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Performance Analysis and Soil Quality Indexing for *Dalbergia sissoo* Roxb. Grown in Marginal and Degraded Land of Eastern Uttar Pradesh, India

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Abstract: The successful utilization of marginal and degraded lands for biomass and bioenergy production depends upon various factors such as climatic conditions, the adaptive traits of the tree species and their growth rate and respective belowground responses. The present study was undertaken to evaluate the growth performance of a bioenergy tree (*Dalbergia sissoo* Roxb.) grown in marginal and degraded land of the Mirzapur district of Uttar Pradesh, India and to analyze the effect of *D. sissoo* plantations on soil quality improvement over the study years. For this, a soil quality index (SQI) was developed based on principal component analysis (PCA) to understand the effect of *D. sissoo* plantations on belowground responses. PCA results showed that among the studied soil variables, bulk density (BD), moisture content (MC), microbial biomass carbon (MBC) and soil urease activity (SUA) are the key variables critically influencing the growth of *D. sissoo*. The SQI was found in an increasing order with the growth period of *D. sissoo*. (i.e., from 0.419 during the first year to 0.579 in the fourth year). A strong correlation was also observed between the growth attributes (diameter at breast height, $R^2 = 0.870$; and plant height, $R^2 = 0.861$) and the soil quality ($p < 0.01$). Therefore, the developed SQI can be used as key indicator for monitoring the restoration potential of *D. sissoo* growing in marginal and degraded lands and also for adopting suitable interventions to further improve soil quality for multipurpose land restoration programs, thereby attaining land degradation neutrality and United Nations Sustainable Development Goals.

Keywords: bioenergy production; energy security; land degradation neutrality; marginal lands; principal component analysis; restoration; sustainable development goals; soil quality indexing

1. Introduction

The current impetus for bioenergy production across the world has been prompted due to concern for global warming and subsequent climatic change. As a result, the average rate of increment in biomass usage for bioenergy production at the global level has become 5%–8% and is expected to double in the near future [1]. While biomass production from terrestrial systems is often considered as a promising avenue for bioenergy [2], there is a growing debate regarding the judicious use of land for bioenergy production as land is a limited resource and there is conflict between fuel versus food production for a growing human population [2,3]. Therefore, the sustainable exploitation of marginal and degraded lands (which are not primarily targeted for food production) has been considered as an additional opportunity for biomass/bioenergy production [4]. Apart from biomass and bioenergy production [2,4,5], the successful restoration of such land types will also lead to agricultural intensification [6], soil quality improvement, soil carbon sequestration [7], and land degradation neutrality [8], thereby attaining United Nations Sustainable Development Goals (UN-SDGs) such as no poverty (Goal No. 1), zero hunger (Goal No. 2), good health and well-being (Goal No. 3), gender equality (Goal No. 5), decent work and economic growth (Goal No. 8), responsible consumption and production (Goal No. 12), climate action (Goal No. 13), life on land (Goal No. 15), and peace, justice and strong institutions (Goal No. 16) [9]. In this context, there is a need to enhance the productivity of degraded lands for multipurpose environmental benefits.

The literature provides ample evidence regarding the importance of the restoration of marginal and degraded lands for environmental sustainability [5–15]. For instance, Tripathi et al. [9] proposed various biotechnological tools for the restoration of marginal and degraded lands for attaining UN-SDGs and also discussed the nexus effect of plant–microbe–soil–pollutant interactions for the restoration of polluted lands under changing climatic conditions [10,11] and also for deriving additional benefits, that is, various bioproducts during the restoration program for supporting a bio-based economy [12]. Similarly, Keesstra et al. [8] proposed four novel concepts to decipher land degradation neutrality and effectual restoration programs for attaining soil related SDGs. In another study, Tianjiao et al. [13] analyzed the effects of land preparation and vegetation on soil moisture in a hilly loess catchment in China, whereas Novara et al. [14] studied the application of organic farming on soil organic recovery in a citrus plantation. Villacis et al. [15] reported the effect of various plant species on rehabilitation of disturbed soils in the Ecuadorian Amazon. However, exploring key soil quality variables as indicators is imperative for evaluating the performance of such restoration programs. Furthermore, the management of key variables is also an essential requirement for the continued and enhanced production of feedstock for bioenergy and other bio-based products [12].

While there are a multitude of variables that help to assess the edaphic condition and monitor the trends of soil quality over the years, monitoring each and every variable over the restoration period is a tedious task [16,17]. As a result, the majority of soil system models consider few variables such as above and belowground plant biomass, soil microbial biomass, microbial nutrient content, soil C and N ratio and its mobilization, immobilization, mineralization rates, etc. for soil quality assessment [18,19]. Developing site-specific key indicators for assessing the soil health of a particular land type is vital for a multipurpose-restoration program. Moreover, assessing the growth performance of the candidate species and their influence on below-ground changes is also important for developing a suitable policy framework for a large-scale land restoration program. Previous studies have reported a principal component analysis (PCA)-based soil quality indexing (SQI) for assessing the performance of plants grown in various soil conditions. For instance, Zambon et al. [20] developed such indicators of land quality and environmental degradation in agricultural fields, whereas Madejón et al. [21] framed SQI for the restoration of contaminated soils by *Paulownia fortunei*. Furthermore, Hebb et al. [22] developed SQI for showing the variation in soil physical quality in explicitly different land use in Northern Prairie regions and Liu et al. [23] developed SQI for *Camellia oleifera* forest land in Southern China. Similarly, Juhos et al. also [24] developed SQIs for a land suitability assessment in Central European arable soils. Since there are no such efforts in India to identify the key variables for assessing the performance of a biomass and biofuel species-based land restoration program, the present work aimed to (i) analyze the growth performance of the hardy, drought tolerant, and fast-growing biomass plant *Dalbergia sissoo* Roxb. in marginal and degraded land of the Mirzapur district of Eastern Uttar Pradesh, India; and to (ii) develop a soil quality index (SQI) for analyzing the impact of growing a plantation on soil quality improvement over the study years.

Dalbergia sissoo Roxb.: A Plant with Bioenergy Value and Multipurpose Environmental Benefits

D. sissoo (Indian Rosewood) is a leguminous, deciduous and fast-growing tropical timber tree belonging to the family Fabaceae (Figure 1). Importantly, it is a multipurpose tree with high fuelwood and bioenergy production potential and is also commonly used as a fodder, shade, shelter and a N-fixing tree for the restoration of marginal and degraded lands [25,26]. Due to its multipurpose ecological and socio-economic benefits, *D. sissoo* is widely used for afforestation, social forestry and land restoration programs [27]. Importantly, *D. sissoo* has the potential to grow under diverse agro-meteorological conditions. For example, it has been reported that *Dalbergia* can grow well in sandy to clay soils up to an elevation of 1500 m, with a pH range from 4.5 to 8.2. It requires an average annual rainfall of 500–4500 mm, and an annual average temperature of −4.0 to 45.0 °C [28]. Though there are many other hard-wood and non-food tree species capable of growing under various conditions, *Dalbergia* is unique among other species due to its non-invasive character. Moreover, the biomass yield is comparable to the yield of other high lignocellulosic tree species like *Acacia nilotica*, *Albizia lebbeck*, *Butea monosperma*, *Cassia siamea*, *Leucaena leucocephala*, *Pithecellobium dulce*, *Prosopis juliflora* (Table 1).

