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Soil quality enhancement in arecanut (*Areca catechu*)-based agroforestry system: Insights from organic farming and integrated nutrient management

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ABSTRACT

Enhancing soil productivity through appropriate land management practices aligns agricultural output with improved ecosystem services. A field survey was undertaken among 70 farmers in five major arecanut (*Areca catechu* L.) growing subdivisions of Goa: Ponda, Bicholim, Satari, Pernem, and Canacona This research aimed to quantitatively assess the effects of nutrient management practices namely no manure (NM), organic manure (OM), and integrated nutrient management (INM), on soil quality in an arecanut-based agroforestry system. The study was carried out during 2021–22 focusing on seven key soil parameters such as microbial biomass carbon (MBC), bulk density (BD), soil organic carbon (SOC), Zn, Mn, P, and B to establish a minimum data set (MDS), which was then converted into a soil quality index using non-linear scoring functions. The results showed that organic farming yielded a significantly higher soil quality index (0.61), followed by integrated nutrient management (0.58). The findings suggest that implementing organic farming techniques alongside effective crop management strategies is crucial for maximizing the potential of arecanut-based agroforestry systems to boost soil quality and achieve long-term sustainability.

Keywords: Fertility, Mixed farming system, Productivity, Soil health, Soil microbial activity

The practice of cultivating two or more crops simultaneously on the same piece of land is technically termed intercropping or bi-cropping systems. This provides multiple benefits over sole cropping. Most importantly, there is a possibility of significant yield improvement over sole cropping (Kumar *et al*. 2021). In arecanut (*Areca catechu* L.)-based agroforestry systems, the presence of a wide range of crop species, such as teak, nutmeg, jackfruit, sapota, banana, and coconut, creates a multifunctional ecosystem and provides numerous benefits, such as fruits, vegetables, spices, and timber (Cerda *et al*. 2014), complementing the overall livelihood improvement of small and marginal farmers. In addition, this system balances agroecosystems by providing multiple ecosystem services, such as enrichment of soil fertility and soil and water conservation, and creating a suitable microclimate for the member species in the system (Sujatha and Bhat 2013). Many studies have demonstrated that multi-story agroforestry systems provide environmentally significant ecosystem services in terms of soil carbon build-up, soil conservation, and soil quality enhancement (Lara-Pulido *et al*. 2018). However, intensive management systems may perturb the natural capability of such systems by polluting the air, water, and soil, thereby disfavouring ecosystems (Ango *et al*. 2014).

Arecanut is a cash crop grown in south and south-east Asia. India accounts for the largest acreage of arecanut (446000 ha), accounting for as much as 50% of global production (Bhatti *et al*. 2006). Because of identical soil and climatic requirements, crops such as teak, nutmeg, jackfruit, sapota, and coconut are intermixed and extensively used as intercropping systems in the humid, subhumid, and west coast tracts of India (Sujatha and Bhat 2013). The main objective of farmers in this region is to enhance their overall productivity. However, agriculture in these farms operate at subsistence level. Therefore, each farm is managed for the production of household requirements for fruits, vegetables, spices, fuel, timber etc. Under this situation of land management, the component crops in the land management system constantly compete for various growth resources such as light, space, water and nutrients. If the species mixture in the agroforestry system is not scientifically

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blended, there is a possibility of productivity impairment in the system (Sujatha and Bhat 2013). Originally, the areca-based cropping system was practiced mainly through organic farming, particularly on the west coast of India. Recently, an increase in subsidies for synthetic fertilizers and plant protection chemicals has promoted the adoption of chemical-based nutrients and plant protection practices. The use of local varieties, reduced land availability due to iron and aluminium ore mining, elevated cost of production, shortage of labour, pests, diseases, and human-wild animal conflict, alone or in combination, have considerably reduced system production over the years.

Good crop management practices, such as crop nutrition, irrigation, weeding, and plant protection measures, are prerequisites for obtaining higher productivity and multiple co-benefits from organic farming. From the study conducted by Albizua *et al*. (2015) revealed that ley incorporation and organic manure incorporation could promote ecosystem services in conventional farming systems in Sweden. Similarly, efficient nutrient management improves soil organic matter and enhances soil nutrient availability in coconut-clove-banana-pineapple multi-storeyed cropping systems (Palaniswami *et al*. 2007). Cerda *et al*. (2017) highlighted the efficient management of coffee-based agroforestry systems to improve soil fertility and conserve natural resources. Vermicompost application increased soil organic carbon and phosphorus availability in laterite soil compared with chemical fertilizers only in arecanut orchards on the west coast of India (Sujatha and Bhat 2012). Several earlier studies on arecanut-based agroforestry systems have largely confined their studies to species compatibility, productivity, and profitability analyses. Comprehensive information on soil health and quality indexing under various nutrient management practices of arecanut-based agroforestry systems is lacking. This study was conceptualized with the objective to evaluate the effects of different nutrient management practices (no manuring, organic farming, and integrated nutrient management) on key soil quality indicators in arecanut-based agroforestry systems. In this study, we analyzed the effects of various nutrient management practices on the maintenance of soil fertility and Soil Quality Index (SQI) in an arecanut-based agroforestry system.

