Journal of Chemical Health Risks

www.jchr.org

JCHR (2025) 15(6), 1508-1517 | ISSN:2251-6727

Evaluation of the Impact of Soil Salinity Level on Intraspecific Variability of Wood Specific Gravity of Five Tree Species (*Azadirachta indica; Tectona grandis; Tamarindus indica; Prosopis Cineraria* and *Mangifera indica*) in Arid and Semi-Arid Areas

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(Received: 27 September 2025 Revised: 05 October 2025 Accepted: 25 November 2025)

KEYWORDS

soil salinity, wood specific gravity, intraspecific variability, arid and semi-arid areas, biomass estimation, carbon stock.

ABSTRACT:

The present study evaluated the impact of soil salinity levels on the intraspecific variability of wood specific gravity (WSG) in five major tree species of arid and semi-arid regions: Azadirachta indica, Tectona grandis, Tamarindus indica, Prosopis cineraria, and Mangifera indica. Wood core samples were collected from juvenile and mature trees across three salinity gradients (moderately saline, highly saline, and very highly saline). Soil salinity significantly influenced WSG, with higher values generally recorded under increased salinity stress. Growth stage exerted the strongest effect, as mature trees consistently displayed higher WSG than juveniles. Among species, Tamarindus indica and Prosopis cineraria showed the highest densities, while Tectona grandis exhibited the lowest. The observed variability highlights species-specific adaptive responses to edaphic stress and underscores the importance of considering salinity when estimating biomass and carbon stocks. These findings provide new insights for reforestation, agroforestry planning, and climate mitigation strategies in salinity-prone ecosystems.

Abbreviations: WSG, wood specific gravity; JT, juvenile trees; MT, mature trees; DBH, diameter at breast height; EC, electrical conductivity; ANOVA, analysis of variance; USDA, United States Department of Agriculture; REDD+, Reducing Emissions from Deforestation and Forest Degradation.

Introduction

Soil salinization has emerged as a critical global environmental challenge, posing a profound and escalating threat to agricultural productivity, ecosystem stability, and global food security. A significant portion of the Earth’s surface, approximately 1.38 billion hectares, or 10.7% of global land, is affected by high soluble salt or exchangeable sodium concentrations. This issue is particularly pronounced in irrigated lands, where it impacts an estimated 33% of the total area (Banyal et al. 2017; Woods et al. 2020). Soil salinity, by its very nature, is a long-term stressor that forces a plant to reallocate resources to defensive and osmotic regulation mechanisms, such as the synthesis of osmo-protectants like proline. This continuous physiological burden can profoundly affect the formation of new wood cells (Singh et al. 2022).

Arid and semi-arid regions are disproportionately susceptible to this form of soil degradation, primarily due to climatic factors such as low precipitation and high evaporation rates, which facilitate the accumulation of salts in the upper soil layers. The problem is further compounded by anthropogenic factors, including inefficient irrigation practices, excessive groundwater extraction, and the overuse of synthetic fertilizers, which

contribute to the accumulation of salts in the soil profile (Banyal et al. 2017).

Wood specific gravity (WSG), commonly referred to as specific wood density, is a fundamental functional trait that significantly influences a tree's physiological performance, mechanical properties, and ecological adaptability (Sylvain, Narendra 2024; Ahmad, Rafeeq 2022). Two main sampling methods are predominantly used to collect wood samples for specific gravity estimation: the disk method and the increment core method (Meena et al. 2016; Sharma 2023). Early studies often adopted the disk method, which involves cutting cross-sections (disks) from the bole or branches at different heights. While this approach allows for comprehensive intra-tree analysis (radial or axial variations), it is destructive as it requires felling of trees or large branches. More recent investigations employ the increment core method, which uses increment borers to extract cylindrical wood cores from standing trees. This method is non-destructive and suitable for long-term monitoring of sample trees (Riki et al. 2019; Petrea et al. 2024).