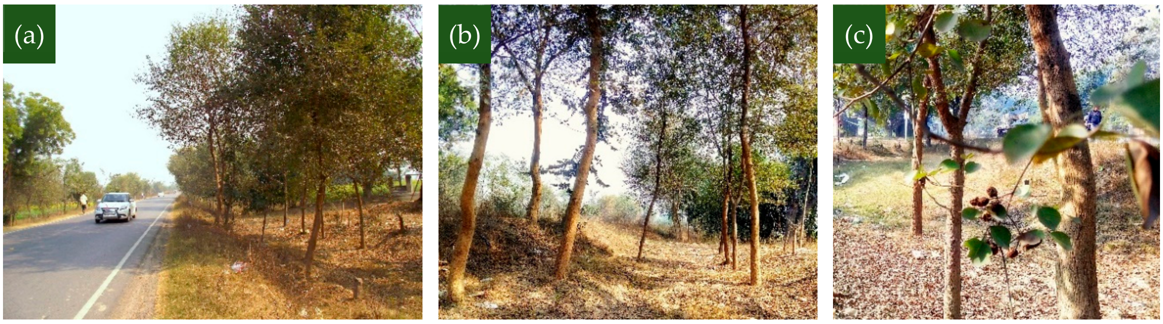


Figure 1. *Dalbergia sissoo* can grow in diverse edaphic conditions as it has habitat plasticity and adaptive capacity: (**a**) *D. sissoo* growing along roadsides, (**b**) marginal land, (**c**) and improving soil fertility through litter turn-over and N-fixation.

The calorific value, wood density, ash percent, biomass-ash ratio, and moisture percent of *Dalbergia* was found to be 25 KJ g^{-1} dry weight, 0.93 g m^{-3}, 1.94%, 35%, and 32%, respectively [29]. Also, the fuelwood value index (FVI) of this tree species is considered to be higher (1176–1230) [29]. Besides these, *D. sissoo* has higher lignin content (39.51%) and other constituents like cellulose (33.77%), pentosane (10.35%) and benzene or alcohol derivatives (6.88%) [30]. Therefore, *Dalbergia* can be considered as a candidate species for biomass or biofuel production. Moreover, the plant is well suited to grow under extreme conditions like contaminated, degraded and marginal lands. [31–33]. The biomass production and carbon sequestration potential of *D. sissoo* has been analyzed in the Tarai region of Central Himalaya [33]. The total biomass of a 10-year-old tree was 94.8 Mg ha^{-1} and the carbon stock was 43.39 Mg ha^{-1} [33]. Another study suggested that five-years aged coppice shoots of the *Dalbergia* plantation on sodic land produced aboveground biomass of 13.52 Mg ha^{-1} [26] with the maximum proportion in the stem-wood (9.84 Mg ha^{-1}), followed by branch-wood (2.92 Mg ha^{-1}) and leaf (0.78 Mg ha^{-1}). Furthermore, Singh et al. [30] reported luxurious growth of *D. sissoo* on sodic land in northern India with higher fuelwood properties, including a wood density of 0.73 g cm^{-3}, and an FVI of 777 [30] Previous studies have also proved that *Dalbergia* plantations can improve soil properties like nitrogen, phosphorus and potassium content [34], and different methods have been employed to enhance the growth of the plant [31].

In this context, the present study was conducted to evaluate the growth performance of *D. sissoo* growing in Barkachha, Vindhyan zone of Mirzapur district, Uttar Pradesh, India and develop an SQI based on PCA for evaluating the restoration potential of the test plant. The development of an SQI will help identify the key soil variables regulating the overall development of soil health and, subsequently, the growth of the test plant. Moreover, this study will provide an insight on how these key variables influence biomass production and the restoration process. Most importantly, this PCA-based standard SQI can be used as a fast and cost-effective approach to check the soil quality improvement at any stages of the restoration program and to assess the effectiveness of multi-purpose restoration programs to achieve LDN, thereby attaining the UN-SDGs for global sustainability.

Table 1. Comparison of *D. sissoo* with other hard-wood, leguminous trees.

S. No.	Tree Species	Adaptive Traits	Invasive Nature/Negative Traits	Usability of Wood/Timber	Major Phytochemicals/ Pharmaceutical Products	Medicinal Values	Additional Benefits	References
1.	*Dalbergia sissoo*	Tolerant under saline, sodic, acidic, arid soils, heavy metal and POPs contaminated soils, control soil erosion, also suitable for the restoration of mine spoils	Little risk in Australia and Florida but easy to manage	Furniture, used in the interiors and floorings, high calorific value, excellent fuelwood, sporting goods, tobacco pipes, etc.	Tannins, terpenes, saponins, alkaloids, chalcone, isoflavone, flavone, biochanin A, rotenoid, dehydroamorphigenin, etc.	Cure of reactive oxygen species (ROS) induced diseases, emesis, ulcers, leukoderma, dysentery, stomach troubles and skin diseases	Fodder and fibre production, livestock management, regaining ecosystem services, alkaloids from woods are good source of insecticides	[26,35,36]
2.	*Acacia nilotica*	Luxurious growth in sodic, saline and arid soils	Water intensive, reduce the quality of pasture and compete with native plants	Fuelwood, charcoal, timber wood	Saponins, tannins and phenols, alkaloids, glycosides, anthraquinones, flavonoids, proteins, phenols, anthocyanins, magniferin, myricetin, taxifolin, vitexin, etc.	Barks used in cough, nerve stimulation, diarrhoea, dysentery and leprosy, bruised leaves can treat ulcers	Leaves and fruits has fodder value, shade and shelter tree,	[37,38]
3.	*Albizia lebbeck*	Can grow well in riverine belts, saline or sodic lands	Potential invader of natural and semi-natural areas	Used in interior moulding, parquet, furniture, panelling, turnery and general construction	Julibroside, budmunchiamines, quercitrin and isoquercitrin, etc.	Leaves and seeds are used for eye diseases, and bark to treat boils. Saponin from pods and roots has spermicidal activity, antitumor, antiplatelets aggregation and bactericidal activities	Fodder for camels, buffalo and cattle, nitrogen-rich leaves are used as mulch and green manure, has ornamental importance, bark is used locally in India for tanning fishing nets.	[39,40]
4.	*Butea monosperma*	Adapted to sodic, saline, marginal and other degraded lands	-	used for utensils, low fuel wood value, charcoal,	dihydrochalcone, dihydromonospermoside, chalcones, butein, monospermoside and isoliquiritigenin, etc.	Flowers are used in liver disorders, seeds are anthelminthic, astringent gum from stem has application in diarrhoea, ethanolic extract of leaves can enhance blood insulin level	Seeds exhibit bactericidal and fungicidal activities, young leaves are good fodder, eaten mainly by buffaloes, coarse fibres from the inner bark used for cordage, caulking the seams of boats and making paper, red exudate is obtained from the bark used as dye and tannins	[41,42]

