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Agroecological Aspects of Black Pepper (*Piper nigrum* L.) Cultivation in Kerala: A Review

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ABSTRACT

Black pepper is a very important spice and medicinal crop of India. The country produces about 62,000 metric tonnes of black pepper annually, of which 10–12% is exported. Kerala with an area of 82,761 ha under the crop is a leading producer of the spice in India. It is grown under varied agro-ecologies in the state ranging from sea-level to High Ranges. The crop, a climber, is cultivated either as a monocrop trailed on different multipurpose support trees (called “standards”, e.g. *Ailanthus triphysa, Erythrina indica, Garuga pinnata, Gliricidia sepium* etc.) or in the homesteads along with assorted trees like *Areca catechu*, *Cocos nucifera*, *Artocarpus heterophyllus*, *Mangifera indica* and the like. Trailing a sciophytic (shade-loving) climber on woody perennial support trees makes it a unique agronomic system and an excellent example of agroforestry. Attractive prices, *albeit* fluctuations, long shelf-life of the produce, and the ability to provide a range of ecosystem services including supporting and regulatory services (e.g. carbon sequestration and soil fertility enrichment), make black pepper production an attractive land use option in Kerala. This paper reviews the literature on agroecology of the crop with particular reference to Kerala.

INTRODUCTION

Black pepper (*Piper nigrum* L.) is a spice (Fig. 1) of extraordinary importance in the international trade and is known as the “King of Spices” or “Black Gold”. The crop is thought to have originated in the wet evergreen forests of the Western Ghats in southern India. However, using divergence dating analysis, Sen et al. (2019) have recently shown that the genus *Piper* originated during the lower Cretaceous period in Southeast Asia around 110 Ma (million years ago) and colonized in the peninsular India five times independently, starting from the Oligocene (about 33.9 million to 23 million years before present). *In situ* diversification/evolution and reverse dispersal would have occurred subsequently. The species, *P. nigrum,* might have evolved during the course of such *in-situ* diversification within the wet-evergreen forests of Western Ghats during the Miocene (Sen et al., 2019). Although the timeline of domestication of this crop is not precisely known, it is clear that the crop was cultivated in the state of Kerala for a long time. Indeed, *Krishi Gita* (*A treatise on indigenous farming practices*)*,* the Malayalam verse composed probably *ca.* 15th century CE (Common Era), which describes the agricultural practices of medieval Kerala (Kumar, 2008), mentions about the profitability of cultivating this crop.

Transnational trading in this commodity started very early. For example, as early as the third millennium BCE (Before the Common Era), both Babylonians and Assyrians were trading in spices, primarily black pepper, with the people of the Malabar

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Coast (Rosengarten, 1969). Clearly, the economic prosperity of ancient cities like Alexandria, Genoa, and Venice was linked to the flourishing trade in spices (Rosengarten, 1969). The Jews, Arabs, Romans and the Chinese were also involved in the early trading of this commodity, which was subsequently dominated by the European maritime powers (Disney, 1978; Nair, 2011). Indeed, the European — especially the British — colonisation of the Indian subcontinent is intimately linked to this early trade in black pepper and other spices.

In fact, black pepper is one commodity that influenced and infused the course of geopolitical history of the Indian subcontinent in ways that probably no other agricultural good has shaped it. The course of Indian history would have been different had Vasco da Gama not took of the historic journey from Lisbon in 1497 and landed at Kappad, Calicut (Kozhikode) on 20 May 1498, in search of black pepper (Disney, 1978). This was a major event that led to the subsequent colonialization of the Indian subcontinent. The Arab and Chinese, however, came to India in search of black pepper much before Vasco da Gama. For example, the ancient Egyptians used spices from Kerala to make perfumes and holy oils for mummification of the dead bodies of their kings and other prominent people (Menon, 2007). During the rule of Ming dynasty in China (1368 to 1644 CE), an extensive seaborne commerce was developed to meet the requirement of the Chinese for spices, aromatics and industrial raw materials. Zheng He, the great Chinese voyager, arrived in Calicut (Kozhikode) in search of black pepper and other spices during 1405–1407 CE, nearly a century before the landing of Vasco da Gama in Calicut (Sasikumar, 1995).

Fig. 1. Malabar black pepper berries, a premium black pepper grade of India (Photo: A. Sudhakaran and B. Sasikumar)

Apart from its enormous importance as a commodity of international trade and as a culinary spice, black pepper has many medicinal uses too. The ancient Indian medical texts, such as *Ashtangahridaya* and the *Samhitas*, are replete with references to the use of black pepper in various medical preparations. The pharmacological properties of black pepper are numerous and include antioxidant, anti-obesity, antitumor, antipyretic, anticonvulsant, anti-thyroid, antifungal, antibacterial, insecticidal, hepatoprotective, anti-asthmatic, larvicidal, antihypertensive, anti-inflammatory, antidiabetic, antidiarrheal, immunomodulator, and antiepileptic activities (Butt et al., 2013: Damanhouri & Ahmad, 2014; Joshi, Shrestha, & Adhikari, 2018). In addition, black pepper acts as an anticancer, diuretic, and aphrodisiac agent, besides being a blood purifier, bio-availability-booster, lipid metabolism accelerator, and a stimulant of the gastrointestinal and central nervous systems, having potential to promote antiplatelet activities (Joshi, Shrestha, & Adhikari, 2018).

