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An Appraisal of the Potential of Sequestering Carbon through Pomegranate Orchards in India

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Abstract: Pomegranate is an important arid and semi-arid fruit crop of Indian origin. Land use change from agriculture to pomegranate orchards not only enhances farmers' income but also helps in sequestering carbon and provides additional ecosystem services. Assessing carbon stocks and stock changes in fruit orchards is crucial under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. In this context, we conducted a study to estimate carbon stocks in pomegranate orchards in India. We developed an exclusive allometric equation to estimate pomegranate tree biomass and collected extensive samples of trees, litter, weeds, and soil. We grouped pomegranate-growing areas by similarity in variety, soil, and climate, and then calculated the carbon held in these pools. Finally, we computed the carbon sequestered by pomegranates per hectare, providing valuable insights for climate change mitigation efforts. The national-level carbon storage in pomegranate orchards was then computed by multiplying the area occupied by pomegranate in these regions by the amount of carbon sequestered in one ha of land. Nearly 42.49 mt of carbon is sequestered in the pomegranate orchards of the country with 18.42 mt (43.36% of the total CS) stored in tree biomass and 24.1 mt (56.71% of the total CS) stored in soil. This study underscores the important role of pomegranate orchards in India, not only as a lucrative agro-economic venture for farmers but also as a significant contributor to carbon sequestration and overall ecosystem services. Such insights are essential for guiding sustainable land use practices and aligning agricultural efforts with global climate change mitigation strategies.

Key words: Allometric equation, carbon sequestration, non-destructive method, pomegranate orchards, tree biomass.

One-half of the terrestrial ecosystem carbon sink is held by forests. It is the most significant land-based carbon sink (Hui *et al*., 2015, Lal and Singh, 2000). During the initial years of establishment, forests may sequester similar amounts of carbon that are sequestered by short-lived fruit orchards such as pomegranate. A literature survey has shown that the information on the contribution of orchards to the carbon cycle, like C storage (Procter *et al*., 1976) root respiration (Sekikawa *et al*., 2003, Wang *et al*., 2007) and net CO_2 flux (Sofo *et al.,* 2005) is limited. The potential for C credits based on standing biomass in orchards compared to forest stands growing in the same climate zone is limited. Current research on orchards is largely based on temperate regions, with a focus on apple and citrus orchards. However, direct comparisons are limited due to differing methodologies. Notably, existing studies have only considered tree biomass in orchards, overlooking indirect carbon emissions linked to orchard management practices. These practices include periodic additions of organic materials and soil organic matter decomposition rates, which significantly impact carbon sequestration. A more comprehensive approach is necessary to accurately assess carbon stocks in orchards (Poulstian *et al*., 2019). Whereas in forests, such external inputs are either nil or limited and are encouraged through closed internal cycling. Information is lacking on the role of litter fall like flowers, fruits, leaves, pruned biomass, microbial respiration, and rhizodeposition in the overall C balance of an orchard. This is determined by planting density, canopy management, tree age, genotype, fruit yield, and external inputs.

The pomegranate, a shrub known for its natural tendency to develop multiple stems and a bushy appearance, stands as one of the most sought-after fruit crops in India. With an annual growth rate exceeding 20% in both area and production, it has become a significant player in the agricultural landscape (Ganeshamurthy, 2023a). In India, the cultivation of pomegranate spans 0.28 mha, yielding a remarkable 3.186 mt of fresh fruits annually (Ganeshamurthy, 2023a). However, the expansion of pomegranate cultivation involves land use changes (LUC), which, according to research (Ganeshamurthy *et al.,* 2019), contributes significantly to greenhouse gas (GHG) emissions related to production. Environmentalists are particularly concerned about the impact of these LUCs on the carbon cycle, as they can potentially lead to abrupt changes. The choice of new crops during such transformations may result in either net carbon sequestration in the biosphere or the liberation of carbon in the form of CO_2, depending on the nature of the previous land use (Ganeshamurthy *et al*., 2019).