MATERIALS AND METHODS

Experimental design: A field survey was undertaken during 2021–22 among 70 farmers in five major arecanut growing subdivisions of Goa: Ponda, Bicholim, Satari, Pernem, and Canacona. The surveyed area in Goa primarily consisted of sloping and undulating terrains, where most of Arecanut-Based Cropping Systems (ABCS) were found. Farmers were classified into three categories based on their nutrient management practices over the past 15 years, viz. No Manure (NM); Organic Farming (OF); and Integrated Nutrient Management (INM). NM plots were characterized by neglected farms with no external addition of organic manure or inorganic fertilizers. These plots only received occasional irrigation and weed management. In contrast, farmers practicing organic farming used farmyard manure, green leaf manure, and recycled organic residues available on their farms to implement various organic farming practices. INM farmers followed nutrient management practices using both organic manure and inorganic fertilizers along with pesticide use for pest control. Goa experiences a typical hot and humid climate, with temperatures ranging between 17 and 35°C and annual rainfall varying from 2,500–3,200 mm. The region receives most of its rainfall during the south-west monsoon season from June–October. The soils in the area are mainly lateritic, coastal saline, clay, and sandy, with high ferric aluminum oxide content. Inland and along riverbanks, soils tend to be alluvial or loamy. These soils are mineral-rich and contain a significant amount of humus, which makes them favourable for the cultivation of plantation crops.

Soil Sampling and analysis: Soil samples were collected from each of the three nutrient management systems at a depth of 0–30 cm. Nine farms were sampled in each nutrient management system, and composite soil samples were prepared by combining individual soil samples. The soil samples were transported to the laboratory for further analysis. In the laboratory, the soil samples were sieved using a 2 mm mesh to remove any coarse particles. Soil fertility was assessed by analysing soil samples for various parameters, including soil pH, Bulk Density (BD), Soil Organic Carbon (SOC), nitrogen (N), phosphorus (P), potassium (K), sulphur (S), and micronutrient contents, such as iron (Fe), copper (Cu), manganese (Mn), zinc (Zn), and boron (B). In addition to nutrient content, the study also examined soil microbial properties. Measurements were taken for Microbial Biomass Carbon (MBC), dehydrogenase (DHA), and urease using standard methodologies. By conducting comprehensive soil analyses, this study aimed to obtain a thorough understanding of the soil properties and fertility status within the different nutrient management systems under evaluation.

Soil quality index: Based on the method suggested by Andrews *et al*. (2002), we assessed the soil quality index (SQI) of arecanut-based agroforestry gardens with varying nutrient management. This study used SPSS (version 9.0) to perform Principal Component Analysis (PCA) to establish a Minimum Data Set (MDS) for better comparison. For each principal component (PC) with an eigenvalue >1, variables with absolute factor loading within 10% of the highest absolute loading were retained. Where multiple variables met this criterion within a PC, correlation analysis was used to eliminate redundancy. Subsequently, these MDS indicators were normalized to unitless scores (0–1) based on soil function performance using a non-linear scoring method (Andrews and Corroll 2001), considering both MDS and weighted SQI approaches to minimize redundancy. The soil indicators used in this study were predominantly 'positive' Standard Scoring Functions (SSF). Thus, the non-linear score using a positive SSF was estimated using the following formula:

$$\mathrm{NL}(x) = \frac{1}{1+\left(\frac{x}{B}\right)^{-b}}$$

where x, Observed value of the soil variable; B, Baseline (the midpoint of the upper and lower thresholds); and –b, Slope of the equation. The weighted additive SQI is computed using the following formula:

$$\mathrm{SQI}=\sum_{i=1}^{n} V_i B_i$$

where V_i, Weight of the indicator based on the PCA; B_i, Score of the indicator; and n, Number of indicators.

Statistical analyses: One-way analysis of variance was performed to determine the differences between different indicators of soil quality using SAS (Version 9.2). The separation of means was subjected to Tukey's honest significant difference test. All statistical significance tests were performed at P=0.05.