The cultivation system of black pepper is unique in that it often involves trailing a sciophytic (shade-loving) vine on live support trees or "standards", which makes it an excellent agroforestry system – wherein a cash crop is trailed on a wide spectrum of support trees. This paper is focused on this distinctive cultural system and the ecosystem services they provide. While the article provides an overview of the agroecology of black pepper production in the state of Kerala, in the West Coast of India (Fig. 2), where it is a dominant commercial crop grown under diverse ecological conditions, aspects relating to propagation (KAU, 2017; Ravindran & Kallupurackal, 2012; Thanuja, Hegde, & Sreenivasa, 2002), phytochemistry (Kapoor et al., 2009; Parthasarathy, Chempakam, & Zachariah, 2008), medicinal properties (Butt et al. 2013; Damanhouri & Ahmad 2014; Joshi, Shrestha, & Adhikari, 2018), processing (Dhas & Korikanthimath, 2003), trade (Menon, 2007; Nair, 2004) and pest and disease management (Anandaraj & Sarma, 1995; KAU, 2017; Ravindran, 2000) of black pepper, which are described elsewhere, are not focussed here.

Fig. 2. Map of Kerala (India)

Black Pepper Ecosystems of Kerala

Black pepper is grown all over Kerala under diverse agroecological conditions from the sea-level to the hills of Idukki and Wayanad districts. In different geomorphological zones of the state such as the coastal plains, midlands and highlands, this crop is grown adopting different cultural systems; for example in the coastal plains, the crop is mainly grown in the homegardens, whereas in the midland region, the crop is extensively cultivated on a plantation-scale and on the hills at an elevation of 800–1500 m elevation, the crop is predominantly trailed on the shade trees of coffee (*Coffea* spp.), cardamom (*Elettaria cardamomum*) and tea (*Camellia sinensis)* plantations (Hamza, Sadanandan, & Srinivasan, 2004).

Fluctuations in Area and Production

The crop is cultivated in Kerala over an area of 82,761 ha with an annual production of 36,776 tonnes (DES, 2020). The area and production of this commodity, however, have been fluctuating over the years (Fig. 3). In the past two decades, black pepper cultivation in Kerala peaked during the agricultural year 2005-2006 with an area of 2,37,889 ha. The area, however, declined by 64% and production by 54% between 2005-2006 and 2014-2015 (DOA, 2016) due to a combination of factors. While climatic shifts and disease incidence, especially the dreaded foot rot disease (caused by *Phytopthora capsici*), were responsible for the production losses in no small measure, the methodology adopted for assessing black pepper area since 2011-2012, has contributed to a substantial decline in the area reported – implying that the drop in area, by and large, is a methodological artefact. Indeed, an expert committee of the Department of Economics and Statistics, Government of Kerala proposed a modified methodology for estimating black pepper area in 2011 (DOA, 2016), which was employed in all subsequent assessments. In this modified method, a stand density of 1111 per hectare was considered against 560 per hectare in the previous assessments, resulting in an approximately 50% drop in area between 2010-2011 and 2011-2012.

The state also accounts for about 60 % of the total Indian area of 1,38,930 ha and 59% of its annual production of 62,430 tonnes (MoAFW, 2020). However, due to inefficient production practises and high pest and disease prevalence, Kerala's black pepper productivity is generally lower than other black pepper-growing countries in Southeast Asia and Amazonia; for example, it was 444 kg/ha in 2018-2019 (DES, 2020), as against 3098 kg/ha in Brazil and 4650 kg/ha in Malaysia (http://www.fao.org/faostat/en/#data/QC).