This issue extends beyond India and holds special importance in regions worldwide experiencing rapid LUCs. Notably, the pomegranate's perennial nature provides a distinct advantage when replacing agricultural crops, as it contributes to carbon sequestration. This environmental benefit adds a layer of significance to the global discourse on sustainable agriculture and land management practices. It is also a mandate for the country to quantify the carbon pool from agriculture and horticulture, as India is a signatory to climate change agreements such as the Paris Agreement (UNFCCC, 2016), which insists on long-term low greenhouse gas emission development strategies. Pomegranate is cultivated only on agricultural lands, which are converted into a form of agroforestry, and these orchards more or less behave like disturbed forests (N.H.B. 2021, Sekikawa *et al*., 2003). In this paper, we report the estimation of the carbon sequestration potential of pomegranate orchards in India.

Materials and Methods

Selection of orchards and sampling

Pomegranate cultivation is spread in many states in the arid, semi-arid and subtropical regions of India (Fig. 1, Table 1). The practical challenges of sampling over such vast areas have prompted the grouping of pomegranate-growing states based on climate similarity and dominant pomegranate varieties. This grouping allowed for a more nuanced understanding of the carbon sequestration potential of pomegranate orchards, crucial for formulating sustainable land use strategies in the context of climate change. Hence, the pomegranate growing states in these regions were grouped for sampling purposes based on climate similarity and dominance of variety of pomegranate grown. In these areas, an extensive survey was carried out to collect allometric data.

Recording of allometric data

Recording allometric data and development of allometric equation are described elsewhere (Ganeshamurthy *et al*., 2023a). Briefly allometric data was collected from one hundred randomly selected bushes from each of the pomegranate growing regions. We used the allometric equation developed for pomegranate by Ganeshamurthy *et al*. (2023a) for estimating the above-ground and below-ground biomass of bush trees. The measurement included the number of stems (NS) originating from the

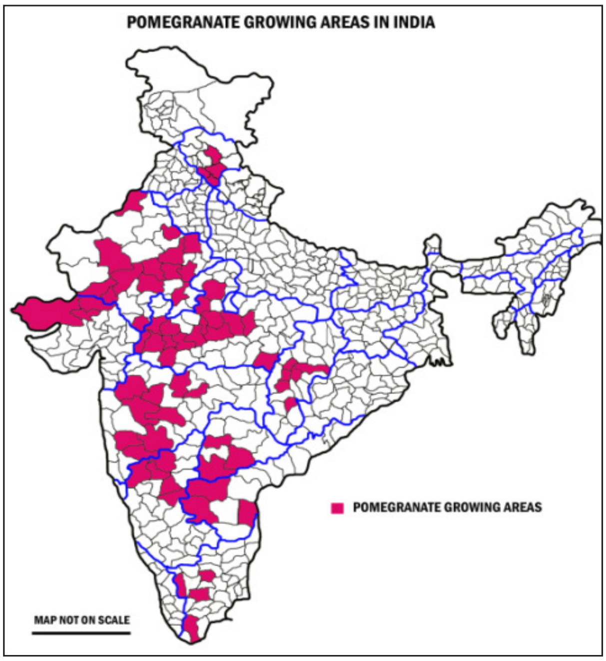

Fig. 1. Distribution of pomegranate growing regions in India (2021-22) (■ Pomegranate growing area. Map not to scale).

ground and the girth of each of the stems (SG) (In India multiple stem systems are practiced and hence NS is selected as an allometric parameter). Briefly, the study involved destructive sampling of over 224 pomegranate bushes (cv. Bagwa) ranging in age from 3 years to 20 years. The bushes were completely uprooted to a depth of one meter to recover the roots completely using a JCB after recording the height and number of stems of each plant and their girth at the base. The tree biomass was recorded fresh for both above-ground and below-ground portions. Moisture content was determined, and dry weight was computed from the green weight.

Different statistical models were used to estimate the bush biomass, like the multiple linear regression model, *the logistic model, the Gompertz model,* and the power model. Based on the best fit, the power model was used for the estimation of bush biomass.