RESULTS AND DISCUSSION

Maintenance of soil fertility: The bulk density (BD) of the soil in the arecanut-based agroforestry systems showed significant differences (P< 0.05) (Table 1). Notably, the NM plots exhibited the highest BD value of 1.36 M g/m, whereas the OF plots displayed the lowest BD value of 1.31 M g/m. The soil *p*H of the ABCS was consistently acidic across all nutrient management systems, with no significant differences observed between them. However, significant variations were observed in soil organic carbon (SOC) concentrations. The INM farms displayed the highest SOC concentrations (1.67%), followed by the OF plots (1.63%) (Table 1). In terms of available nutrients, OF plots showed significantly higher levels of available nitrogen (N), potassium (K), sulphur (S), and boron (B) than other nutrient management systems (Table 1). The INM plots also exhibited relatively high values for these nutrients, although this was not as pronounced. Available phosphorus (P) and other micronutrients (Fe, Cu, Mn, Zn), however, doesn't showed significant differences among the nutrient management systems. Implementing organic farming practices consistently throughout the year had a positive impact on the soil microbial properties. The microbial biomass carbon (MBC) and urease activity (UA) significantly improved in OF plots compared to NM plots, with values of 615.9 µg C/g and 117.4 µg urea/g/h, respectively (Table 1). These values are similar to those observed in the INM plots. Notably, the highest dehydrogenase activity (DHA) was observed in the INM plots at 183.5 µg TPF/g/day. Enhanced microbial biomass carbon (MBC) and enzymatic activity observed in organic farming (OF) and integrated nutrient management (INM) systems have contributed to improved soil biological activity. This increase likely facilitated the mineralization of organic matter and enhanced the availability of nutrients within these systems, surpassing the nutrient availability in the no-manuring (NM) system. As a result, intercrops in the OF and INM systems potentially experienced better root growth and nutrient uptake, particularly in the deeper soil layers. Similarly, Roy and Hore (2011) suggested that incorporating bio-organic nutrient management practices into an intercropping system of arecanut and turmeric resulted in increased nutrient availability and water retention in the cropping system.

Soil quality index (SQI): Seven variables were selected

Table 1 Soil quality indicators influenced by different nutrient management practices

Ecosystem service	Soil quality indicators	NM (14)	OF (34)	INM (22)
Maintenance of soil fertility	Bulk density (Mg/m^3)	1.36^a	1.31^b	1.35^a
	Soil *p*H	6.7^a	6.8^a	6.76^a
	Soil organic carbon (%)	1.04^b	1.63^a	1.67^a
	Available nitrogen (kg/ha)	97.24^b	150.07^a	150.8^a
	Available phosphorus (kg/ha)	6.78^a	6.87^a	6.67^a
	Available Potassium (kg/ha)	280.9^b	390.8^a	444.1^a
	Available Sulphur (kg/ha)	2.22^a	1.93^a	1.75^a
	Available Boron (ppm)	1.14^b	1.32^a	1.24^{ab}
	Available Fe (ppm)	52.92^a	58.73^a	77.19^a
	Available Cu (ppm)	10.73^a	11.88^a	15.1^a
	Available Mn (ppm)	111.57^a	116.06^a	129.69^a
	Available Zn (ppm)	6.60^a	7.66^a	6.67^a
	MBC (Mg C/g)	404.4^b	615.9^a	581.3^{ab}
	DHA (Mg TPF/g/day)	164.8^a	176.2^a	183.5^a
	UA (Mg urea/g/h)	47.6^b	117.4^a	108.4^a

NM, No manuring; OF, Organic farming; INM, Integrated nutrient management; MBC, Microbial biomass carbon; DHA, Dehydrogenase activity; UA, Urease activity.

Table 2 Principal components analysis (PCA) of soil quality indicators

	PC1	PC2	PC3	PC4	PC5	PC6
Eigenvalue	2.641	2.448	1.552	1.417	1.271	1.090
Variance (%)	17.606	16.320	10.347	9.445	8.476	7.264
Cumulative variance (%)	17.606	33.925	44.272	53.717	62.193	69.457
Factor loading/eigenvector						
*p*H	0.078	-0.096	0.305	-0.515	0.584	-0.183
BD	-0.030	**-0.755**	0.108	0.010	0.099	0.024
SOC	-0.046	**0.815**	0.165	0.036	-0.053	-0.026
N	0.184	0.603	0.051	0.013	0.054	-0.111
P	0.050	0.124	0.268	-0.155	**-0.822**	0.015
K	0.007	0.407	0.302	0.123	0.459	0.212
S	-0.262	0.039	-0.139	-0.427	0.007	0.552
B	0.257	-0.220	0.060	0.153	-0.018	**0.757**
Fe	-0.136	0.305	0.391	0.634	-0.099	0.307
Zn	-0.074	0.000	**0.898**	-0.177	-0.003	0.013
Cu	-0.190	0.090	0.774	0.188	-0.059	-0.042
Mn	0.107	-0.063	-0.076	**0.783**	0.174	-0.092
MBC	**0.894**	0.077	-0.013	-0.100	0.018	0.064
DHA	0.812	-0.103	-0.206	0.131	-0.085	-0.135
Urease	0.774	0.359	-0.127	0.098	0.073	0.223