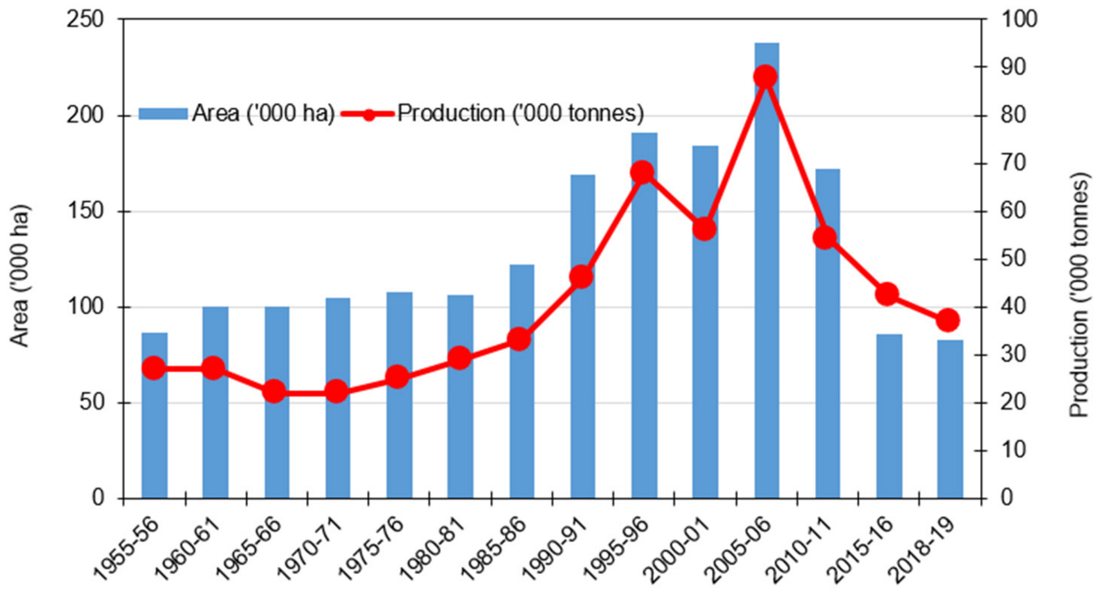

Fig. 3. Quinquennial changes in area and production of black pepper in Kerala (Indiastat-agri indiastatagri.com and DES, 2020)

Climate and Soil

Black pepper generally prefers a humid tropical climate. The black pepper growing areas in India generally receive a mean annual precipitation of 1500 mm to over 4000 mm (Pillay, Sasikumaran, & Ibrahim, 1988). Being a crop of the warm humid tropics, however, it requires approximately 250 rainy days with a total annual rainfall of 2000–3000 mm for vigorous growth and production. The crop does not tolerate excessive heat and dryness and a relative humidity of 60–95% is considered optimal. Although black pepper can tolerate temperatures between 10°C and 40°C, the ideal range is between 23°C and 32°C with a mean annual temperature of 28°C. Optimum soil temperature for root growth is between 26°C and 28°C (Wahid & Sitepu, 1987).

Black pepper generally grows well on a wide range of soils from heavy clays to light sandy clays, having a friable structure and a pH of 5.5 to 6.5. High exchangeable base, organic carbon and micronutrient status, especially zinc, constitute other important soil attributes for this crop. In its natural habitat, it thrives well on red laterite soils. The major soils in the black pepper growing tracts of Kerala include Alfisols, Mollisols, Oxisols and Entisols (Nair, 2011). Well-drained soils having adequate moisture holding capacity, and rich humus and available plant nutrient contents are generally considered essential for sustaining high productivity. The crop is also grown in the areca plantations (*Areca catechu*) with deep alluviums that are sandy or loamy in texture, and moderately rich in plant nutrients (Srinivasan, Dinesh, Hamza, & Parthasarathy, 2007).

Black Pepper + Support Tree System

Broadly, three types of black pepper production systems can be recognized in Kerala: (1) commercial plantations established on cleared sites, where black pepper is the principal crop – mostly existing in a bicultural system involving the vine and support trees (Fig. 4), (2) black pepper vines trailed on the shade trees of tea/coffee/cardamom estates in the midlands and high ranges (Fig. 5 and Fig. 6) and (3) black pepper as a component of the mixed species (polycultural) homegarden system (Fig. 7) – a dominant and time-tested example of sustainable tropical land use system (Kumar & Nair, 2004). While input intensive production practices are adopted for the commercial plantations and, to a great extent, for the vines trailed on shade trees in plantations (KAU, 2017), the largely smallholder homegardening system involves less capital-intensive approaches for production. “Bush pepper”, which is generally grown in pots and fields in small-scale, is another variant of the black pepper production system. As the name signifies, it is a “bush” and does not require any external support for trailing.

Fig. 4. Black pepper + support tree system in Kerala: black pepper vines are trailed on to different live supports, often called standards

Fig. 5. Black pepper vines trailed on silver oak (*Grevillea robusta*) trees in a tea (*Camellia sinensis*) estate in Vandiperiyar, Kerala

Fig. 6. Shade trees in cardamom (*Elettaria cardamomum*) plantations used as support trees for trailing black pepper vines in Idukki district of Kerala

Fig. 7. Black pepper trailed on areca palms (*Areca catechu*) in the Kerala homegarden, which consists of a multitude of tree and other species. *Reprinted/adapted by permission from Springer-Nature (Tropical Homegardens: A Time-Tested Example of Sustainable Agroforestry (Kumar, 2006))*

As regards to standards, tree species such as *Erythrina indica* (Indian coral tree; Fig. 8) and *E. stricta* (corky coral tree) are foremost in many commercial black pepper plantations, while a range of multipurpose trees (MPTs) are used by the homegardeners. Salam et al. (1991) documented 31 tree species that support the growth of black pepper vines in the Kerala homegardens. Indeed, most of the tree components that occur in Kerala homegardens are used for trailing black pepper vines. Tree species such as areca palm, coconut palm (*Cocos nucifera*), jackfruit tree (*Artocarpus heterophyllus*), mango (*Mangifera indica*) and forest trees such as teak (*Tectona grandis*) and *A. triphysa* are a case in point (Manjusha, 2007). Gunaratne & Heenkenda (2004) reported that *Gliricidia sepium* is another useful MPT in this respect. In addition, most shade trees in cardamom, coffee and tea plantations (e.g., *Grevillea robusta*; Fig. 5), and an array of avenue trees and trees on farm boundaries are also used as standards for trailing black pepper vines.