Table 1. *Cont.*

S. No.	Tree Species	Adaptive Traits	Invasive Nature/Negative Traits	Usability of Wood/Timber	Major Phytochemicals/ Pharmaceutical Products	Medicinal Values	Additional Benefits	References
5.	*Cassia siamea*	Adapted to diverse soil conditions including aluminium mine tailings.	-	Fuelwood, charcoal, high timber value, often used for poles, posts, bridges, mine poles and beams	Flavonoids, tannins, terpenes, saponins, alkaloids, anthraquinones, etc.	Used against intestinal worms, heartwood as laxative and scabies can be cured from its decoction	Ornamental importance due to yellow flowers, leaves used as green manure, used in mulching, acts as a host plant for *Santalum* spp.	[43,44]
6.	*Leucaena leucocephala*	Potential to grow under saline, sodic or acidic soils, slower down surface run-off	High risk of invasiveness in the disturbed sites even in the agricultural land where it has been planted as a shade tree.	Excellent firewood and charcoal, also used as sawn timber, mine props, furniture and parquet flooring,	Diterpene, triterpene, palmitic acid, fatty acid ester, terpene alcohol, linolenic acid ester, dicarboxylic acid, etc.	Antimicrobial, antibacterial, antioxidant, anti-inflammatory, diuretic, antihistaminic, nematicide, pesticide, anti-androgenic, hypocholesterolemic and hepatoprotective	Red, brown and black dyes from pods, leaves and bark respectively, paper, pulp, rayon and particleboard production, used in green manuring, mulching, weed control, etc.	[44,45]
7.	*Pithecellobium dulce*	Potential to grow in nutrient poor soil, including saline and arid soils	-	Low calorific value thus not attractive as fuelwood, it is often used in drums, and matchsticks	Triterpenoids, glycosides, saponins and flavonoids, pitheduloside, oleanane glycosides, arabinose, D-glucose, L-rhamnose, and D-xylose, 1, 1-Diphenyl-2-picrylhydrazyl (DPPH), etc.	Used against diarrhoea, pulverised seeds are ingested for internal ulcers, root bark may be used to cure dysentery	Bark exudes gum and resins, popular as an ornamental, useful shelter belts, Seeds contain a greenish oil used in soaps, used as tannin, its flower supports apiculture, fodder for livestock	[44,46,47]
8.	*Prosopis juliflora*	Adapted to many types of the soils including alkaline, saline, sodic soils, tolerant to drought and even seasonal waterlogged conditions, soils contaminated with specific metals, heavy metals or organic contaminants	Highly invasive in nature, invade various grassland ecosystems, savannas, pastures and even abandoned and agricultural land	Good firewood and excellent charcoal, seasoned wood is used for fence posts, furniture, crafts and corrals	alkaloids, flavonoids, terpenoids, saponins and phenolic compounds, juliflorine, juliprosinene, sceojuliprosopinol, juliprosine, L-manopyranoside, julifloravizole, mesquitol, catechin, quercetin, etc.	syrup prepared from ground pods provide weight gain and enhanced motor development, enhanced lactation, expectorants, helpful in digestive disturbances and skin lesions	Low quality tannin or dyestuff, phenol-formaldehyde polymeric resins, pods serves as for making alcoholic products	[48–50]

2. Materials and Methods

2.1. Study Area and Field Sampling

The *Dalbergia* plantation on the marginal lands of Barkachha, Vindhyan region of Eastern Uttar Pradesh (25°03′09.8″ N, 82°35′51.3″ E) was selected as the experimental field (Figure 2). Seasonal sampling was carried out during the months of May to June (summer) and November to January (winter) to analyze the growth performance of *Dalbergia* and collect rhizospheric soil samples for soil quality indexing. The size of the experimental plot was 2700 m^2, which was further divided into 3 sub-plots, each comprising an area of 900 m^2 (30 m × 30 m). The geographical and meteorological features of the study sites are provided in Table 2. Sampling was done for four consecutive years, that is, 2014 (I year), 2015 (II year), 2016 (III year), and 2017 (IV year), and soil samples were also collected from the nearby unplanted plot as control. The height of the individual tree species was recorded and their diameter measured at a height of 1.4 m from the ground. The rhizospheric soil samples were collected at a depth of 0–15 cm. The soil samples were collected from three different points around each selected tree and the weight of each replicate was reduced to 500 g via conning-quartering method.

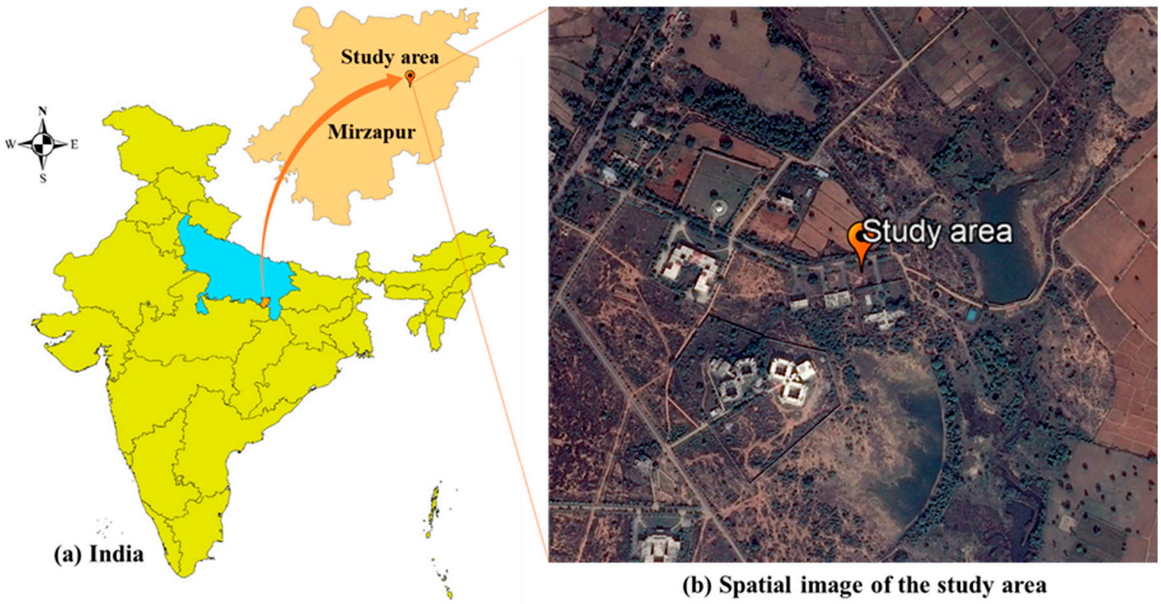


Figure 2. Geographical location of the study area.

Table 2. Geographical and meteorological characteristics of the area studied (Mirzapur).