Pomegranate Power Model

$Y = 0.215\ X^{1.998}\quad R^2 = 0.979$

where $X = (SG \times NS)$

The use of the allometric equation developed for the Bagwa variety of pomegranate is applicable to all other varieties due to several reasons. Firstly, all pomegranate varieties share a similar botanical structure and growth pattern, which allows the use of same underlying principles of the allometric equation developed for one variety to be applicable across different varieties. Secondly, the physiological processes related to biomass accumulation and carbon estimation are

Table 1. Area and production of pomegranate in major pomegranate growing states of India

State	Districts	Area, 000 ha	Production (000 metric tons)	Dominant variety
Maharashtra	Solapur, Nashik, Sangli, Satara, Ahmednagar and Pune and to a limited extent in Osmanabad, Jalna, Beed, Aurangabad, Jalgaon and Dhule	171.02	1,795	Bagwa, Solapur Lal, Ganesh
Gujarat	Kutch, Banaskantha, Ahmedabad, Sabarkantha and Bhavnagar	44.57	684	Bagwa, Dhokla, Jalore seedless,
Karnataka	Bijapur, Bagalkot, Koppal, Belgaum, Gadag, Bellary, Raichur, Tumkur, Chitradurg and Davanagere districts	27.37	297	Bagwa, Solapur Lal, Rubi
Andhra Pradesh	Anantapur Kurnool,Chittur,	18.7	280	Bagwa, Araktha
Madhya Pradesh	Khargone, Shajapur, Khandwa, Dhar, Dewas, Ratlam, Ujjain and Vidisha	8.59	103	Bagwa, Ganesh, Araktha
Rajasthan	Jaipur, Ajmer, Alwar, Tonk, Sriganganagar, Pali, Kota, Jalore, Banswara, Sawai Madhopur, Bhilwara, Jhunjhunu, Bikaner and Sirohi	10.84	77	Shendri, Kesar, Araktha, Bagwa
Telangana	Rangareddy, Medhak, Mehaboobnagar, Nalgonds	1.29	18	Bagwa, Ganesh
Chattisgarh	Raipur,Durg,Mahasamund	0.90	6	Bagwa, Rubi
Tamil Nadu	Salem, Coimbatore and Periyakulam	0.58	4	Bagwa, Ganesh, Rubi
Himachal Pradesh	Solan, Kullu, Sirmour	2.83	3	Anardana type, Daru, nana
All India		288	3270	

consistent among various pomegranate types, making the equation a reliable tool for extrapolation. Finally, empirical evidence from studies suggests that the differences in growth dynamics between pomegranate varieties are minimal, thus supporting the generalization of the Bagwa-specific equation to other varieties for practical and efficient carbon estimation.

For below-ground biomass estimation, we followed the ratio of 1:0.231 as suggested by Ganeshamurthy *et al*. (2023a) for pomegranate.

Using the allometric data, the bush biomass of these orchards was computed, and the total bush biomass of each state was computed by multiplying the biomass produced per ha with the total acreage in that particular state.

Samples of stem, twigs, and mature leaves were collected from 20 random trees/bushes from each sampling area for estimation of carbon content. These samples were pooled, washed, and dried at 65°C in a hot-air oven until they reached a constant weight. The samples were then powdered for C estimation.

Litter and weed sampling was conducted in a representative area of orchards where the litter was left unattended. Samples of litter and weed biomass were collected, dried, and processed for carbon estimation. In cases where direct sampling was not possible, data was obtained from published works or through personal contacts with authors from these states. The carbon content of pomegranate bush samples was estimated using a CHNS analyzer (Elementar) and expressed as a percentage of carbon in the sample. Similarly, the litter and weed biomass collected from these orchards was processed and analyzed for its carbon content using the same CHNS analyzer, with the results also expressed as percent carbon in the sample.