Also, there are two main methods to evaluate Wood specific gravity of trees, the first one is the Gravimetric method set up by the Forest Products Laboratory of United States Department of Agriculture (USDA) in 1952, which uses a formula that divides the oven-dry weight by the green volume. The green volume can be found by either water displacement or by using a dimensional method. The second is the Maximum Moisture Content Method developed by Smith in 1954, which is more convenient as it doesn't require volume measurement. Instead, it uses the weight of both saturated and oven-dried wood samples. However, to avoid errors, it's crucial that the samples are properly saturated (Kutchartt et al. 2022; Petrea et al. 2024; Farias et al. 2023).

Environmental gradients such as soil type, land use, precipitation, and elevation directly influence the anatomical and functional characteristics of tree species, including WSG (George et al. 2019; Gazol et al. 2023; Pati et al. 2022). Trees in arid regions characterized by low rainfall, high evapotranspiration, and poor soil fertility often develop higher wood density as an adaptive trait for hydraulic safety and structural strength (Farias et al. 2023; Clough et al. 2017). In contrast, species in moist or nutrient-rich environments may exhibit lower WSG due to trade-offs favouring rapid growth (Rosner 2017; Li et al. 2024). Several studies have demonstrated the influence of salinity level on the variability of wood specific gravity in mangrove ecosystems. Chowdhury et al. (2024) investigates the impact of salinity on the wood density in the mangrove ecosystem of the Sundarbans. Specifically, the document presents findings on wood density variation across different salinity zones (low, medium, and high). The research suggests a relationship between salinity levels and WSG, as it states that a "Salinity zone" affects the radial wood density variation.

However, limited research has examined its influence on Wood Specific Gravity of trees in arid and semi-arid environments. Meghwal (2020) states that the physical, chemical, and mechanical properties of wood, including wood density in the Jhalawar District, Rajasthan, India (aride and semi-arid area) are subject to inter-species and intra-species variability. He also state that chemical composition of wood can also vary based on the tree part, type of wood, geographic location, climate, and soil conditions.

Several studies in last decade shows that woody species like *Azadirachta indica, Prosopis cineraria, Acacia nilotica, Tectona grandis, Tamarindus Indica* and *Mangifera indica* etc… are among the most important trees species in Arid and Semi-Arid areas due to their resilience and economic value (Arya et al. 2017; Bhagat et al. 2021; Dhamsaniya et al. 2024; Forest Survey Of India 2023; Maisuria et al. 2022; Sadhu et al. 2022).

Some species in the literature have benefited from an assessment of salinity conditions on their growth conditions and biomass.

Singh et al. (2022) confirms that soil salinity and waterlogging have a differential impact on Eucalyptus growth. In his research, a decrease in soil Electrical Conductivity (E.C.) was associated with an increase in tree survival rate, girth, height, and biomass. However, no study has yet been carried out on the influence of salinity level on Intraspecific Variability of Wood Specific Gravity of the giving important Species in Arid and Semi-Arid Area: *Azadirachta indica; Tectona grandis; Tamarindus indica; Prosopis Cineraria* and *Mangifera indica*.

Given this backdrop, the study has been carried out in Patan District in North Gujarat, India which represent an Arid and semi-arid environment, varied soil types with different level of Salinity, and abundance of trees species (*Azadirachta indica; Tectona grandis; Tamarindus indica; Prosopis Cineraria* and *Mangifera indica*) in agricultural, urban and rural settings. Understanding how salinity level influences the specific wood density of dominant woody species in arid and semi-arid region is vital for improving the accuracy of local, regional, national and international biomass and carbon stocks estimation, informing tree-based climate mitigation strategies under the mechanism like REDD+ (Reducing Emissions from Deforestation and Forest Degradation, with conservation, sustainable management of forests and enhancement of forest carbon stocks).

Methodology

Description of Study area

Situated in the northwestern part of Gujarat, India, Patan District spans an estimated 5,600 square kilometers and lies between latitudes 20°41'–23°55' N and longitudes 71°31'–72°20' E (Figure 1). It shares borders with several key regions: to the northwest lies the Rann of Kutch, while Banaskantha and Palanpur border it to the northeast, Mehsana to the southeast, and Surendranagar to the south (Dadhich et al. 2017).