Geographical Characteristics *		Meteorological Characteristics		
Total Geographic Area (km^2)	Mean Elevation (m)	Climate Pattern *	Mean Annual Temp. (°C) ± SD #	Mean Annual Precipitation (mm) #
4521	80	Warm and tropical dry	23.25 ± 5.25	975

* Zonal Project Directorate Kanpur (Available at: www.zpdk.org.in). # Weather Underground (Available at: www.wunderground.com).

The collected soil samples were subjected to experimental analyses of different physico-chemical and biological parameters including pH, electrical conductivity (EC), bulk density (BD), moisture content (MC), cation exchange capacity (CEC), total organic carbon (TOC), available nitrogen (AN), available phosphorus (AP), available potassium (AK), microbial biomass carbon (MBC), soil dehydrogenase (SDA), soil urease (SUA) and soil peroxidase activity (SPA).

2.2. Soil Physico-Chemical Parameters

Physico-chemical parameters of fresh soil samples were analyzed. pH (pH meter; Cyber Scan-500) and EC (EC meter; Cyber Scan-500) were measured using instrumental method [51]. Apart from that, soil samples were also analyzed for BD, MC [52], CEC [53] and TOC [54]. Furthermore, AN, AP and AK were also estimated accordingly [55–57].

2.3. Soil Biological Parameters

MBC was estimated by Vance et al. [58], SUA (EC 3.5.1.5; URE) was measured by indophenol colorimetry considering urea as a substrate. The amount of NH_4^+ released over 24 h was assayed colorimetrically at 578 nm and expressed as μmol NH_4^+ g^{-1} dry sample [59]. SDA was determined by monitoring the conversion rate of 2,3,5-triphenyltetrazolium chloride (TTC) to the reddish pink, water insoluble triphenyl formazan (TPF) obtained after the incubation for 24 h at 30 °C followed by colorimetric analysis at 485 nm [60]. SPA was performed with 3,3′,5,5′-tetramethylbenzidine (TMB) as a substrate depicting the method of Johnsen and Jacobsen [61].

2.4. Soil Quality Index (SQI)

Principal component analysis (PCA) has been extensively used by various researchers to identify key soil quality indicators [62–68]. The reclaimed mine soil index (RMSI), described by Bastida et al. [69], Masto et al. [70], Sinha et al. [71], and Mukhopadhyay et al. [72] was taken as the basis for developing the current soil quality index (SQI) and it was developed for the four consecutive growth years of the *Dalbergia* plantation. PCA was employed to extract the suitable soil properties and their relative weights. Principal components (PCs) with eigenvalues ≥1 [73] that described at least 5% of variation in the data were studied further [62,64]. Under a particular principal component (PC), only the variables with high factor loadings were further considered for the index. When more than one variable was obtained under a single PC, a correlation test was done to examine if the variables could be further considered as redundant and hence excluded from the SQI [65]. If the highly loaded factors were not correlated, then each of them was considered significant and included in the SQI. Among the well-correlated variables, the highest factor loading variable was chosen for SQI. The final PCA-based SQI equation can be explained as

$$\mathrm{SQI} = \sum\nolimits_{i=1}^{n} \mathrm{W}_i\,\mathrm{S}_i \quad (1)$$

where W is the PC weighting factor, S is the indicator score for each variable i, and n is the number of variables in the MDS (minimum data set). To convert the real figures of degraded soil parameters into scores (S) the following equation was used that defined a sigmoidal type [65,69], with an asymptote scale ranging from 0 to 1:

$$\mathrm{S} = \frac{a}{1+(x/x_0)^b} \quad (2)$$

where a is the maximum score (=1.00) of the soil property, x is the soil parameter value, x_0 is the mean value of each soil parameter corresponding to the different aged restored soil, b is the value of the slope of the equation. The slope was −2.5 for the “more is better curve” and 2.5 for the “less is better curve” to obtain a sigmoidal curve tending to 1 for all the proposed soil properties.

After calculating the S-values for all soil quality parameters, each variable was weighted using the results of PCA. Each PC demonstrated a certain amount (%) of variation in the total data set. This percentage, when divided by the total percentage of variation demonstrated by all the PCs with eigenvalues >1.0, provided that the weighting factor (W) for variables selected under a given PC. After determining the values of S and W, the SQI for each tree of different age was then calculated using Equation (1). Higher index scores represent better soil quality or improved performance of soil functions.

2.5. Data Analyses

A one-way ANOVA (analysis of variance) was performed to analyze the improvements in the soil characteristics with respect to the control. The significant F value was estimated and the differences between individual means were tested using DMRT (Duncan's Multiple Range Test), at the 0.05 significance level. For PCA, regression analysis and scoring functions, Microsoft Excel (13.0) and SPSS for windows version 16.0 (SPSS Inc., Chicago, IL, USA) software were used.

3. Results and Discussions

3.1. Soil Physico-Chemical Parameters

The physico-chemical characteristics of the rhizospheric soil of *D. sissoo* growing in the marginal and degraded lands of the study sites are given in Table 3. The higher BD (1.48 g cm^{-3}) was found in the control site (unplanted) as compared to the planted area with *D. sissoo*, showing that the plantation and the growth of the plants could be beneficially related to a lowering of the BD. Other parameters that may contribute to the higher BD of the control site are differences in soil texture, soil aggregation, a lack of organic matter and higher stone content than the plantation site [74]. Irrespective of the seasons, the MC was found to be lower in the control site (Table 3). As discussed earlier, MC is highly dependent on the presence of organic matter in the soil and also depends on the soil fraction and bulk density. Furthermore, the AN was also found to increase with the growth of the plant (i.e., from the first year to the fourth year) and ranged between 70.46 ± 3.57 to 194.11 ± 7.38 mg kg^{-1} in plantation sites during the summer season, in contrast to the control site during the same period which remained similar (66.40 ± 7.36 mg kg^{-1}). The difference was more pronounced in the winter season. In winter, AN in the plantation site varied from 85.45 ± 7.36 to 212.46 ± 4.76 mg kg^{-1} whereas in the control site, it was found to be 67.74 ± 4.81 mg kg^{-1}. The increasing trend of AN with respect to the growth of plants might be due to the symbiotic nitrogen fixing capacity of *Dalbergia*. A similar trend was also found for AK during both the summer and winter seasons. Apart from these variables, TOC, AP and CEC were also estimated and a considerable increment was observed in the *Dalbergia* plantation site compared to the unplanted control site. However, the pH and EC values decreased over the period (i.e., form first year to fourth year) as the growth of trees considerably increased.

3.2. Soil Biological Parameters

The biological parameters, MBC, SDA, SUA and SPA were found to increase with the growth of *D. sissoo*. These results are depicted in the Figure 3a–d.