Soil carbon stocks

Getting representative data on the soil carbon stock of a region is a difficult task. Arriving at a state-wise average soil carbon stock was practically difficult because the data is not available for a political boundary-based average SC as no such effort has been made in India (Ganeshamurthy *et al*., 2019). Further, whatever data were available they were generated from agricultural lands mainly cultivating annual crops and hence do not represent a perennial crop system. The Forest Survey of India has made efforts to generate state-wise soil carbon stocks of forests, and the latest data was published in 2021 (FSI.2021). By and large, fruit crops imitate a disturbed forest ecosystem. The sampled orchards were aged 10 years and older. These orchards have attained steady-state equilibrium with respect to soil organic carbon similar to that of a forest ecosystem despite the differences in the management as long term stabilization of soil organic carbon is considered. As a result, we used this data to calculate the state average values of SC. The method adopted by FSI is similar to those normally adopted to estimate soil carbon stocks. Briefly, the method followed by FSI for collecting the data on SC is given here. Representative sites (ten sites from each region) were selected from different regions of the state. While collecting the soil sample, the floor was first swept, and then a pit was dug, and a composite sample was collected, analysed for organic carbon content, and used for the calculation of the SC in the soil profile.

The C held in pomegranate bushes was calculated based on the C content and the dry biomass of different parts of the trees.

Results and Discussion

Pomegranate is a bush with multiple stems emerging from the ground. The number of such stems (NS) vary from place to place. The NS in different states varied from 3.26 to 3.82, with a mean of 3.54 across the country (Table 2). There was only a small difference in the girth of the stems (SG) in different regions. Depending upon climate and variety, the SG varied from 7.64 to 8.44 cm in different states, with a mean value of 7.73 cm. However, within this range, the girth of trees was lower in Tamil Nadu (7.64 cm) and Himachal Pradesh (7.73cm), while the highest girth was recorded in Andhra Pradesh, Karnataka, and Maharashtra (8.44 cm). The robustness in the growth of pomegranates was higher (8.44 cm) in regions representing semiarid climates (Andhra Pradesh, Karnataka, and Maharashtra) than in true tropical (7.64 cm) and subtropical (7.73 cm) regions. The product SG × NS was used as the allometric parameter to calculate the above-ground biomass of pomegranate bushes following the allometric equation developed for pomegranates by Ganeshamurthy *et al*. (2023a).

Table 2. Mean allometric parameters and tree carbon sequestered in pomegranate orchards in India (Range)

States/UT	Mean No of stems (100 trees)	Mean Girth of stem, cm (100 trees)	Stem Girthx (No. of stems)	AGB (kg tree^{-1})	AGB Carbon (kg tree^{-1})	BGB (kg tree^{-1})	BGB Carbon (kg tree^{-1})	Total Carbon (kg tree^{-1})	*Total tree Carbon t ha^{-1} 4x3=833 plants/ha
Maharashtra	3.46 (3.02-3.67)	8.44 (7.96-8.53)	29.20	131.81	62.74	30.45	14.50	77.24	64.34
Gujarat	3.37 (2.89-3.54)	8.27 (8.02-8.41)	27.87	120.10	57.16	27.74	13.21	70.37	58.62
Karnataka	3.46 (3.17-3.59)	8.44 (7.93-8.67)	29.20	131.81	62.74	30.45	14.50	77.24	64.34
Andhra Pradesh	3.46 (3.22-3.61)	8.44 (8.11-8.65)	29.20	131.81	57.94	28.12	13.39	71.34	59.42
Madhya Pradesh	3.82 (3.67-3.98)	8.06 (7.73-8.28)	30.79	146.54	69.75	33.85	16.12	85.88	71.54
Rajasthan	3.37 (3.16-3.54)	8.27 (7.98-8.43)	27.87	120.10	57.16	27.74	13.21	40.55	33.78
Telangana	3.46 (3.27-8.60)	8.44 (8.23-8.61)	29.20	131.81	56.63	27.48	13.09	69.72	58.08
Chattisgarh	3.82 (3.56-3.98)	8.06 (7.68-8.27)	30.79	146.54	64.12	31.12	14.82	78.95	65.76
Tamil Nadu	3.76 (3.56-3.94)	7.64 97.49-7.82)	28.73	127.61	60.74	29.48	14.04	74.78	62.29
Himachal Pradesh	3.26 (3.07-3.46)	7.73 (7.59-7.94)	25.20	98.20	46.74	22.68	10.80	57.55	47.94
All India Mean	3.52	8.18	28.80	128.63	59.57	28.91	13.77	70.36	58.61