The region is predominantly rural, comprising around 517 villages across eight administrative divisions (talukas). Agricultural activity is extensive, with nearly 3,910 km² dedicated to net sown area and about 4,860 km² under gross cultivation. Irrigation covers a significant portion of the district, with 1,330 km² of net irrigated land and 1,450 km² gross irrigated (Dadhich et al. 2017).

Climatically, Patan experiences semi-arid conditions marked by high evaporation rates, variable precipitation, and elevated temperatures. Historical climate records (1982–2011) show an average annual rainfall of roughly 539 mm. These conditions pose several agricultural challenges, including recurring droughts, irregular rainfall, salinity intrusion, and the degradation of soil and water resources (Dadhich et al. 2017).

Soil characteristics vary across the district. While the general pH level is neutral, some parts particularly in the Santalpur and Sami talukas near the Kutch region exhibit saline soils. The area's soil shows medium electrical conductivity, low organic carbon, and a mix of nutrient levels: nitrogen is generally low, phosphorus is moderate, and potassium content is high. Despite these constraints, the district's soils maintain satisfactory fertility for crop production (Dadhich et al. 2017).

Data collection

Soil Salinity map of the Study Area

The salinity map in Figure 2 of Patan District setting up by (Dadhich et al. 2017) was used. It was obtained by combining remote sensing, GIS techniques and soil laboratory data. Satellite images from IRS P6 LISS-III were first used to prepare the land use and base maps of the area. Soil salinity values, measured as electrical conductivity (EC in dS/m), were collected from the Soil Testing Laboratory in Gandhinagar along with supporting information from the State Water Data Centre in Gandhinagar. These salinity values were then classified according to FAO and NBSS–LUP standards into four categories: less saline when EC was below 4 dS/m, moderately saline when EC ranged between 4 and 6 dS/m, highly saline when EC ranged between 6 and 10 dS/m, and poor or unsuitable when EC exceeded 10 dS/m. Using GIS, the data were spatially interpolated and integrated with other thematic layers to generate a continuous surface showing the distribution of salinity across the district. The resulting map revealed that areas near the Rann of Kutch are highly saline, while other regions of Patan showed moderate or poor salinity conditions. This integration of laboratory-measured soil data with spatial analysis allowed the production of a detailed salinity map for land suitability evaluation.

Sampling Methods and Experimental Design

In this study, the simple random experimental design was used. The simple complete random sampling method was used. The selection was done randomly by the method of slips of paper in a basket. The Talukas were randomly selected according to their salinity level on the map. When the talukas having the same salinity level were randomly selected and when the sampling size of a given salinity level was reached, the paper was returned into the basket and the operation was repeated until all the Talukas representative of the total salinity level

(moderately saline, highly saline and poor) in the Patan District were reached.

The Talukas (08) of Patan district have been classified in Table 1 according to the soil salinity levels appearing on the map. Moderately saline soils include Vagdod, Siddhpur, Chanasma and Patan district, highly saline soil include Radhanpur and Santalpur while very highly saline soils (poor) include Harij and Sami Talukas.

Siddhpur, Harij, Radhanpur and Santalpur were the talukas where wood samples of different species were collected as they are representative of the study area (four out of eight talukas, 50%) and cover the entire salinity variability gradients in the study area (Table 2). Trees has been classified into two distinct categories: Juvenile Trees (JT) with the Diameter at breast height (DBH) lower than 30 cm (DBH≤ 30 cm) and Mature Trees (MT) with the diameter greater than 30 cm (DBH ≥30 cm). Five (5) samples consisting of wood cores taken at the trunk level at breast height (DBH = 1.30 m) of each tree at different stages of development (Young and Mature) and for each species (*Azadirachta indica*, *Tectona grandis*, *Tamarindus indica*, *Prosopis Cineraria* and *Mangifera indica*) were chosen within each Talukas. A total of 10 wood core samples per species and 50 samples for all species were taken from each Talukas randomly selected, making a total of 200 wood samples for the entire study area.

Core sample collection

In this study, increment core method were used where the different samples of wood cores of the different tree's species were taken at chest height (Sharma 2023).