Despite various types of MPTs are being used for trailing black pepper vines, only a few studies have assessed their relative merits. In a comparative evaluation of seven fast growing trees raised from cuttings (*Moringa oleifera, Thespesia populnea, Garuga pinnata, E. indica, Erythrina stricta, Erythrina lithosperma* and *G. sepium*) as black pepper standards, Mathew, Kumar, Babu, & Umamaheswaran (1996) found that *G. pinnata* outperformed all other species in terms of black pepper yield. Kunhamu, Kumar, & Jamaludheen (2012) while comparing the relative performance of black pepper vines trailed on six seedling-grown fast growing multipurpose trees observed that Australian wattle (*Acacia auriculiformis*) and jackfruit tree (*A. heterophyllus*) gave higher yields than *A. triphysa* and *Macaranga peltata*. This implies the importance of selecting the right support trees to maximise black pepper yield, as well as the possibility of using exotic tree species like *A. auriculiformis* for trailing this vine. However, tree management techniques such as pruning and lopping are required to keep the support trees in shape and avoid excessive shading of the vines; otherwise, species such as *A. auriculiformis* (which has a dense spreading crown) may cause over-shading and significantly impact vine output.

An ideal standard or support tree for trailing black pepper vines, therefore, should have light crowns facilitating better light infiltration to the understorey, be tolerant to pests and diseases, be easy to propagate and exhibit rapid growth rates (Kunhamu et al., 2018). Typically, such trees should possess rough, non-exfoliating bark and deep root systems (Kumar, 2007). Non-exfoliating bark is vital to provide anchorage for the vines (on to the tree trunks), while deep penetrating root systems may reduce the potential for inter-specific competition between the vine, generally a surface feeder, and the standards. Biological nitrogen fixation potential, ability to tolerate intensive pruning and lopping, and the capacity to retain foliage during summer (when shade is essential for the vines) and shed the same during the rainy season (the so-called “reverse phenology” as observed in *Faidherbia* (syn. *Acacia*) *albida* in its native drylands of West Africa) constitute other desirable traits in this regard (Kumar, 2007; Kunhamu et al., 2018). Ability of the trees to yield commercially valuable timber, fruits, foliage, green manure etc. (Krishnamurthy, Parthasarathy, Saji, & Krishnamoorthy, 2010) and high carbon sequestration potential **(see section: ecosystem services)** are also important design norms for highly productive and profitable black pepper ecosystems. While the attributes described above constitute the characteristics of an ideal support tree (*ideotype)*, such trees are seldom found in most agroecosystems, implying the need for tree improvement programs to possibly look for such traits.

Black pepper vines are also trailed on various non-living standards, such as concrete posts, granite pillars and wooden poles (e.g. teak poles) and specially devised PVC columns. While dead wood standards are popular in countries such as Malaysia, Viet Nam, Brazil and Indonesia facilitating closer spacing (high stand density) and thereby high yields (Reddy, Sadanandan, Sivaraman, & Abraham, 1992), such systems are relatively new in Kerala. Table 1 provides a comparative account of the living and non-living (dead) supports for trailing black pepper vines. Yield gains owing to the non-competitive nature of non-living supports is clearly an advantage. Kumar & Cheeran (1981), in a comparative evaluation of the living and non-living standards, found that for a relatively shade intolerant black pepper variety such as "Panniyur-1", teak poles (non-living supports) gave higher yields than *E. indica*. Conversely, interspecific competition between the support tree and vines resulted in lower productivity of the *E. indica*-based system. Cheeran, Wahid, Kamalam, Kurien, & Mathew (1992) and Sankar, Wahid, & Kamalam (1988) also reported competition-related yield reduction for vines trailed on *E. indica* and *G. pinnata* standards, compared to that on teak poles. Experimental evidences also suggest that pepper vines and the support trees absorb nutrients from the same soil nutrient pool. For instance, Wahid, Suresh, & George (2004), using ^{15}N-labelled urea, showed that *Erythrina* support trees of black pepper vines absorbed 24 to 40 % of the urea applied to black pepper, implying competition for nutrients especially for nitrogen between the vine and the live support trees. Despite such advantages, non-living supports like teak poles are rarely used for commercial black pepper production in Kerala, presumably because of the high capital costs and durability problems (Kumar, 2007).