The above-ground biomass of pomegranate bushes in different states varied from 98.20 kg m^{-2} to 146.54 kg m^{-2}. Above-ground biomass averaged across states was 128.6 kg bush^{-1}. The data varied with the groups of states for sampling (Table 2). The AGB recorded were higher in Madhya Pradesh and Chhatisgarh (146.54 kg bush^{-1}), followed by Andhra Pradesh, Karnataka, and Maharashtra (131.81 kg bush^{-1}), and were relatively lower in Rajasthan and Gujarat (120.10 kg bush^{-1}) and Himachal Pradesh (98.2 kg bush^{-1}). This trend coincided with the climate, which favoured pomegranate growth in semiarid states.

Published information on pomegranate bush biomass is very limited. However, Dhanumjayarao and Subramanyam (2010) reported similar growth of pomegranate in the Anantpur district of Andhra Pradesh. Similarly, the below-ground biomass was estimated following the root-to-shoot ratio of 0.231 recommended by Ganeshamurthy *et al*. (2023a) for pomegranate. BGB's (Table 3) trend followed a similar pattern as that of AGB, as it was only a conversion factor of AGB. The pomegranate bush BGB in different states ranged from 22.68 kg bush^{-1} to 33.85 kg bush^{-1}. The average tree root biomass across all states was 28.91 kg bush^{-1}. Similar to the AGB, the BGB recorded was higher in Madhya Pradesh and Chhatisgarh, followed by Andhra Pradesh, Karnataka, and Maharashtra (30.45 kg bush^{-1}), and were relatively lower in Himachal Pradesh (22.68 kg bush^{-1}). Utilizing the mean carbon content of the above- and below-ground biomass, the total above- and below-ground carbon sequestered by pomegranate bushes was estimated. The total carbon sequestered per pomegranate bush ranged from 40.55 to 85.88 kg bush^{-1} across the country. The pomegranate bush sequestered 70.36 kg C bush^{-1} across India.

The floor-level C sequestration includes contributions from the bush biomass and also the contributions from weeds and litter. The weeds collected from sampled orchards were analysed for their C content. These weeds are generally seasonal and ephemeral and grow profusely during the monsoon. On the other hand, litter biomass is higher during the fruiting season (Ambi, Mrig, and Hasta bahars) when the senesced leaves (mainly through induced defoliation by spraying ethereal to induce flowering) and fruit parts drop to the ground. Often, the weed biomass exceeds the litter biomass in this country. Both weed and litter biomass enter the C cycle and contribute to the SOC.

Table 3. Litter and weed biomass carbon in pomegranate orchards in India

States/UT	Weed biomass (kg ha^{-1})	Weed Carbon (kg ha^{-1})	Litter biomass (kg ha^{-1})	Litter carbon (kg ha^{-1})	Total carbon (Weed + Litter) (kg ha^{-1})	Total carbon (Weed + Litter) (t ha^{-1})
Maharashtra	1807	840.26	1304	595.93	1436.18	1.44
Gujarat	1526	709.59	1440	658.08	1367.67	1.37
Karnataka	2019	938.84	1460	667.22	1606.06	1.61
Andhra Pradesh	2049	952.79	1540	703.78	1656.57	1.66
Madhya Pradesh	2332	1084.38	1460	667.22	1751.60	1.75
Rajasthan	1142	531.03	1438	657.20	1188	1.19
Telangana	2049	952.79	1540	703.78	1656.57	1.66
Chattisgarh	1941	902.57	1460	667.22	1569.78	1.57
Tamil Nadu	2164	1006.26	1460	667.22	1673.48	1.67
Himachal Pradesh	1294	601.71	1380	630.66	1232.37	1.23
All India(Mean)	1832	852	1448	662	1514	1.52