Statistical Analysis

Moisture content

Moisture content was calculated using the following formula (McMillen 1956):

$$\text{Moisture Content} = \left(\frac{\text{Original Weight}}{\text{Oven dry weight}} - 1\right) \times 100 \qquad (1)$$

Wood specific density evaluation

In this study, the maximum Moisture Content Method (Smith 1954):

$$Gf = 1 / ((Mm - Mo)/Mo + 1/Gso) \qquad (2)$$

Where, Gf = Wood specific Gravity; Mm = saturated weight, Mo = oven-dry weight, and Gso (specific gravity of the cell wall substance also called the true density of wood substance) = 1.53. This method is convenient but requires proper saturation to avoid errors.

Evaluation of Intraspecific variability of Wood Specific Gravity of trees

To Compare the Intraspecific variability of wood specific density of the different trees species, the Analysis of Variance (ANOVA) was performed from the Simple complete randomized design where the treatments (independent variables) were the different level of soil salinity.

Results

The distribution of wood specific gravity (WSG) values was first assessed for normality using the Shapiro–Wilk test. Most subgroups (species × stage × salinity) did not significantly deviate from normality ($p > 0.05$), with only a few minor departures observed in small samples. Levene's test for homogeneity of variances was also non-significant ($W = 1.24$, $p = 0.204$), confirming that the assumptions for ANOVA were met.

In Table 3, A two-way ANOVA (Growth Stage × Salinity level) showed a highly significant main effect of Growth Stage ($F_{1,194} = 104.51$, $p < 0.001$, $\eta^2 = 0.29$), indicating a consistent increase in WSG from juvenile to mature trees. A significant effect of Salinity was also found ($F_{2,194} = 30.31$, $p < 0.001$, $\eta^2 = 0.07$), although weaker in magnitude compared to growth stage. In contrast, the interaction between Stage and Salinity was not significant ($F_{2,194} = 0.02$, $p = 0.981$, $\eta^2 \approx 0.00$), suggesting that the stage-related increase in WSG occurred uniformly across salinity levels.

The results on wood specific gravity (WSG) of the five studied species were presented by considering both growth stage (juvenile and mature) and soil salinity level (very highly saline, highly saline, and moderately saline) in Table 3.

Across all species, WSG consistently increased from the juvenile to the mature stage, confirming that wood density becomes higher as trees age. *Azadirachta indica* increased from 0.68 ± 0.03 (juvenile, very highly saline) to 0.83 ± 0.11 (mature, very highly saline), while *Tamarindus indica* increased from 0.69 ± 0.04 to 0.87 ±

0.07 under the same conditions. *Prosopis cineraria* followed a similar pattern, with values rising from 0.68 ± 0.03 to 0.84 ± 0.01.

When averaged across species, juvenile trees recorded mean WSG values of approximately 0.62 in very highly saline soils, 0.55 in highly saline soils, and 0.50 in moderately saline soils. Mature trees showed significantly higher means of 0.78, 0.68, and 0.64 for the respective salinity levels. These differences were statistically confirmed: upper case superscripts within rows indicate significant differences ($p < 0.05$) between growth stages for the same salinity level, whereas uppercase superscripts within columns indicate significant differences ($p < 0.05$) among salinity levels for the same growth stage.

Intraspecific variability was evident in the relatively wide standard errors observed for some species, particularly at the mature stage. *Tectona grandis* displayed a mature WSG of 0.62 ± 0.09 under very highly saline conditions, showing greater variability compared to *Prosopis cineraria* (0.84 ± 0.01) or *Mangifera indica* (0.65 ± 0.01) under the same salinity level. This suggests that certain species are more phenotypically plastic and potentially more responsive to micro-environmental conditions.

Species-wise comparison revealed that *Tamarindus indica* and *Prosopis cineraria* exhibited the highest mean WSG values at both growth stages, whereas *Tectona grandis* consistently showed the lowest values (mature WSG ranging between 0.50–0.62). One-way ANOVA followed by Tukey's post hoc test confirmed that these interspecific and intraspecific differences were statistically significant ($p < 0.05$).

