Chapter 12
Integrated Weed Management in Plantation Crops

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Introduction

Plantation crops are long-term crops established for commercial interest. Major plantation crops are tea (*Camellia* spp.), coffee (*Coffea arabica* L.), oil palm (*Elaeis guineensis* Jacq.), areca nut (*Areca catechu* L.), cardamom (*Elettaria cardamomum* Maton and *Amomum subulatum* Roxb.), coconut (*Cocos nucifera* L.), cashew (*Anacardium occidentale* L.), cocoa (*Theobroma cacao* L.), and rubber (*Hevea brasiliensis* Mull. Arg.). Being long-term crops, and often grown as monocultures, plantation crops are severely infested with weeds. This chapter deals with the nature and effect of the weed menace in the above mentioned crops along with methods adopted for weed management. In the plantation crops, weeds are managed by physical, mechanical, and chemical methods similar to those generally adopted in arable/field crops. However, there are reports on the use of low-density polyethylene sheets for mulching interrow space and mowing between the rows to control weeds. Planting smother crops or leguminous cover crops and intercropping in the row space, and deploying grazing animals are the biological methods for weed management in some of these crops. Integrated approach involving a combination of cultural, me-

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B. S. Chauhan, G. Mahajan (eds.), *Recent Advances in Weed Management,*
DOI 10.1007/978-1-4939-1019-9_12,

chanical, and biological weed control methods is also adopted for combating weeds in an effective, economical, and eco-friendly manner.

Weed Menace in Plantation Crops

Nature of Weed Infestation

Tea

Weed management in tea is the second most expensive input after plucking [1]. In tea plantations, grasses generally predominate the weed flora followed by broad-leaf weeds [2]. The major weeds in different tea-growing areas of the world are *Ageratum conyzoides* L., *A. houstonianum* Mill., *Artemisia vulgaris* L., *Arundinella benghalensis* (Spreng) Druce, *Axonopus compressus* (Sw.) P. Beauv., *Borreria alata* (Aubl.) DC., *B. hispida* (L.) K. Schum., *Commelina benghalensis* L., *Cynodon dactylon* (L.) Pers., *Eupatorium odoratum* L., *Imperata cylindrica* (L.) P. Beauv., *Mikania cordata* (Burm. f.) B. L. Robins, *M. micrantha* H.B.K., *Oxalis acetosella* L., *Panicum repens* L., *Paspalum conjugatum* Berg., *Paspalum scrobiculatum* L., *Pennisetum clandestinum* Hochst. ex Chiov., *Polygonum chinense* L., *Saccharum spontaneum* L., *Scoparia dulcis* L., and *Setaria palmifolia* (Koen.) Stapf. Sedges are not serious weeds in tea plantation [2]. Ferns, such as *Nephrodium* sp. and *Pteridium aquilinum* (L.) Kuhn., have also been reported to infest tea plantation. In tea gardens, owing to high humidity and limited sunny days throughout the year, mosses tend to cover soil surface under the canopy along with a large part of tea trunk and branches [3].

In India, studies in young tea plants have revealed that the critical period of weed competition is generally from spring to rainy season (April to September). Delay in weeding during this period adversely affects branching, growth, and yield of young tea plants [4]. In Sri Lanka, the critical period for weed competition in young tea was reported to be between 8 and 16 weeks after planting and the threshold period of competition was about 12 weeks after planting [5].

Coffee

In Cuba, total 266 weed species, belonging to 189 genera, were identified in coffee plantations [6, 7]. In central Cuba, *Elaterium carthaginense* Jacq. [8], a climbing weed, was reported to smother coffee plants and to be poisonous to cattle. Broad-leaved species predominate the coffee plantations, and Asteraceae and Poaceae were the dominant families [9]. In Kenya, while *Bidens pilosa* L., *Chloris* sp., *Commelina benghalensis, Cynodon dactylon, Cyperus* sp., *Digitaria velutina* (Forssk.) P. Beauv., *Gnaphalium* sp., *Oxalis* sp., and *Parthenium hysterophorus* L. are major weeds in the coffee plantations [10], the tough-to-combat weeds are *Cynodon* *dactylon, Cyperus rotundus* L., *Digitaria scalarum* (Schweinf.) Chiov., *Oxalis* sp., and *Pennisetum clandestinum* [11].