BD, Bulk density; SOC, Soil organic carbon (%), MBC, Microbial biomass carbon; DHA, Dehydrogenase activity, NM, No manuring; OF, Organic farming; INM, Integrated nutrient management.

for the minimum dataset (MDS) and transformed using non-linear scoring functions (Table 2). These included microbial biomass carbon (MBC) in PC4, phosphorous (P) in PC5, and boron (B) in PC6. BD was considered as 'lower is better' and all other variables were considered as 'higher is better" because most of the selected variables, such as P, B, and Zn, were found to be low in the soil. The weighted factors (percentage variation of each PC divided by the cumulative percentage variation explained by all PCs) for PC1, PC2, PC3, PC4, PC5, and PC6 were 0.25, 0.23, 0.15, 0.14, 0.12, and 0.10, respectively. The continuous addition of organic matter in terms of FYM, green leaf manuring, and mulching with crop residues resulted in a higher SQI in the OF plots (0.61), which was consistent with the combined application of organic and inorganic nutrients in farms (Fig. 1). The lowest SQI was observed in the NM plots, indicating deterioration in soil quality over the year (0.39). The increase in the availability of major nutrients in the INM and OF observed in the present study is consistent with previous reports (Baishya *et al*. 2015, Saha *et al*. 2010). The increased SOC content and decreased BD in the OF and INM systems could be related to the in situ and ex situ addition of organic matter through dead and decayed roots, litterfall, and reduced/no-tillage practices. The higher MBC, DHA, and urease values in the OF and INM systems may be due to better substrate availability for microbial growth in these systems than in the NM system (Majumder *et al*. 2008). The decrease in MBC and enzymatic activity in NM indicates that the soil capacity for C and other nutrient cycling under such systems has reduced in the absence of adequate soil organic matter over the years. The stronger relationship between biomass turnover and SQI implies a better nutrient management system enhances nutrient recycling, microbial activity and organic matter use, and sustains the agroecosystem. (Ango *et al*. 2014) reported that balanced fertilization along with manures and good agronomic management is a prerequisite in maintaining soil quality under a long-term cropping system in an acidic Alfisol. Dodiya (2018) reported that legume intercropping and management practices increased nutrient availability and nutrient recycling and improved

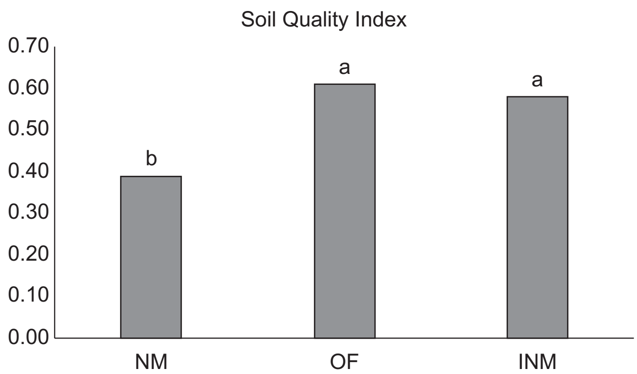

Fig. 1 Effect of different nutrient management practices on soil quality index.

soil fertility in arecanut intercropping systems. Hairiah *et al*. (2006) reported that increased organic matter addition increases dry matter production, soil microbial activity, and earthworm density.

The effectiveness of different nutrient management systems in improving soil quality depends mainly on both the level of management and biomass turnover in the arecanut-based cropping system. The different indicators of the soil quality index were significantly influenced by the nutrient management practices. Furthermore, the study also highlights the importance of biomass addition in improving soil carbon sequestration to make the system more climate-resilient. This indicates that it is possible to increase the provision of ecosystem services without affecting environmental quality. These results also suggest that soil fertility enhancement is dependent on biomass turnover and the level of management in the system. This study concludes that organic farming is the best nutrient management practice to improve soil quality and energy efficiency and to enhance the environmental quality of arecanut-based cropping systems in the west coast of India.

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