Taken together, the statistical analysis confirmed that both growth stage and soil salinity had significant main effects on WSG, and their interaction further influenced wood density variation across species. The presence of distinct superscript letters in the table reinforces that the observed differences are not random but statistically supported. The observed intraspecific variability indicates that some species, particularly *Tectona grandis* and *Mangifera indica*, show a wider range of WSG responses within the same salinity class.

Discussions

The present study provides new insights into the influence of soil salinity gradients on the intraspecific variability of wood specific gravity (WSG) in five key arid and semi-arid tree species: *Azadirachta indica*, *Tectona grandis*, *Tamarindus indica*, *Prosopis cineraria*, and *Mangifera indica*. The results confirmed that WSG significantly increased with tree maturity, in line with previous reports that link ontogenetic development to changes in wood density (Bhat 2000; Bhat, Priya 2004). More importantly, our findings also revealed a measurable effect of soil salinity on WSG, suggesting that salinity stress exerts selective pressure on wood structural traits.

The observed salinity-related variability is consistent with studies in other ecosystems. For instance, Chowdhury et al. (2024) reported that salinity zones in the Sundarbans mangrove forests induced significant radial variation in wood density. Similarly, Singh et al. (2022) demonstrated that reductions in soil electrical conductivity enhanced tree survival and growth in *Eucalyptus*, highlighting the negative impact of salinity on biomass accumulation. Our findings extend this evidence by showing that even in inland arid and semi-arid regions, salinity exerts a quantifiable influence on the structural properties of wood.

When comparing WSG values across species, our results align with previously reported ranges. *Azadirachta indica* in our study displayed mean WSG values comparable to those found in Tamil Nadu (0.778 ± 0.015) by Sundarapandian et al. (2014) and in Rajasthan (0.711) by Meghwal et al. (2020), although slightly higher than values reported from Uttar Pradesh (0.646) by Chavan (2016). Similarly, *Mangifera indica* showed moderate WSG values, consistent with records from Lucknow (0.6) by Kushwaha (2022) and Kerala (0.53) by Shanavas and Kumar (2003). *Tectona grandis* exhibited a broad WSG range (0.56–0.68), which parallels findings across multiple zones (Bhat 2000; Thulasidas, Bhat 2012; Sundarapandian et al. 2014). These comparisons indicate that while genetic and environmental factors co-determine wood density, salinity may amplify the natural intra-species variation already documented in the literature.

The ecological implications of these findings are twofold. First, increased WSG under higher salinity can be interpreted as an adaptive strategy for enhancing hydraulic safety and mechanical strength in stressed environments (Clough et al. 2017; Farias et al. 2023). Second, salinity-induced variability complicates biomass and carbon stock estimations. Rahman et al. (2015) demonstrated that strong salinity zones in mangrove forests reduce above-ground carbon stock, while enhancing below-ground storage. In inland arid systems, similar shifts may affect carbon allocation patterns and, consequently, the accuracy of REDD+ monitoring frameworks.

It is noteworthy that the growth stage exerted a stronger effect on WSG than salinity in this study. This suggests that while salinity imposes stress-mediated modifications, intrinsic developmental processes remain the dominant drivers of wood density. Such interactions between ontogeny and environment echo the findings of Meghwal (2020), who observed inter- and intra-specific variability in wood quality parameters shaped simultaneously by soil conditions and tree age.

Conclusion

This study demonstrates that soil salinity exerts a significant influence on the intraspecific variability of wood specific gravity (WSG) among five key tree species in arid and semi-arid environments. Although tree growth stage emerged as the primary determinant of wood density, salinity imposed additional stress-mediated variations that cannot be overlooked. Elevated WSG under higher salinity conditions suggests an adaptive strategy for hydraulic safety and structural resilience. However, this variability complicates accurate biomass and carbon stock estimations, which are essential for forest management and climate mitigation initiatives such as REDD+. Future research should focus on radial and axial variations within trees, while also integrating other environmental factors, to better elucidate the combined effects of ontogeny and edaphic stressors on wood traits.

Acknowledgement

The author gratefully acknowledges the Department of Environmental Sciences, Gokul Global University, Sidhpur (Patan), India, for providing infrastructural and academic support during this research. Authors have declared that no competing interests exist.