Weeds commonly found in coffee in Costa Rica were *Bidens pilosa, Borreria latifolia* (Aubl.) Schum., *Drymaria cordata* Willd., *Emilia fosbergii* Nicolson, *Portulaca oleracea* L., and *Richardia scabra* L. [12]. In Brazil, *Amaranthus retroflexus* L., *Bidens pilosa, Brachiaria plantaginea* (Link) Hitchc., *Coronopus didymus* (L.) Smith., *Digitaria horizontalis* Willd., *Emilia sonchifolia* (L.) DC., *Galinsoga parviflora* Cav., *Ipomoea grandifolia* Lam., *Lepidium virginicum* L., and *Raphanus raphanistrum* L. have been reported to infest coffee plantations [13]. In Cuba, grass weeds, viz., *Brachiaria subquadriparia* (Trin.) Hitchc., *Digitaria sanguinalis* (L.) Scop., and *Eleusine indica* (L.) Gaertn. dominated the coffee crop. Among the broad-leaved species, *Amaranthus dubius* Mart. ex Thell. was the major species in the open fields while *Solanum nigrum* L. predominated the pockets under shade [14]. Other weed species reported in coffee in Cuba are *Alternanthera tenella* Colla syn. *A. ficoidea* (L.) R. Br., *Mikania cordifolia* (L. f.) Willd., *Paspalum conjugatum, Petiveria alliacea* L., *Phyla nodiflora* (L.) Greene, and *Pseudelephantopus spicatus* (Juss.) C.F. Baker. [15]. In Venezuela, *C. dactylon* had the highest frequency and abundance while broadleaf weeds were in majority in coffee [16].

A study on different cultivation regimes in coffee indicated that the type of cultivation practices adopted can be detected from the associated weed communities [17]. A study on floristic composition of weeds in coffee in Costa Rica revealed reduction in the relative frequency of climbing plants, Cyperaceae, and monocot species, and increase in broadleaf species and grasses [18].

In Monagas state, Venezuela, the critical period of weed interference in coffee was observed to be between May and September, coinciding with the fruiting stage [16]. Weed-free conditions increased the yield to 36% compared to weedy plots during the same period. In Ethiopia, loss in coffee yield was recorded to be as high as 65%, depending on the type and frequency of weeding operations [19]. In El Salvador, total weed-free conditions provided highest coffee yield followed by the plots remaining weed-free during the dry spell of November–April. Thus, the period from November to April was found to be critical from the weed management point of view [20].

Oil Palm

In oil palm plantation in Nigeria, Gill and Onyibe [21] revealed a total of 174 weeds comprising of five ferns, 52 monocotyledons, and 117 dicotyledons. A majority of the weeds, numbering 142 (81.6%) were broad leaved, whereas 22 (12.6%) were grasses, and remaining 10 (5.7%) were sedges. *Chromolaena odorata* (L.) King and Robinson, *Panicum laxum* Swartz, and *Pueraria phaseoloides* (Roxb.) Benth. were the predominant weed species. In the plains of the eastern Himalayan region of West Bengal, India, a total of 20 angiosperm families were reported; of these, 17 belonged to dicots, and 3 to monocots while 5 were pteridophytes. Three species, viz., *Ageratum conyzoides, Oxalis corniculata* L., and *Vandelia* sp. were more widely distributed [22]. Two major problematic weed species in oil palm plantations reported from Selangor are *Calopogonium caeruleum* (Benth.) Sauv. and *Paspalum conjugatum* [23]. In Nigeria, *Asystasia coromandeliana* Wight ex Nees, *M. micrantha, Ottochloa nodosa* (Kunth) Dand, *P. conjugatum,* and some legumes constituted major weed flora [24]. In addition, *C. odorata* also poses problems [25]. Ikuenobe [26] and Ikuenobe and Utulu [27] also described *Aspilia africana* (Pers.) C. D. Adams, *C. odorata,* and *P. phaseoloides* as major weeds in the oil palm. In West Java, *Ischaemum timorense* Kunth, *M. micrantha, O. nodosa,* and *P. conjugatum* were the major species [28]. *Ottochloa nodosa* and *P. conjugatum* were also dominant weeds in young plantations in Malacca, Malaysia, whereas in mature plantations, *Ageratum conyzoides* and *Axonopus compressus* were the predominant weeds [29]. The weed flora in palm nursery comprised of *Acalypha ciliata* Forssk., *Ageratum conyzoides, Amaranthus spinosus* L., *Brachiaria miliiformis* (Presl) A. Chase, *Cyathula prostrata* (L.) Blume., *E. indica, Mariscus alternifolius* Vahl, and *P. oleracea* [30].