MBC tends to increase in the rhizospheric soil of *D. sissoo* more than the unplanted control and also significantly varied between seasons (lower in summer than winter) with the growth periods (Figure 3a). Further, the results regarding the enzymatic activities of dehydrogenase, urease and peroxidase were interesting. Particularly, SDA and SUA were strongly correlated with the growth of plants in the studied region (Figure 3b,c). Comparatively higher SPA was found during the first year (2014), but reduced activity was observed from the second year onward, which clearly indicates that growing plants improved soil quality over the years and reduced soil stress factors, which in turn resulted in reduced SPA activity (Figure 3d). Moreover, there was a marked difference in seasonal variation of soil enzymatic activities (i.e., higher in summer than winter). The occurrence of low enzymatic activities (SDA, SUA, SPA) in winter was mainly due to the low soil temperature during the winter season. However, enzymatic activities were enhanced with the growth of the tree species in both seasons accordingly (Figure 3).

Table 3. Effect of *D. sissoo* plantation on the physico-chemical properties of the rhizospheric soil samples of Barkachha, Mirzapur, Eastern UP, India (n = 4; mean ± SD) during the four-year study period (2014–2017), in comparison to the soil properties of a control site at the same locality (without plantation) during the year 2014 as a reference/initial value.

Soil Samples	BD (g cm^{-3})	MC (%)	pH (1:4 *w*/*v*)	EC (ds m^{-1})	TOC (%)	AN (mg kg^{-1})	AP (mg kg^{-1})	AK (mg kg^{-1})	CEC (cmol kg^{-1})
Summer Season									
Control (unplanted)	1.48 ± 0.03 ^{d}	2.33 ± 1.33 ^{a}	7.46 ± 0.08 ^{b}	0.23 ± 0.01 ^{c}	0.36 ± 0.01 ^{a}	66.40 ± 7.36 ^{a}	4.56 ± 0.03 ^{a}	21.87 ± 2.02 ^{b}	12.92 ± 0.05 ^{a}
2014	1.56 ± 0.01 ^{e}	8.16 ± 1.70 ^{b}	7.91 ± 0.06 ^{c}	0.29 ± 0.009 ^{e}	0.35 ± 0.35 ^{a}	70.46 ± 3.57 ^{a}	4.75 ± 0.17 ^{a}	18.04 ± 2.67 ^{a}	13.21 ± 0.10 ^{b}
2015	1.45 ± 0.02 ^{c}	5.82 ± 1.90 ^{b}	7.62 ± 0.06 ^{d}	0.27 ± 0.004 ^{d}	0.38 ± 0.38 ^{b}	89.00 ± 4.71 ^{b}	5.11 ± 0.18 ^{b}	28.14 ± 1.73 ^{c}	14.64 ± 0.11 ^{d}
2016	1.34 ± 0.01 ^{b}	5.99 ± 1.37 ^{b}	7.49 ± 0.05 ^{b}	0.19 ± 0.002 ^{b}	0.43 ± 0.43 ^{c}	121.67 ± 6.73 ^{c}	5.41 ± 0.33 ^{b}	32.69 ± 1.01 ^{d}	16.30 ± 0.20 ^{e}
2017	1.23 ± 0.01 ^{a}	1.61 ± 0.53 ^{a}	7.24 ± 0.08 ^{a}	0.18 ± 0.004 ^{a}	0.49 ± 0.49 ^{d}	194.11 ± 7.38 ^{d}	5.36 ± 0.18 ^{b}	35.40 ± 0.82 ^{d}	14.40 ± 0.03 ^{c}
Winter Season									
Control (unplanted)	1.47 ± 0.04 ^{d}	1.88 ± 0.17 ^{a}	7.31 ± 0.04 ^{a,b}	0.19 ± 0.01 ^{a}	0.41 ± 0.03 ^{a}	67.74 ± 4.81 ^{a}	5.19 ± 0.16 ^{a}	25.84 ± 3.05 ^{a}	13.61 ± 0.03 ^{a}
2014	1.51 ± 0.01 ^{d}	7.78 ± 1.00 ^{c}	7.84 ± 0.18 ^{c}	0.27 ± 0.02 ^{b}	0.44 ± 0.44 ^{a,b}	85.45 ± 7.36 ^{b}	5.39 ± 0.37 ^{a}	23.45 ± 0.48 ^{a}	14.66 ± 0.05 ^{b}
2015	1.41 ± 0.03 ^{c}	6.13 ± 0.60 ^{b}	7.43 ± 0.20 ^{b}	0.26 ± 0.01 ^{b}	0.46 ± 0.46 ^{b}	104.36 ± 4.36 ^{c}	6.32 ± 1.43 ^{a}	31.75 ± 1.75 ^{b}	14.77 ± 0.07 ^{b}
2016	1.30 ± 0.01 ^{b}	6.12 ± 0.28 ^{b}	7.32 ± 0.12 ^{a,b}	0.18 ± 0.01 ^{a}	0.51 ± 0.57 ^{c}	140.42 ± 4.97 ^{d}	6.09 ± 1.07 ^{a}	38.32 ± 1.80 ^{c}	15.75 ± 0.03 ^{c}
2017	1.21 ± 0.01 ^{a}	2.79 ± 0.62 ^{a}	7.18 ± 0.05 ^{a}	0.17 ± 0.01 ^{a}	0.57 ± 0.51 ^{d}	212.46 ± 4.76 ^{e}	6.14 ± 0.65 ^{a}	41.16 ± 0.90 ^{c}	16.37 ± 0.12 ^{d}

Note: values with different letters in a particular column are significantly different at the 95% confidence level ($p \leq 0.05$) as per DMRT.