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Tables

Table 1: Overview of the Level of soil salinity of each Talukas based on the thematic maps

Talukas	Level of Salinity
Vagdod	Moderately Saline
Siddhpur	
Chanasma	
Patan	
Harij	Poor (Very highly saline)
Sami	
Radhanpur	Highly Saline
Santalpur	

Table 2: Trees sample size (N=200)

Talukas	*Azadirachta indica*		*Tectona grandis*		*Tamarindus indica*		*Prosopis Cineraria*		*Mangifera indica*	
	JT	MT	JT	MT	JT	MT	JT	MT	JT	MT
Siddhpur	5	5	5	5	5	5	5	5	5	5
Harij	5	5	5	5	5	5	5	5	5	5
Radhanpur	5	5	5	5	5	5	5	5	5	5
Santalpur	5	5	5	5	5	5	5	5	5	5

JT=Juvenile Trees; MTrees= Mature wood

Table 3. Wood specific gravity (WSG) of five tree species across growth stages (Juvenile, Mature) and soil salinity levels.Data are means ± SE. Different uppercase superscripts within rows indicate significant differences ($p < 0.05$) between growth stages. Different uppercase superscripts within columns indicate significant differences ($p < 0.05$) among salinity levels.

Species	**Growth Stage**	**Very Highly saline**	**Highly saline**	**Moderately saline**
Azadirachta indica	Juvenile	0.68 ± 0.03^{a}	0.60 ± 0.01^{bb}	0.56 ± 0.01^{abc}
	Mature	0.83 ± 0.11^{aa}	0.74 ± 0.03^{abb}	0.71 ± 0.01^{feg}
Tectona grandis	Juvenile	0.48 ± 0.06^{b}	0.41 ± 0.03^{bc}	0.36 ± 0.01^{bcd}
	Mature	0.62 ± 0.09^{bb}	0.54 ± 0.01^{bcc}	0.50 ± 0.11^{cdf}
Tamarindus indica	Juvenile	0.69 ± 0.04^{c}	0.61 ± 0.02^{cd}	0.57 ± 0.03^{e}
	Mature	0.87 ± 0.07^{cc}	0.79 ± 0.10^{cdd}	0.75 ± 0.14^{def}
Prosopis cineraria	Juvenile	0.68 ± 0.03^{d}	0.60 ± 0.01^{de}	0.55 ± 0.02^{e}
	Mature	0.84 ± 0.01^{dd}	0.76 ± 0.01^{def}	0.72 ± 0.07^{feg}
Mangifera indica	Juvenile	0.59 ± 0.01^{e}	0.51 ± 0.04^{ef}	0.47 ± 0.01^{efg}
	Mature	0.65 ± 0.01^{ee}	0.58 ± 0.08^{eff}	0.52 ± 0.06^{ef}

