.85	0.96	0.87	0.870
MaxEnt	Training	0.95	0.86	0.92	0.91	0.90	0.930
	Validation	0.94	0.82	0.91	0.92	0.88	0.908

4. Linkages between development and drivers of desertification

It would be quite fascinating to see how urbanisation and development connect to desertification if we were to consider desertification and changes in LU patterns. The factors that contribute to desertification are taken into account by the composite development index. The majority of desert-covered districts are regarded as undeveloped areas where inhabitants mostly engage in subsistence activities. Among the western dry region's decertified districts, Jodhpur, Nagar, and Jhunjunu are in better shape. It will be feasible to determine the optimal and suboptimal district conditions concerning development and desertification factors using the composite development index. Drivers who are less intense signify drivers who are in better physical and mental shape. The results of the spearman's correlation coefficient test demonstrate an inverse relationship between the factors driving desertification and development.

5. Discussions

5.1. Changes of LULC and desertification

To comprehend and analyze the desertification process in the arid regions of India, it is essential to have knowledge about the evolving land use patterns and rainfall [61]. One of the significant victims of desertification is the NV. Deterioration of NV and LULC alterations brought on by contemporary urbanisation are key factors in the process [62]. The forest area in western dry Rajastan (Churu, Jhunjunu and Sikar) is really in an alarming situation where most of the land has been converted from forest land to non-forest land for road, building and agricultural practices purposes. In this arid area, wind erosion of soil is a regular issue for agricultural fields that are ploughed by strong winds in the summer, stripping the land of its vegetative protection. Sand dunes change as a result of deforestation since trees provide natural protection, which makes the issue worse overall [63]. Such a dry region's tendency to redirect its already minimal forest area to other purposes might have major consequences that could hasten desertification and put further strain on already-stressed resources.

The arid and uncultivated region is also included as land in steep terrains. Because of their longevity and ability to grow extensive root systems, short grass and shrub vegetation safeguards the soil against soil erosion. Shifting them away or disappearing can increase the degradation and make the land waste or unused barren land. In many dry districts in India, the unproductive terrain is transformed into arable land to meet the increasing need for food. According to (UNEP, 2007), LD and excessive grazing on delicate soil are related. The accelerated conversion of rangelands and pastoral land systems into cropland, driven by rising demand for the limited available rangelands and unsustainable agricultural practices, contributes to the hastening of desertification [64]. Culturable wasteland is now used for cultivation purposes. The land that is not used for agriculture, was formerly used for cultivation but is no longer being utilized, or has been left uncultivated for five years may be fallow land with bushes and jungles that are not put to any use. Wastelands may be caused by inherent or imposed impairments, such as those caused by geography, climate, the characteristics and attributes of the soil, encompassing both its physical and chemical nature, monetary or managerial restrictions. Therefore, the land in this group is very susceptible to degrading [65]. A favourable sign from any variation would be the culturable wasteland. The primary factors contributing to desertification were mostly agricultural intensification. This then results in excessive groundwater withdrawal for irrigation, which lowers the water table in certain areas. More chances exist to take both adaptation and mitigation requirements into consideration as a result of changing practices in response to CC. There are several adaptation and mitigation strategies that can assist combat CC, but no one strategy is sufficient on its own. Integrated solutions that align mitigation and adaptation efforts with broader social objectives could enhance the effectiveness of implementation. This necessitates a focus on policies and collaborative efforts at every stage of the process. Incorporating CC into all elements of the planning process for LU can help mitigate climatic consequences such as floods, drought, water shortages, and heat stress, as well as lower the risk that these hazards would jeopardise valuable assets. Strategic LU planning may aid in the prevention and mitigation of other natural disasters, both climate-related and otherwise.

Effective desertification control requires a mix of preventative and restorative interventions. The resilience of the environment and the communities in impacted regions may be improved by implementing sustainable land-management practices, reforestation and afforestation programmes, and efficient water conservation and management measures. Additionally, the consequences of desertification can be lessened, and the sustainable use of natural resources (NR) can be supported through the restoration of degraded land and plant cover using soil and vegetation restoration techniques. Desertification must be avoided if we are to preserve the environment and maintain social stability. Tree planting may help rehabilitate damaged land and enhance the quality of the soil. By lowering erosion and boosting soil fertility, afforestation the growth of woods where none previously existed—can assist to lessen the consequences of desertification. Improved soil quality, lessened erosion, and increased biodiversity may all be achieved by using sustainable land-management techniques, including agroforestry, sustainable grazing, and conservation agriculture. Through increased agricultural production and the creation of new income-generating options, these practices can also help local communities economically.