What factors make living trees the preferred support for black pepper vines in Kerala are perhaps the low initial cost of establishment and the long-term productivity of such systems. Indeed, the studies cited in the preceding paragraph portraying the advantages of non-living supports are largely snap-shots in time and do not represent long-term evaluations. Sivaraman, Kandiannnan, Peter, & Thankamani (1999), after a review of the agronomic literature on black pepper, concluded that using living standards will increase the productivity of black pepper on a long-term basis. Consistent with this, Kunhamu et al. (2018) found that multipurpose jackfruit trees performed well as a support tree for trailing black pepper and the system maintained high black pepper yields up to about 25 years of tree age. Yet another advantage of using living trees as standards for black pepper vines is the potential for soil fertility enrichment. Kunhamu et al. (2018) and Kunhamu, Kumar, & Jamaludheen (2012) reported that multipurpose support trees of black pepper enriched soil fertility through addition of pruned materials, litterfall, biological nitrogen fixation and rhizodeposition.

Nutritional management of the crop is another key determinant of soil fertility status, apart from the quantity of organic matter returned to the soil through organic recycling. Consistent with this, Srinivasan, Dinesh, Hamza, & Parthasarathy (2007) found that application of NPK at the rate of 100:40:140 kg/ha and organics like farmyard manure (FYM) at the rate of 5.0 kg/vine per annum enhanced soil fertility of black pepper plantations. However, when the crop is not adequately fertilized, competitive interactions between the support trees and the vines are plausible. Excessive shading of the vine is another concern in this respect. To avoid excessive shading and to maintain optimum productivity of the vines trailing on live support trees, proper canopy management practices (pruning, lopping and pollarding) are imperative.

Fig. 8. Black pepper vines trailed on *Erythrina indica* (Indian coral tree), the predominant support tree in Kerala

Table 1. A comparative account on living and non-living support trees for trailing black pepper vines

Parameter	Living standards	Non-living standards
Ability to provide shade during summer	Yes	No
Ability to provide timber, firewood, green leaf manure etc.	Yes	No
Agrobiodiversity conservation	Yes	No
Biological nitrogen fixation potential	Yes, for legumes/ actinorhizal plants	No
Carbon sequestration potential (vegetation and soil)	Medium to high	Nil
Competitive/complementary interactions	Yes	No
Cost of initial establishment	Low	High
Eco-friendly	Yes	No; especially for concrete poles
Height of vines/harvestable height	Variable	Fixed to the column height
Lead time required for planting/trailing pepper vines	1 to 2 years	Simultaneous
Longevity	High	Medium
Mortality of climbing roots due to heating of the supports and poor anchorage of vines	No	Yes, especially for concrete poles
Nutrient cycling and soil fertility enrichment	Yes	No
Pest incidence/damage of the support trees	Yes	Usually no; however, if the central column is filled with coir dust/ compost, foot rot occurs.
Potential for establishing high density plantations	No	Yes
Provision of shade for the vines/shade regulation	Yes	No
Radiation load on the vines in summer	Low	High
Recurring costs: pruning, lopping, and pollarding	Yes	No
Soil microbiological properties	Improved	No effect
Wild animal damage	Yes	Low

Remarks: Synthesized from authors' experience and observations

Nutrient Management of Black Pepper

As mentioned, black pepper production represents a unique cultural system, often involving a live support tree and a sciophytic vine, which throws up daunting challenges in the nutritional management of the crop. The guiding philosophy for nutritional management in most mixed and inter cropping systems is to "adequately and separately fertilize" the component crops in the mixture based on the nutritional requirements of individual crop components, often derived from experiments conducted under monocropping systems. However, such studies are rarely conducted for most multipurpose trees like *E. indica, G. pinnata* and others, which are the common standards for trailing black pepper vines. As discussed earlier, interspecific interactions (often competitive in nature) between the vine and the support trees are also likely under certain situations, implying the need for proper soil and fertilizer management to maintain optimal levels of black pepper productivity.

Generally, yield-based fertilizer recommendations are considered appropriate for black pepper in view of the fact that the quantities of macro and micronutrients exported through harvested produce are directly proportional to crop yield. The general recommendation for >3-year-old vine in Kerala is: 50:50:150 N: P_2O_5:K_2O g/vine/year; but higher doses may be applied at sites where soil fertility is low (KAU, 2017). The chemical fertilizers are usually applied in basins (10–15 cm deep and having a radius of 50–75 cm) around the plant in two split doses: in May-June with the receipt of a few soaking rains and in August-September.

In experimental studies on mineral nutrition of the cultivar "Panniyur-1" on a laterite soil, poor in major nutrients, application of 140 g N, 55 g P_2O_5 and 270 g K_2O/vine/year, gave a significant increase in crop yield and soil availability of N, P and K (Sadanandan, 1994). Application of organic manures such as castor and cotton cakes @ 1–2 kg per plant or poultry manure @ 1–2 kg or cattle manure @ 3–5 kg, 200–300 g NPK (12:12:17) mixture, 500 g of lime and 300 g thermo-phosphate per plant per year in addition to foliar sprays of micronutrients have been suggested for increased crop yields (Sadanandan, Hamza, Bhargava, & Raghupathi, 2000). Cattle manure/compost/green leaves @ 10 kg/vine/year just before the onset of the southwest monsoon, followed by light soil working and liming @ 500 g/vine in April-May (in alternate years), are also recommended for sustaining reasonable levels of productivity under the ecoclimatic conditions of Kerala (KAU, 2017).