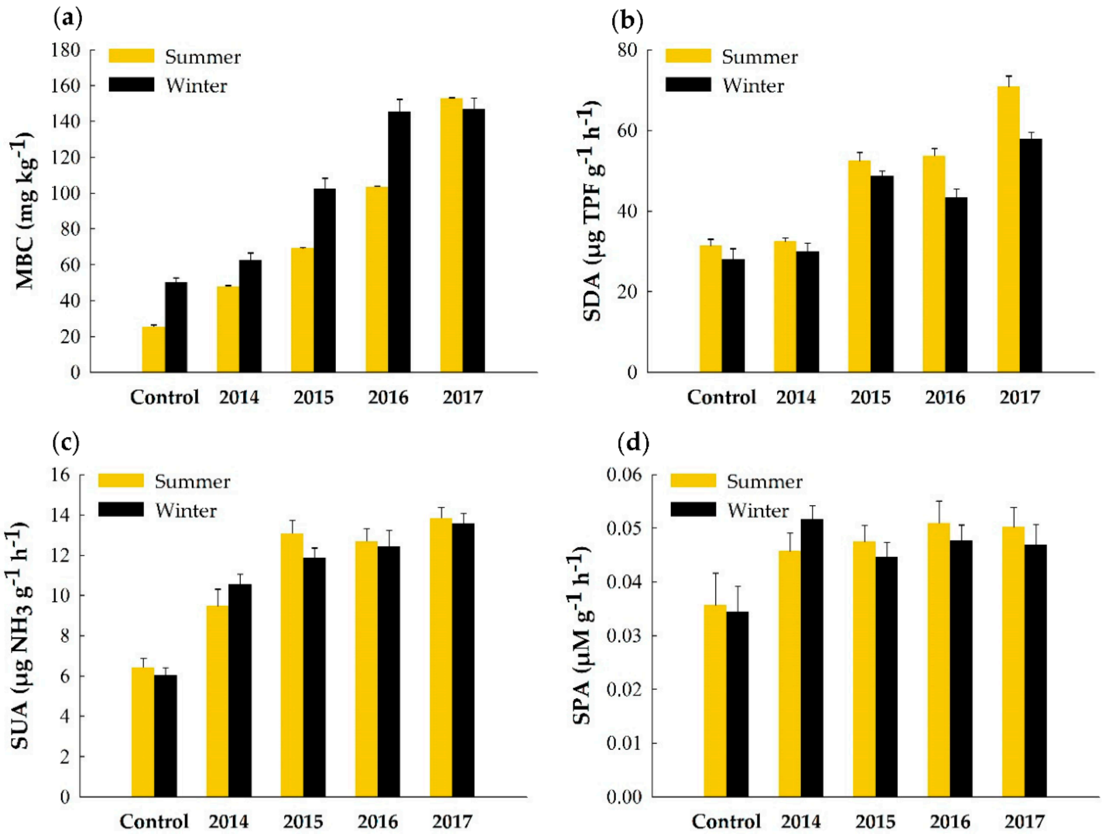


Figure 3. Effect of a *D. sissoo* plantation on the biological and biochemical properties of the rhizospheric soil samples of Barkachha, Mirzapur, Eastern UP, India, during the four-year study period (2014–2017), in comparison to the soil properties of a control site at the same locality (without plantation) during the year 2014 as a reference/initial value. (**a**) Microbial biomass carbon (MBC), (**b**) Soil dehydrogenase (SDA), (**c**) Soil urease (SUA), and (**d**) Soil peroxidase activity (SPA).

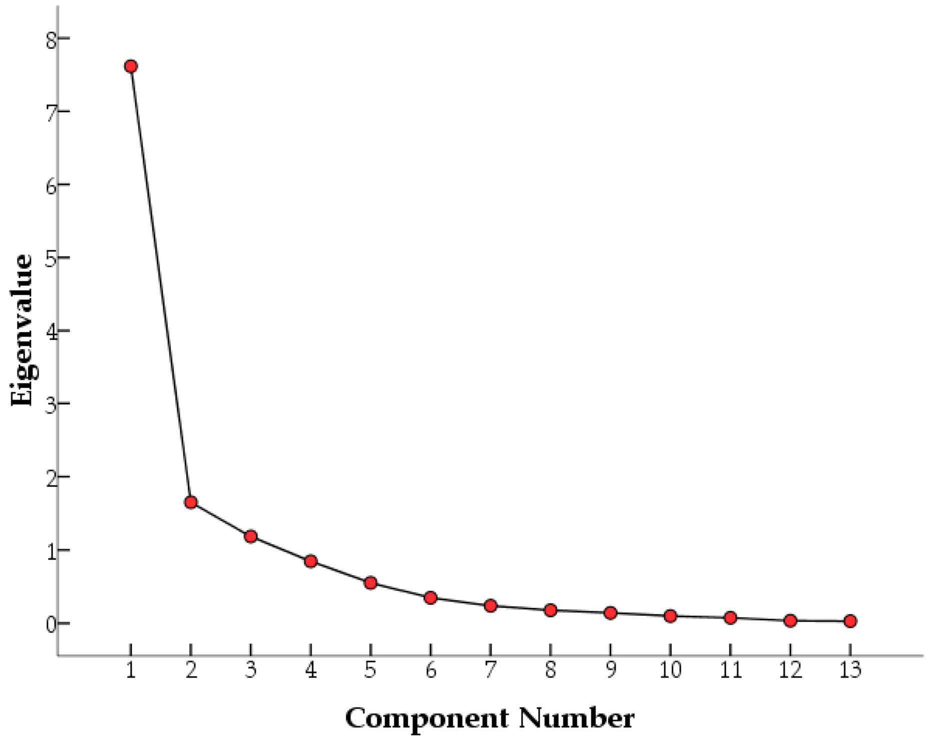
3.3. Developing PCA-Based SQI

The entire dataset of soil properties over a period of the *Dalbergia* plantation on the degraded land of Barkachha, Mirzapur district and the control site (nearby unplanted soil) were subjected to PCA to identify the key variables as indicators of the soil quality improvement in the degraded soil. The first three PCs with eigenvalues >1.0 were considered for the present study (Figure 4a and Table 4).

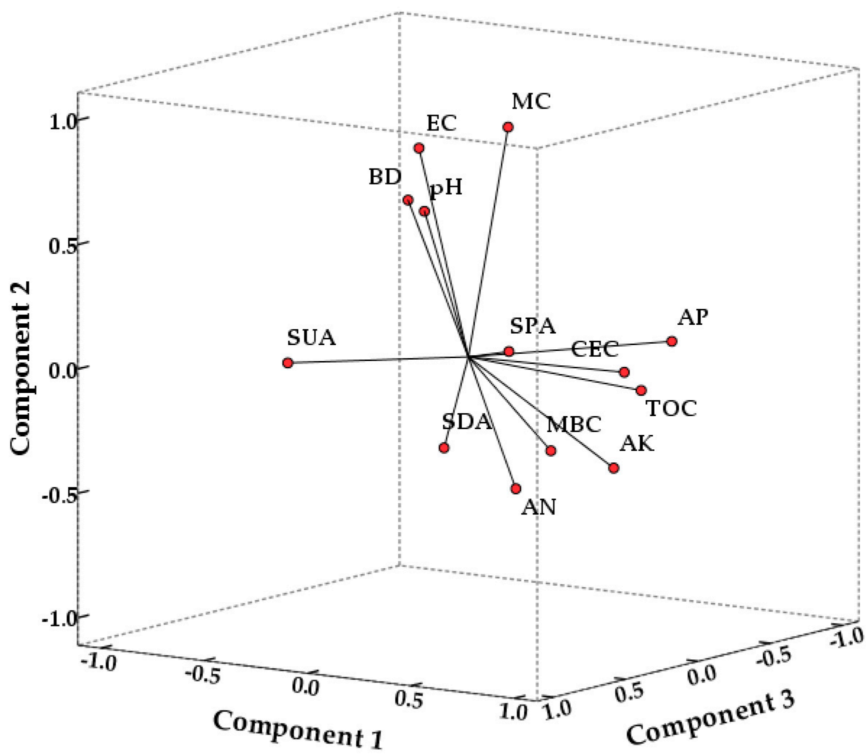
The highly weighted variables under PC-1 were BD, MBC, AK, AN. The most highly loaded factor under PC-1 was BD, which was also found to be highly correlated ($r > 0.99$) with rest of the highly loaded parameters in PC-1 (Table 5).