Weed biomass varied from 1142 kg ha^{-1} in Rajasthan to as high as 2164 kg ha^{-1} in Tamil Nadu. The mean weed biomass in pomegranate orchards in the country as a whole was 1832 kg ha^{-1}. The weed biomass records were higher in Madhya Pradesh (2332 kg ha^{-1}), followed by Tamil Nadu (2164 kg ha^{-1}), and were relatively lower in Rajasthan (1142 kg ha^{-1}) and Himachal Pradesh (1294 kg ha^{-1}) (Table 3). The differences are attributed to the active monsoon period and the general management of orchards. This is reflected in the C captured through weeds in different regions. The litter biomass in orchards varied from 1304 kg ha^{-1} in Maharashtra to as high as 1540 kg ha^{-1} in Andhra Pradesh and Telangana. The mean litter biomass in pomegranate orchards in the country as a whole was 1448 kg ha^{-1} (Table 3). The litter biomass depended more on the tree growth, fruiting seasons, fruiting behavior, and variety. The weeds are ephemeral in nature and are both dicots and monocots. The weeds are also specific to the location and season. The ephemeral weeds grow aggressively during the monsoon season and produce biomass rapidly, which can therefore surpass the quantity of litter from the bush biomass in the orchards. Therefore, the litter biomass could be less than the ephemeral weed biomass. As a result, the overall mean carbon credited from weed biomass was 852 kg ha^{-1}, compared to 662 kg ha^{-1} carbon credited from litter (Table 3), indicating that the proportions of both litter and weed carbon are very low when compared to the total C sequestered in pomegranate orchard. In the forest floor, this pool of carbon generally represents less than 10% of the total carbon sequestered. The litter and weed biomass reported under mango, guava, and sapota orchards from India (Ganeshamurthy, 2019, 2023a, 2023b) in these states were very well comparable with the floor-level biomass in these pomegranate orchards. This pool of C is highly variable because it is highly dependent upon the management practices followed in different orchards. If weeding is practiced regularly, the fraction of this C will be low.

In the present study, this proportion contributed about one percent across pomegranate orchards in the country, although there are regional differences in weed and litter biomass production that depend mainly on orchard growth, variety, the bearing habits of the orchards, and the management practises followed in these regions. Weeds and litter, despite their minor contribution to total carbon, play an important role in the C biogeochemical cycle as the interface between vegetation and soil.

Soil carbon

The SOC tends to attain a quasi-equilibrium (QEV) in about 20-50 years under different agricultural systems and in about 30 years for horticultural systems (Arrouays *et al.*, 1995, Batjes, 2001, Dickson and Crocker, 1953, Johnson, 1995, Naitam and Bhattachaarya, 2004). When orchards are planted on agricultural lands, SOC levels often show tooth-like cycles of accumulation and loss during the beginning years and slowly attain an equilibrium level after the accumulation of dry matter and loss of SOC over time. Ganeshamurthy (2012) has shown that horticultural systems under these tropical land uses attain QEV in 25 years. The pomegranate orchards are generally replanted

Table 4. Soil carbon in pomegranate orchards in India

States/UT	Soil C ($t\ ha^{-1}$)	Area (000 ha)	Total soil carbon stock (000 tons)
Maharashtra	88.91	171.02	15205
Gujarat	72.20	44.57	3218
Karnataka	97.16	27.37	2659
Andhra Pradesh	46.02	18.7	861
Madhya Pradesh	78.63	8.59	675
Rajasthan	66.52	10.84	721.
Telangana	76.36	1.29	98.
Chattisgarh	89.09	0.90	80
Tamil Nadu	81.22	0.58	47
Himachal Pradesh	167.10	2.83	473

Source: FSI, 2021. India State of Forest Report, Chapter 9.

after 10-15 years or shifted to new areas and have been more frequently replanted in recent decades. In any case, soils under pomegranate orchards aged 10 years and older have partially reached the QEV stage due to dry matter accumulation and SOC loss over time. This is the age range of the orchards we sampled (10 years). As mentioned, it was difficult to obtain representative state averages of soil C stocks under pomegranate orchards. The majority of published information is about agricultural ecosystems, with very little about horticultural ecosystems.Because state-level SOC stock information from forest ecosystems was available, and pomegranate orchards were more closely related to bush forest ecosystems, we used the available data to compute C stocks by pomegranate orchards. The soil C stocks in different states varied from 46.02 tons ha^{-1} in Andhra Pradesh to 167.01 tons ha^{-1} in Himachal Pradesh (Table 4).