5.2. Rising temperatures, along with reduced rainy days and desertification

The large irrigation potentiality is created by population growth and their growing demand for food security. Because of the volatility in absolute rainfall, precipitation intensity, and glacier melt brought on by CC, irrigation will be increasingly negatively impacted, leading to alternate irrigation and groundwater overdrafts. On the other hand, it can be said that the availability of water and its limit will be controlled by CC indirectly. Due to climate while, some states in the country are suffering from floods while others are facing acute water problems. Increased rainfall intensity, fewer rainy days, increased runoff, and glacier melt as a result of CC's effects on the hydrological cycle created the ideal conditions for drought. CC is mainly represented by reduced rainy days and rising temperatures. The ranges of average rainfall for the decades 1920–1970 and 1971–2021 are 258.148–3444.27 and 302.328–3397.31 mm, respectively. From various work and different data, it is clear that the amount of rainfall and rainy days is decreasing in various states of India while temperature abnormality is reaching its peak.

5.3. Alternative irrigation and groundwater overdraft intended desertification

Rainwater harvesting can be considered a national initiative in India. In order to maintain the groundwater recharge-related problem, many governmental and non-governmental organizations are studying it and trying to build new innovations to boost the movement of groundwater recharge in depleted areas; the most common way to replenish the groundwater table is using a percolation tank and pond. The construction of a percolation tank over a stream and the sinking of a permeability-rich land area aids in the percolation of surface runoff downward. In India, many methods were used in accordance with the various soil textures and water percolation capabilities. The govt. has given emphasis on the establishment of a percolation tank in Maharashtra. The awareness campaigns in Tamilnadu, Gujrat, and Maharastra are boosting the construction of percolation tanks by offering land. In dry regions, rocky land faces difficulties for construction, and sometimes the water table is unavailable. Ponds are filled with water in the monsoon period, but in recent times, due to insufficient rainfall and a decrease in rainy days, most of the ponds remain empty. To fulfil the huge population's food demand, the people are impulse to extract groundwater or search for substitute water sources for agriculture.