The available literature on nutrient management of black pepper has been comprehensively reviewed by Srinivasan, Dinesh, Hamza, & Parthasarathy (2007). Since black pepper is grown on a diverse range of soils with differing nutritional status, it is advisable to develop site-specific fertilizer recommendations (site-specific nutrient management, SSNM) based on soil fertility levels, rather than a generalized fertilizer recommendation. Consistent with this, soil application of zinc (6 kg/ha) as zinc sulphate or foliar spray of Zn (0.5%) during flowering and at the pin-head stage of black pepper has been recommended for Zn-deficient areas and molybdenum (Mo) application (1 kg/ha) for areas deficient in Mo. Soil test-based fertilizer recommendations for specified dry yield levels of black pepper have been developed by the scientists of the Indian Institute of Spices Research, Kozhikode (IISR, 2015). According to Srinivasan, Dinesh, Hamza, & Parthasarathy (2007), integrated plant nutrition management (IPNM) involving organic manures, mulches, chemical fertilizers and biofertilizers are ideal for sustaining soil fertility and productivity. Furthermore, substitution of 50% of the recommended inorganic fertilizer dose with FYM on equivalent nitrogen-basis may increase soil nutrient availability and yield levels (Srinivasan, Dinesh, Hamza, & Parthasarathy, 2007). Organic black pepper production is a relatively recent trend and it is gaining importance day-by-day. However, experimental studies reporting the effects of organic nutrient addition and organic pest management on black pepper are few and far between.

Varietal Performance of Black Pepper

While black pepper yields are generally a function of the local climatic and edaphic conditions, varietal characteristics are key determinants of local adaptability. Presently, there are 21 high yielding varieties/hybrids of black pepper suited to various agroecological regions of Kerala (Sasikumar, 2018). Table 2 summarizes the information on pedigree, yield potential, dry recovery (%), and quality attributes (piperine, oleoresin, and essential oil contents), besides aspects like tolerance to biotic/abiotic stresses and the geographical locations where these cultivars are predominantly grown. Indeed, the location-specific differences in performance of some black pepper varieties are well-known. For example, "Panniyur-1" performs well in Wayanad district and the nearby areas but this hybrid is not much preferred in Idukki district. Likewise, many local cultivars are also identified for specific regions; for example, "Neelamundi" in Idukki, "Kalluvally" and "Balankota" in North Kerala, "Chumala" in Gudallur, "Kottanadan" in South Kerala and so on. In addition to these, many local varieties like "Arakulam Munda", "Balankota", "Karimunda", "Kalluvally", "Kottanadan", "Kuthiravally", and "Neelamundi" are also popular in some localities (Sasikumar, 2018). But cultivars like "Karimunda" and "Aimpiriyan" generally give a good pan-Kerala performance. Hybrids like "IISR Malabar Excel" and "IISR Girimunda" are known for their suitability for trailing on to the shade trees in tea and coffee plantations. "IISR Thevam", a cultivar evolved through clonal selection from "Thevamundi", is another suitable variety for the shade trees in tea and coffee plantations and is considered tolerant to the foot rot disease (Sasikumar et al., 2004). The farmer's variety, "Zion Mundi" is another shade tolerant hybrid suited for agroforestry (George, Saji, & Hemesh, 2018).