Total C sequestered in orchards

The C-pool compartment of pomegranate orchards is presented in Table 5. As previously stated, soil C played a significant role in all states where pomegranate is grown. Hence the total sequestered C in the pomegranate orchard followed the soil C stocks in different states. Himachal Pradesh had the highest SC stocks, and hence it also had the highest sequestered carbon in sapota orchards (216.26 t ha^{-1}). The total C sequestered in pomegranate orchards was 148.9 t ha^{-1} on average across all states.

The state-wise C sequestration by pomegranate orchard was computed by multiplying the per-hectare C sequestration by pomegranate orchard with the area under pomegranate cultivation in the respective states (Table 6).

The total carbon sequestered in pomegranate orchards in different states was proportional to the area under pomegranate in each state. Maharashtra has the most pomegranate land in India (171.02 thousand ha), and it sequesters the most carbon (26456.79 thousand tons). This is followed by Gujarat with 5891.26 thousand tons. The country as a whole, with 288 thousand hectares of pomegranate orchards, sequestered 42.49 mt of carbon.

The SC is the major C pool in an orchard, and the proportion of soil C always exceeds the tree

Table 5. Carbon pool compartment ($t\ ha^{-1}$) in pomegranate orchards in India

States	AGB Tree C ($t\ ha^{-1}$)	Litter C ($t\ ha^{-1}$)	Weed C ($t\ ha^{-1}$)	Total Above ground C $t\ ha^{-1}$	Root C ($t\ ha^{-1}$)	Soil C	Total Below ground C	Total C sequestered in orchard ($t\ ha^{-1}$)
Maharashtra	52.26	0.60	0.84	53.70	12.08	88.91	101.00	154.70
Gujarat	47.61	0.66	0.71	48.98	11.00	72.20	83.20	132.18
Karnataka	52.26	0.67	0.94	53.87	12.08	97.16	109.24	163.11
Andhra Pradesh	48.26	0.70	0.95	49.91	11.15	46.02	57.17	107.08
Madhya Pradesh	58.10	0.67	1.08	59.85	13.43	78.63	92.06	151.91
Rajasthan	47.61	0.66	0.53	48.80	11.00	66.52	77.52	126.32
Telangana	47.17	0.70	0.95	48.82	10.90	76.36	87.26	136.08
Chattisgarh	53.42	0.67	0.90	54.99	12.35	89.09	101.44	156.43
Tamil Nadu	50.60	0.67	1.01	52.28	11.70	81.22	92.92	145.20
Himachal Pradesh	38.93	0.63	0.60	40.16	9.00	167.10	176.1	216.26

Table 6. Carbon sequestered (CS) in pomegranate orchards in India (tons)

States	Area (000 ha)	Total CS ha^{-1} (t ha^{-1})	Total CS (000 tons)	Total CS (mt)	% contribution tree	% contribution soil
Maharashtra	171.02	154.70	26456.79	26.46	42.54	57.46
Gujarat	44.57	132.18	5891.26	5.89	45.36	54.64
Karnataka	27.37	163.11	4464.32	4.46	40.38	59.62
Andhra Pradesh	18.7	107.08	2002.40	2.00	56.95	43.05
Madhya Pradesh	8.59	151.91	1304.91	1.30	48.08	51.92
Rajasthan	10.84	126.32	1369.31	1.37	47.37	52.63
Telangana	1.29	136.08	175.54	0.18	45.56	54.44
Chattisgarh	0.90	156.43	140.79	0.14	42.86	57.14
Tamil Nadu	0.58	145.20	84.22	0.08	41.25	58.75
Himachal Pradesh	2.83	216.26	612.02	0.61	22.46	77.54
All India				42.49	43.36 (18.42 mt)	56.71 (24.10 mt)