Figures

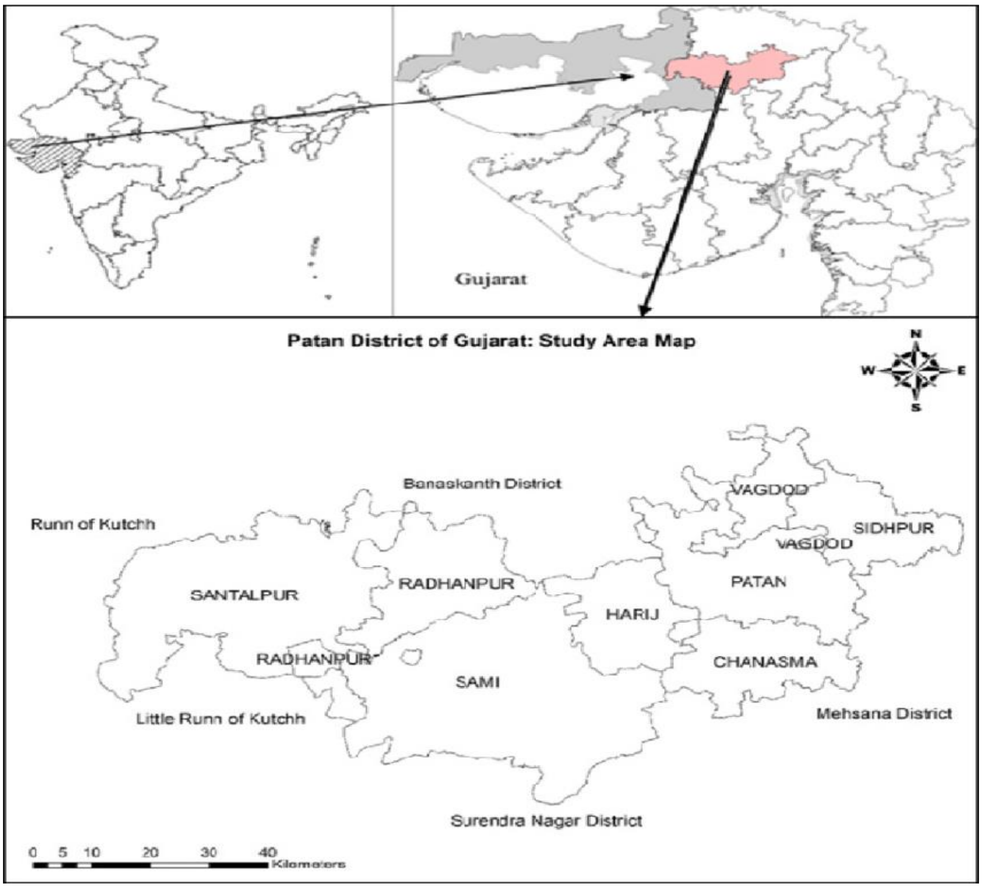

Figure 1: Study area map (Dadhich et al. 2017)

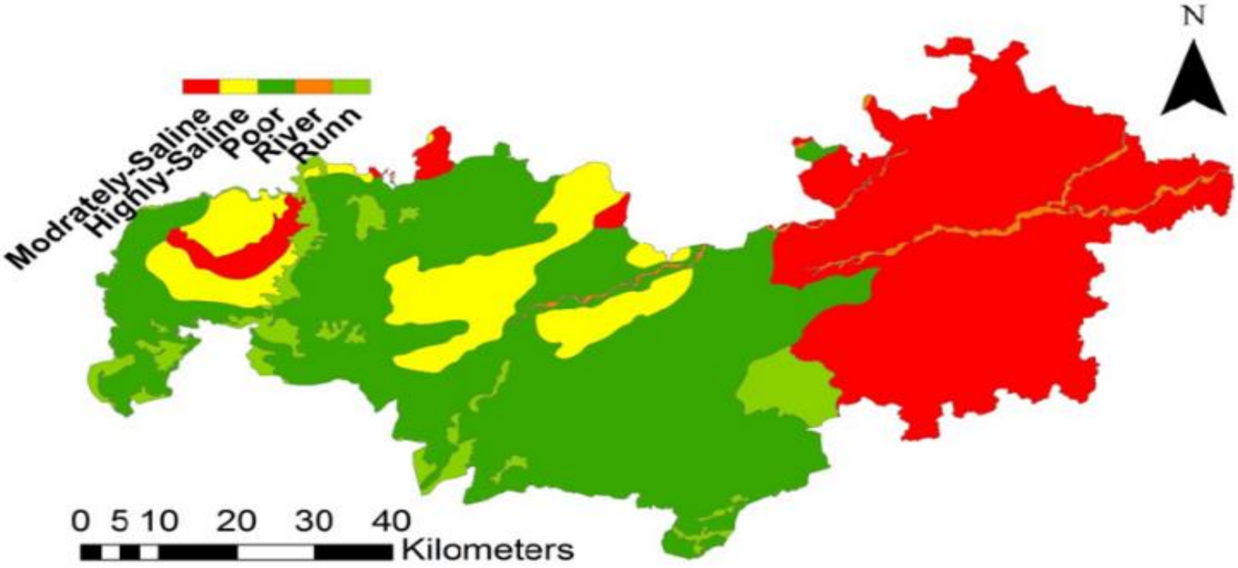

Figure 2: Soil salinity map of study area (Dadhich et al. 2017).