Table 2. Improved genotypes of black pepper and their salient features

Variety/Hybrid	Pedigree	Mean dry yield (kg/ha)	Dry recovery (%)	Piperine (%)	Oleoresin (%)	Essential oil (%)	Salient features
"Panniyur-1"	Hybrid between "Uthirankotta" x "Cheriyakaniakadan"	1242	35.3	5.3	11.8	3.5	Not suited to heavily shaded areas
"Panniyur-2"	Selection (Cul. 141) from cv. "Balancotta"	2570	35.7	6.6	10.9	3.4	Shade tolerant
"Panniyur-3"	KAU Hybrid (Cul. 331) "Uthirankotta" x "Cheriyakaniakadan"	1953	27.8	5.2	12.7	3.12	Late maturing
"Panniyur-4"	Selection from "Kuthiravally" Type	1277	34.7	-	9.2	3.12	Stable yielder
"Panniyur-5"	Open pollinated progeny selection from "Perumkodi"	1098	-	5.5	12.3	3.8	Tolerant to shade
"Panniyur-6"	Clonal selection from "Karimunda"	2127	32.9	4.9	8.3	1.3	Suited to all black pepper tracts
"Panniyur-7"	Open pollinated progeny selection from "Kalluvally"	1410	33.6	5.6	10.6	1.5	Suited to all black pepper tracts
"Panniyur-8"	Hybrid (HB20052), "Panniyur-6" x "Panniyur-7"	1365	39.0	5.7	12.2	1.2	High yielding, tolerant to disease.
"Panniyur-9"	Open pollinated Progeny Selection from "Panniyur-3"	3150	40.0	6.11	12.71	5.0	Suited to Kerala, Karnataka and Andhra Pradesh; drought tolerant and good berry characters
"Panniyur-10"	"Panniyur-1" x Cul 54 (open pollinated progeny of cv. "Karivally"	2.3*	-	-	-	-	High yielding climate resilient variety; long spikes, bold berries.
"Vijay"	"Panniyur-2" x "Neelamundi"	4.0*	-	-	-	-	Medium long spikes and bold berries.
"Subhakara"	Selection from "Karimunda" (KS-27)	2352	35.5	3.4	12.4	6.0	Suited to all black pepper tracts
"Sreekara"	Selection from "Karimunda" (KS-14)	2677	35.0	5.3	13.0	7.0	Suited to all black pepper tracts
"Panchami"	Selection from "Aimpiriyan" (Coll. 856)	2828	34.0	4.7	12.5	3.4	Late maturing
"Pournami"	Selection from "Ottaplackal" (Coll. 812)	2333	31.0	4.1	13.8	3.4	Tolerant to root knot nematode
PLD-2	Clonal selection from "Kottanadan"	2475	-	3.3	15.5	3.5	Suited to Thiruvananthapuram and Kollam districts of Kerala
"IISR Shakthi"	Open pollinated progeny of "Perambramundi"	2253	43.0	3.3	10.2	3.7	Tolerant to *Phytophthora* foot rot.
"IISR Thevam"	Clonal selection of "Thevamundi"	2481	32.0	1.65	8.15	3.1	Tolerant to *Phytophthora* foot rot; Suited to high altitudes and plains
"IISR Girimunda"	Hybrid between "Narayakodi" x "Neelamundi"	2880	32.0	2.2	9.65	3.4	Suited to high altitudes and plains
"IISR Malabar Excel"	Hybrid between "Cholamundi" x "Panniyur-1"	1440	32.0	4.95	14.6	4.1	Suited to high altitudes and plains; rich in oleoresin.
"Arka Coorg Excel"	Open pollinated seedling selection	3267	37.8	2.1	6.9	1.6	High yielding with long spike

Remarks: *dry yield per vine; Source: Adapted from Sasikumar (2018) and updated

Fig. 9. Black pepper trailed on various multipurpose trees including teak (*Tectona grandis*) and intercropped with ginger (*Zingiber officinale*) another important spice crop of the humid tropics (Photo: A. Sudhakaran, ICAR-IISR)

Ecosystem Services of Black Pepper + Support Tree Production Systems

As mentioned earlier, black pepper is an important commodity of international trade, largely because of its unique pungency and the characteristic aroma. The berry contains a volatile oil that contributes to the aroma, and an alkaloid (piperine) that gives the distinctive pungency (for a synthesis on phytochemical aspects of black pepper, see Nair, 2004). Solvent extraction of dry powdered berries yields an oleoresin (a mixture of both piperine and volatile oils), which has high commercial value, and is an excellent food additive. Apart from its umpteen culinary uses, black pepper is also an important ingredient of many indigenous medicines owing to its anti-inflammatory, anti-bacterial, anti-oxidant, gastro-protective and antidepressant properties (Butt et al., 2013). Based on a comprehensive review of literature on the topic, these authors also reported that the free-radical scavenging action of black pepper and its active ingredients may aid in chemoprevention and controlling the progression of tumour growth, besides piperine stimulating cognitive brain functioning, nutrient absorption and gastrointestinal functionality.

Given the importance of the crop in international trade, black pepper is gown primarily as a crop for export in most countries. In India, the export volume of black pepper increased from around 16,000 tonnes in 1950–51 to 32,000 tonnes by the end of the 20th century — a 100-fold increase. However, the 1990s saw a fluctuating trend because of price volatility (Nair, 2011). Worldwide, especially in the industrialized countries, there is also a growing demand for premium organically grown black pepper, of late. Sustainable production, especially of organic black pepper by smallholder producers (e.g., homegardeners) may not only bolster the resilience of the black pepper crop against biotic and abiotic stresses, but also help the local community to secure livelihoods. In fact, some organizations, like the Peermade Development Society in Idukki, Kerala, are promoting the production and certification of organic black pepper and other spices by smallholder growers.