biomass carbon. Other than Himachal Pradesh, the highest soil C stock in major pomegranate belts was recorded in Chhattisgarh (89.09 tones ha^{-1}). In this study, the proportion of soil carbon to total sequestered carbon varied from state to state. It represented 77.54% in Himachal Pradesh, 59.62% in Karnataka, 52.63% in Rajasthan, and 43.05% in Andhra Pradesh, with an average of 56.71%. Since SC in pomegranate orchards is not available, a fair comparison can only be made from the data published on other systems such as mango, sapota, and guava, as well as with forest systems. Gupta (2011) reported that the soil C stock in mango orchards in Mangalore was 41 tons ha^{-1} at the surface and 50 cm depth. Ganeshamurthy *et al*. (2012) reported a soil C stock of 53.7 tons ha^{-1} under mango orchards in India, 54.1 tons ha^{-1} under sapota orchards (Ganeshamurthy *et al*., 2023b) and 48.4 tons ha^{-1} under guava orchards (Ganeshamurthy *et al*., 2023b). Chhabra *et al*. (2003) also reported that the soil C sequestered in Indian forest soils ranged from 37.5 tons ha^{-1} in tropical dry deciduous forests to 92.1 tons ha^{-1} in littoral swamp forests. Our values are fairly similar to those reported in the literature for different regions under different systems.

Area expansion under fruit crops is increasing, and large areas under agriculture are getting shifted to fruit crops. This shift in land use changes the C fluxes under the new system. It is therefore necessary to critically understand the land-use and land-use change dynamics and examine the related changes in C fluxes derived from such land-use change patterns in a given region in order to formulate viable strategies for climate change mitigation. The present study involved a comprehensive effort, above all in the integration of different methodologies for field work and data processing. The study generated unique information on pomegranate orchards. But on a national scale, there is a need to generate information on all such perennial horticulture systems, such as other fruit crops, orchards, plantations, and coffee and tea estates in India, with larger sample sizes, to be able to determine the percentage of carbon sequestered in perennial horticultural crops in the country as a whole.

Because of the increased demand for fresh pomegranate fruits, pomegranate orchards are becoming prime agricultural lands. This is reinforced by the thrust given to horticulture in the country. Large tracts of tribal land and waste and degraded lands in semiarid and subtropical regions of the country, such as Chhattisgarh, Chambal ravines, Madhya Pradesh, etc., are available and can be brought under pomegranate cultivation. Consequently, where forests have disappeared, such lands may be brought under perennial fruit orchards, which reasonably imitate forests, sequester carbon in similar quantities, and can augment climate change risks. Policymakers can refer this information to calculate carbon credits for the benefit of farmers and the local population.

Conclusions

The estimation of carbon stocks, encompassing tree biomass, litter, weed, and soil samples, provides a comprehensive understanding of the carbon sequestration potential across different states. The total carbon sequestered in pomegranate orchards, averaging 148.9 t ha^{-1}, underscores their significant role in contributing to carbon sequestration at the national level. The national-level calculation indicates that India has sequestered a substantial 42.49 million metric tons of carbon in its pomegranate orchards, with tree biomass and soil contributing 43.36% and 56.71%, respectively. These findings highlight the pivotal role of pomegranate orchards in the country's carbon balance and emphasize their ecological significance. The comparison with traditional forest ecosystems and other fruit orchards reveals the comparable carbon sequestration potential of pomegranate orchards, challenging conventional notions about short-lived fruit orchards. The findings of this study not only sheds light on the carbon sequestration potential of pomegranate orchards but also calls for a broader recognition of their ecological importance. The findings provide valuable insights for policymakers, guiding sustainable land use practices and contributing to global climate change mitigation efforts outlined in international frameworks. The study contributes to the growing body of knowledge on the role of agroforestry in carbon sequestration and underscores the need for continued research in understanding and optimizing the ecological services provided by fruit orchards like pomegranate in the context of a changing climate.

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