A single soil property cannot be considered for developing the SQI and, therefore, multiple parameters were considered for the development of the SQI. MC and SUA were highly weighted under PC-2 and PC-3, respectively. As a result, the final variables selected for SQI by PCA are BD, MBC, MC and SUA (Figure 4b and Table 4) and the weights for selected variables were identified by percent variation in the dataset demonstrated by the first three PCs. Weights were allocated between the correlated variables according to the factor loading within PC-1 and the full weights were designated for the non-correlated variables.

$$\text{SQI} = 0.5858\ (\text{BD} + \text{MBC}) + 0.1269\ (\text{MC}) + 0.0911\ (\text{SUA}) \quad (3)$$



(a)



(b)

Figure 4. (**a**) Scree plot for the different components considered for the principal component analysis with eigenvalues greater than 1 and (**b**) component plot in the rotated space depicting the factor loading on the respective axes.

Table 4. Results of the PCA of rhizosphere soil parameters under *D. sissoo* growth in the degraded land of Barkachha of Mirzapur district in Uttar Pradesh.

Principal Components	PC-1	PC-2	PC-3
Eigen values [a]	7.616	1.650	1.184
Variation (%)	58.584	12.690	9.111
Cumulative variation (%)	58.584	71.274	80.386
Eigenvectors [b]			
Bulk density (BD)	**−0.960** *	0.189	−0.035
Moisture content (MC)	−0.288	**0.870** *	−0.011
pH (1:4; *w*/*v*)	−0.812	0.217	−0.039
EC (1:4; *w*/*v*)	−0.696	0.567	0.097
Total organic carbon (TOC)	0.779	0.248	−0.294
Available N (AN)	0.932	−0.089	0.094
Available P (AP)	0.486	0.302	−0.472
Available K (AK)	0.941	−0.009	−0.215
Cation exchange capacity (CEC)	0.781	0.333	−0.216
Microbial biomass carbon (MBC)	**0.951** *	0.086	0.023
Soil dehydrogenase activity (SDA)	0.855	0.065	0.351
Soil urease activity (SUA)	0.399	0.225	**0.782** *
Soil peroxidase activity (SPA)	0.682	0.393	0.159

[a] Boldface eigenvalues correspond to the PCs examined for the index; [b] boldface factor loadings are considered highly weighted; bold-asterisked factors correspond to the parameters included in the index.

Table 5. Correlations between the highly loaded variables of PC-1.

	BD	AN	AK	MBC
BD	1			
AN	−0.930 **	1		
AK	−0.903 **	0.843 **	1	
MBC	−0.913 **	0.908 **	0.901 **	1

** Correlation is significant at the 0.01 level (2-tailed).

The SQI values were further classified on a 0 to 1 scale by dividing each weighing factor by the total weighing factor (0.8039); hence, the final SQI can be explained as per the following equation:

$$\text{Final SQI} = 0.3644 \times \text{S (BD)} + 0.\ 3644 \times \text{S (MBC)} + 0.1579 \times \text{S (MC)} + 0.1133 \times \text{S (SUA)} \quad (4)$$

where S is the score of the individual variables and the coefficients are the weighing factors obtained from PCA results.

The various parameters of the scoring curves have been represented in Table 6 and the variables shown in the Equation (4) are considered as the most critical soil indicators that depict the overall soil health of the degraded site and the performance of the *D. sissoo* plantations over the years.

Table 6. Parameters for scoring curves.

Parameter	BD	MBC	MC	SUA
Curve type	Less is better	More is better	More is better	More is better
Mean (x_0)	1.39	90.58	4.86	44.92
Slope (b)	2.50	−2.50	−2.50	−2.50
R^2	0.998	0.986	0.975	0.980
F significance	0.000	0.000	0.000	0.000

Similar studies related to PCA-based development of soil quality index have been performed by various researchers [64,75]. They proposed that testing of various other indicators on a broad scale may not be required to assess the soil quality over the time period once the MDS is established. Therefore, these key indicators may be used for the evaluation of the degraded soil in the near future to monitor the performance of various bioenergy tree-based restoration process.

The PCA concludes that these four significant soil parameters can be used to develop the SQI which can designate the improvement of soil conditions of the degraded soil in the study site. Furthermore, several other researchers have considered some other properties of the soil, including coarse soil fraction and soil organic carbon, as important soil quality indicators based on the type of soil degradation [76,77]. Another study suggested the selection of metabolic quotient, water soluble carbon, soil respiration, cellulose, and urease activity as the five critical parameters for developing the rhizosphere soil index under various vegetation types in the Loess Plateau of China [76]. Similarly, another work suggests that the inclusion of key factors such as CO_2 flux, organic carbon, dehydrogenase activity, coarse fraction, soil moisture and base saturation for the development of SQI for the evaluation of reclamation success in a mine site [78]. Similarly, in another case, PCA-based SQI development was performed for the subtropical region of China which included SOC, AN, AP, AK, and sand as critical soil indicators [79].

Therefore, in the current study, the obtained four critical indicators of SQI are either induced by the positive response of the plant system or related to the hydrological interventions, such as the irrigational and mulching practices. Parameters like BD, MBC may be regulated by the growth of the plant system. BD is usually considered a chief indicator of soil quality as it affects the soil moisture, aggregation and the organic matter content of the soil [80,81]. It is usually affected by the soil organic matter, particle structure, compaction and soil porosity that may be indirectly related to the growth of the root system of the plant, which provides the soil binding affinity and affects the porosity and aid for the organic matter in the belowground domain of the plant system.

Moreover, parameters like MC and SUA are associated with hydrological processes. Particularly, most of the enzymatic processes are mediated by the involvement of water molecule with substrate. For example, urease is directly related to the hydrological process that involves the hydrolytic transformation of urea and, therefore, it has been widely used for the estimation of soil quality changes in accordance with the irrigational practices adopted [82,83] and can be considered as a good indicator of soil health. Also, MC reflects the presence of water in the soil that is mainly regulated by BD, porosity and the irrigational practices adopted. Therefore, any decrease in the figures of BD is related with an enhancement in the soil moisture. Also, it has been observed in the various studies that MC and BD play a critical role in the establishment of the soil quality indices [78,80,81].

The SQIs obtained after utilizing the PCA are presented in Figure 5a,b for the summer and winter seasons, respectively, where the influence of each soil indicator on the estimated SQI is also shown, reflecting the cause for measured SQI.