Apart from the direct benefits as a food additive of immense significance and a source of income and livelihood security, especially for smallholder producers, the black pepper ecosystems provide several other useful ecosystem services too. The most important of all such co-benefits is its potential for climate change mitigation through creating and enhancing carbon sinks by capturing carbon from the atmosphere through photosynthesis and storing it in the biomass and soil (particularly by the tree components of the system). However, a clear gap exists in our knowledge that links the studies on carbon stocks and footprints from black pepper plantations (especially in situations where such plantations are established on cleared sites). Support tree species, tree density, and soil organic matter are biophysical aspects showing a significant positive correlation with the level of carbon stocks. However, such aspects apparently have not received adequate research attention in the past. In a lone study, Kunhamu et al. (2018) evaluated the carbon sequestration potential (tree + soil) of six MPTs used for trailing black pepper vines in Kerala (*A. auriculiformis, A. heterophyllus, Grevillea robusta, M. peltata, A. triphysa and Casuarina equisetifolia*). The results indicate that the total C stock was highest for *G. robusta* (230.5 Mg C/ha), followed by *A. auriculiformis* (226 Mg C/ha). Timber and firewood production from the support trees are other important considerations, along with on-farm carbon accumulation and the associated environmental goals. In addition, attributes such as the ability of the trees to yield fruits, foliage, green manure etc. are important (Krishnamurthy, Parthasarathy, Saji, & Krishnamoorthy, 2010), but such aspects have been seldom studied in black pepper ecosystems.

The black pepper ecosystems are essentially polycultural in nature (e.g. black pepper in homegardens; Kumar, George, & Chinnamani (1994), implying their potential for agrobiodiversity conservation. Apart from the multitude of support trees on which the vine is trailed, many field crops including commercial crops such as banana (*Musa* spp.), ginger (*Zingiber officinale*), turmeric (*Curcuma longa*), are also grown in the inter spaces of black pepper plantations (Fig. 9). The canopy management practices which are integral to avoid excessive shading of the vines by the support trees **(see section: Black Pepper Ecosystems of Kerala)**, also have the potential to add significant quantities of organic materials, which in turn, enrich soil fertility and microbial activity. Different tree species used as supports in black pepper plantations, however, may have differential effects on soil nutrient availability, enzyme and microbial activities. In general, soils under tree species which return more biomass including pruned materials, litter and root exudates (rhizodeposition) may have a more favourable influence. Consistent with this, Dinesh, Srinivasan, Hamza, Parthasarathy, & Aipe (2010) observed that tree species such as *Gliricidia sepium,* and to a lesser extent *Garuga pinnata*, can be used as live supports for soil fertility restoration of black pepper plantations on degraded sites. They also found that tree rhizospheres favoured higher activities of enzymes such as dehydrogenase, urease, acid phosphatase, aryl sulphatase and β-glucosidase, implying greater soil microbial activities.

CONCLUSION

Overall, black pepper is an important spice crop for commerce and an apparent driver of the European colonization process of the Indian subcontinent. It is grown under diverse agroecological situations. The black pepper ecosystems are unique in that it involves growing a sciophytic vine on a range of support trees. The black pepper vine + standard system also has the intrinsic potential to provide a range of ecosystem services such as food, fuel, fodder, timber, green leaf manure etc. (provisioning). In addition, several supporting and regulatory services such as climate change mitigation, nutrient cycling and enrichment of soil fertility are associated with it. They also have the potential to improve the livelihood security of smallholder producers.

For optimising black pepper productivity, however, shade adaptability, foot rot tolerance and niche-compatibility – or, phenotypic plasticity – of the cultivars are important. The available improved black pepper varieties broadly fall under categories such as "shade sensitive" (e.g. "Panniyur-1") or "shade tolerant" (e.g. "Panniyur-2", "Panniyur-5", "Panniyur-8"). Many traditional cultivars (e.g. "Karimunda", "Neelamundi", "Thottamundi", "Balankota") are often regarded as shade tolerant. In future, more efforts should be made for evolving shade and disease tolerant black pepper cultivars. As shade favours "pollu" beetle (*Lanka ramakrishnai*) infestation, resistance to "pollu" beetle should also be an important breeding objective.

Regulating the light (radiation) profile through adopting appropriate shade tree management practices such as pruning/lopping of branches is an important aspect of manipulating photosynthesis in the black pepper+support tree system. Identifying appropriate shade tree ideotypes which do not cast excessive shade on the associated vine is yet another important but neglected aspect of black pepper production. Agroforesters have been discussing about the phenomenon called "reverse phenology" (shedding the foliage during the wet season, when understory crops require no shade, but retaining it during the hot and dry season). However, shade tree improvement programs incorporating such concepts have not made any headway so far, owing to a multitude of challenges. Nonetheless, evolving a shade tree ideotype for trailing black pepper vines with appropriate canopy attributes (e.g. narrow, non-spreading and light crowns), tree growth characteristics (fast growth, biological nitrogen fixing ability, non-exfoliating bark, deep root systems etc.), and ability to provide multiple products and services, besides possessing an appropriate phenological pattern should receive better focus in future. Adopting a "system approach", in contrast to a "commodity-centric" approach focusing on yield maximization will be appropriate. Site-specific nutrient management and integrated pest and disease management are two other aspects that also should receive better research focus in future.

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