5.4. Growing population, desertification and sustainable development

Goal 15 of the 2030 Agenda for Sustainable Development (SD) calls for the preserve, restore, and encourage the sustainable utilization of terrestrial ecosystems; manage forests in a sustainable manner; combat desertification; and strive to both halt and reverse land degradation and biodiversity loss. The Future we require, it is acknowledged the economic and social importance of proper LU planning, particularly soil, and its contribution to the economy and social advancement. In this framework, Participating Countries voice their concern about the obstacles that desertification, LD, and drought pose to SD, especially for Africa, Least Developed Countries (LDCs), and Landlocked Developing Countries (LLDCs), the implementation of the "United Nations Convention to Combat Desertification (UNCCD)" along with its 10-Year Initiative and Strategy is crucial. Countries in these regions stress the importance of concerted efforts at the national, regional, and international levels to curb land degradation during the specified period (2008–2018). The significance of collaborations and efforts for preserving land resources, as well as the continued development and use of sensible, socially inclusive, scientifically based monitoring and assessment tools and indicators, is recognized and encouraged by Member States. Additionally, the UNCCD's attempts to develop the scientific foundation of actions to combat desertification and drought are discussed in relation to their importance. The Commission on SD explored combating desertification and droughts in multiple meetings. Regarding the interconnected concerns of Land, Agriculture, Rural Development, and Africa, CSD 16–17 concentrated on desertification and drought in 2008 and 2009, respectively, as part of the Committee's multi-year work agenda. According to its multi-year planning process, CSD-8's sectoral topic in 2000 was the coordinated development and management of land resources. The Commission on SD recognized the significance of addressing environmental sustainability through a comprehensive view, such as "ecosystem management". This was noted in its decision 8/3 on incorporated planning and oversight of land resources. Desserts are one of the delicate environments highlighted in Agenda 21 are the focal point of attention, with a specific emphasis on combating desertification and drought outlined in Chapter 12. Degradation of land in regions characterized by arid, semi-arid, and dry sub-humid climates because of a variety of reasons, such as CCs and human activity, is known as desertification. Being one of the world's largest geographical areas, 70% of its drylands and one-sixth of its people are all impacted by desertification. It causes a billion hectares of crops and rangeland to deteriorate, as well as massive poverty. In Chapter 10 of Agenda 21, the focus is on addressing the interconnected aspects of decision-making across various sectors to promote the sustainable management and utilization of natural resources. This encompasses elements like soils, minerals, water, and the diverse biota constituting the land. This chapter also addresses the coordinated planning and execution of natural assets. The foundation for Agenda 21's and the Commission on SD's study of land concerns is this comprehensive, integrated perspective on land resources, which are crucial for systems that sustain life and the ecosystem's ability to produce goods and services. Increasing economic activity and expanding human needs are exerting considerable pressure on land resources at a constantly increasing rate, leading to rivalry and conflict as well as less-than-ideal resource utilization. It is feasible to minimize disputes, achieve the optimal trade-offs, and connect socio-economic growth via nature conservation and improvement by looking at all LUs holistically, which aids in achieving the goals of SD. Desertification must be prevented effectively by both local management and broad-based policies that support the long-term viability of ecosystem services. Prioritizing prevention is optimal because efforts to restore desert regions are expensive and frequently yield subpar results. To stop, avoid, or reverse desertification, significant policy interventions and management paradigm shifts are required at both the local and global levels. When formulating policy decisions, it is essential to take into account the cost-effectiveness of prevention compared to rehabilitation efforts. When desertification is just getting started or is already well underway, drylands can be greatly protected by establishing a "culture of prevention" that encourages alternative lifestyles and conservation methods. Even after a piece of land has been damaged, restoration and rehabilitation efforts can assist in replacing lost ecological functions. The accessibility of infrastructure, funding, and human resources determines how well rehabilitation practices work. It necessitates the integration of various technologies and strategies and the close participation of regional communities. The main contribution of this research is that it can access the current status of desertification in India and project the potential impact of CC on desertification in the upcoming decade.

6. Conclusion

Environmentalists and soil scientists have recently encountered difficulties determining the exact scope of soil deterioration and its effects on the ecosystem. Today, managing soil resources—including those that are degraded—to supply food, fibre, and fuel for basic human requirements is a significant problem. As more data from remote sensing satellites that are pertinent to NR become available to academics and scientists, more improvements in cutting-edge database analytic systems should be achievable. People and planners must take immediate action to address the critical issue of LD and desertification in India's dry, arid areas. The high rate of population expansion depends on the use of the land for agriculture and other frequent LUs to meet the rising food demand in order to provide revenue and jobs. It won't be able to produce more food in the future to meet the requirements to leave a better legacy for future generations unless urgent action is made to stop the degradation process and restore the productivity of damaged soils. For the country's expanding population to have access to food, livelihoods, and environmental security, as well as biodiversity, it is essential to characterize fundamental resources, including soil, water, climate, and biodiversity. To prevent desertification due to human activities, there is an urgent need for policy intervention. The indices of desertification and LD would decline as a result of scientific understanding and methodical use of soil, characterization of fundamental resources including soil, water, climate, and biodiversity, and improvements in their distribution and efficiency. To attain the objectives of environmental security and the sustainability of human civilization, policymakers and the general public need advances in research and agricultural methods. This kind of research is very meaningful to the policy maker and decision maker to implement the outcome in the planning purpose. It should be considered for long-term planning taking into account the dynamic nature of the changing climate. Apart from this, the outcome of this research should be considered as a national-level database of the country in regard to desertification vulnerability. The limitation of this research is that the impact of CC has been assessed by considering the related components. The various sub-components have not been considered here. The essential responsibilities of the future scientist or researcher is to access desertification vulnerability considering the mentioned sub-parameters for a more optimal outcome.

CRediT authorship contribution statement

Subodh Chandra Pal: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Uday Chatterjee:** Investigation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Rabin Chakrabortty:** Investigation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Paramita Roy:** Investigation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Indrajit Chowdhuri:** Investigation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Asish Saha:** Investigation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Abu Reza Md. Towfiqul Islam:** Investigation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Edris Alam:** Investigation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Md Kamrul Islam:** Investigation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pdisas.2023.100303.

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