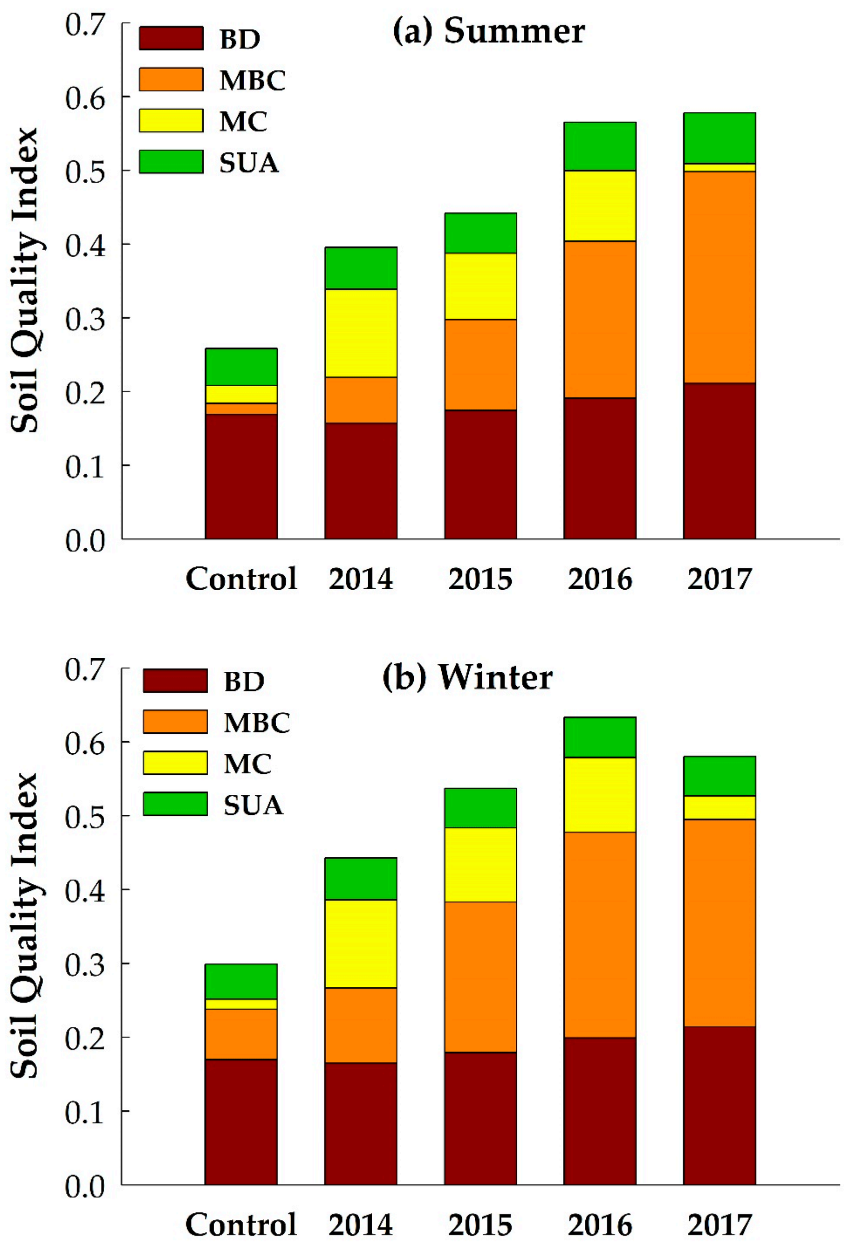


Figure 5. Effect of *D. sissoo* plantation on the soil quality index (SQI) of the study site (Barkachha, Mirzapur, Eastern UP, India) during the four-year period (2014–2017), in comparison to the SQI of a control site at the same locality (without plantation) during the year 2014 as a reference/initial value. (**a**) SQI for summer season, and (**b**) SQI for winter season.

A low SQI was observed for the control site (i.e., unplanted site) and the *Dalbergia* plantation in first year due to the lower score for all the four attributes considered in the SQI. The evaluated SQI varied between 0.258 for the control (unplanted) and 0.578 for the fourth-year plantation in summer season (Figure 5a). Similarly, during winter, the SQI value was 0.299 for the control soil whereas it enhanced to 0.580 during the fourth year in the *Dalbergia* plantation. However, the SQI for the winter season of 2016 (0.633) was more pronounced than that of 2017. This was due to the lesser index of MC in the developed SQI. Lower soil moisture conditions generally arise due to various factors such as drought conditions, scanty rainfall or mismanaged irrigational practices during the period of soil sampling. Furthermore, plant growth played a vital role in regulating the nutritional and microbial characteristics of the degraded soils in the studied region.

To validate the estimated SQI, regression analysis was conducted with DBH and height of the different aged trees in the studied region. The determinant coefficients, R^2 value for DBH and plant height from 2014 to 2017 were 0.870 and 0.861, respectively (Figure 6).

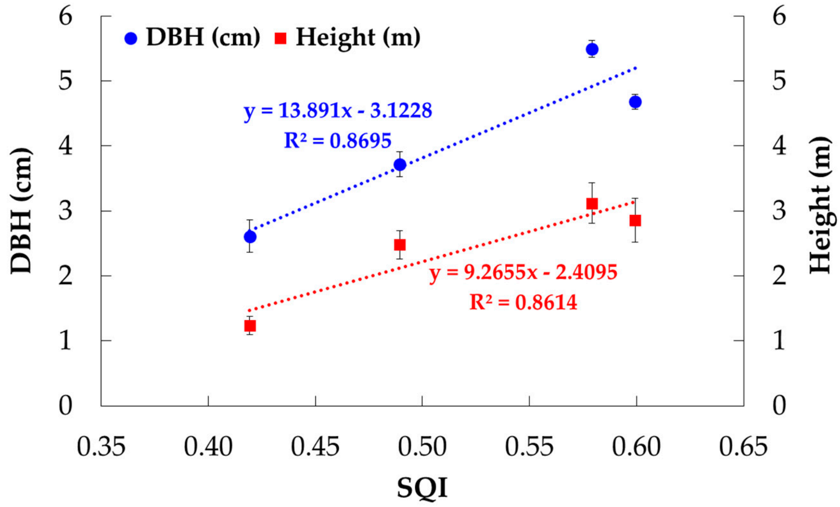


Figure 6. Correlation between SQI and plant growth attributes: DBH and plant height, of different ages (2014–2017).

The regression results show the significant correlations between the SQI and both plant growth attributes (i.e., DBH and plant height). Hence, it can be anticipated from the SQI results that the growth of *D. sissoo* over the years improved the degraded soil of the study site and this can be further improved by suitable soil amendments [84].

4. Conclusions and Future Recommendations

Land restoration activities must be concurrently targeted for deriving additional benefits such as biomass and bioenergy while improving the soil quality for better plant growth and biomass. It is of the utmost importance to develop robust monitoring mechanisms to ensure the effectiveness of such restoration activities. In this context, the present study aimed to analyze the performance of *D. sissoo* planted on the marginal and degraded lands of Barkachha, Mirzapur district of eastern Uttar Pradesh, India and to develop a suitable SQI based on PCA for assessing soil quality improvement by the plantation over the years. The PCA results proved that among the studied variables BD, MBC, MC and SUA are the key variables that influence the overall development of soil health. Interestingly, the developed SQI is strongly correlated with the growth attributes of *Dalbergia* and could able to decipher the soil quality changes over the study period. Since *Dalbergia* has a high calorific value, the biomass of this tree species can be utilized for successful bioenergy program. Moreover, the developed SQI can be used as a key indicator for monitoring the restoration potential of *D. sissoo* growing in marginal and degraded lands and to adopt suitable interventions to further improve the soil quality for multipurpose land restoration programs, thereby attaining LDN and UN-SDGs.

Author Contributions: P.C.A., S.A.E. and V.T. designed the study; S.A.E., and V.T. perform the seasonal sampling; S.A.E. performed the statistical analysis and analyzed the results; S.A.E., V.T. and P.C.A. prepared, reviewed and revised the manuscript. All authors read and approved the final manuscript.

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