In the West Kalimantan region of Indonesia, *I. cylindrica* and *Melastoma malabathricum* L. were the widespread weed species in oil palm, whereas *A. coromandeliana, C. odorata, Mikania micrantha, Mimosa pigra* L., and *Pennisetum polystachion* (L.) Schult. were distributed in a limited area [31]. *Asystasia intrusa* Blume has been categorized as a noxious weed in oil palm [32]. *Rottboellia cochinchinensis* (Lour.) Clayton is another noxious weed in the young plantations, which interferes with agronomic operations like fertilization, spraying, pest and disease control, and harvesting, and causes reduction in oil palm yield [33]. Ismail et al. [34] reported *Asystasia gangetica* (L.) T. Anders., *B. alata, Cleome rutidosperma* DC., and *P. conjugatum* to account for more than 80 % of the total weed seeds in an oil palm field.

Coconut

In coconut, wide spacing favors a variety of weeds to grow, occupy the space, and compete with the crop [35]. In Brazil, a comprehensive weed survey revealed 201 weed species in coconut, mostly belonging to Poaceae, Amaranthaceae, Asteraceae, Euphorbiaceae, Leguminosae, and Malvaceae, with Poaceae being present in all areas of coconut cultivation. The weed species with the greatest frequency were *Amaranthus deflexus* L., *Cenchrus echinatus* L., *D. horizontalis,* and *Herissanthia crispa* (L.) Briz. [36]. In Kerala, India, Thomas and Abraham [37] identified 85 weed species in coconut gardens from 19 locations. In the eastern Himalayan region of West Bengal, India, *A. conyzoides, B. alata, Centella asiatica* (L.) Urban, *Gnaphalium* sp., *O. corniculata, S. nigrum,* and *Vandelia* sp. recorded 100 % frequency followed by other species, viz., *Clerodendron infortunatum* L., *Dryopteris* sp., *I. cylindrica, Melastoma* sp., *Mimosa pudica* L., *Selaginella* sp., and *Solanum nigrum* [22]. Major weed species reported in Sri Lanka are *Allmania nodiflora* (L.) R.Br. ex Wight., *Chloris barbata* Sw., *Chromolaena odorata, Croton hirtus* L'Herit, *Cynodon dactylon, Hyptis suaveolens* L. Poit., *I. cylindrica, Lantana* *camara* L., *Mimosa pudica, Mitracarpus villosus* (Sw.) DC., *Panicum maximum* Jacq., *Panicum repens, Pennisetum polystachion, Scoparia dulcis, Sida acuta* Burm. f., *Stachytarpheta jamaicensis* (L.) Vahl., *Tephrosia purpurea* (Linn.) Pers., *Tridax procumbens* L., *Urena lobata* L., and *Vernonia cinerea* (L.) Less. [35, 38].

Cashew

Similar to the case of coconut, the wide spacing between cashew trees provides ample scope to the weed menace in cashew farms. *Avena sativa* L., *Cynodon dactylon, Cyperus compressus* L., *I. cylindrica, Pennisetum polystachyon* (L.) Schult., and *Setaria glauca* (L.) P. Beauv. among grasses and sedges, and *Chromolaena odorata, Lantana indica* Roxb., *M. pudica, Smilax zeylanica* L., and *T. procumbens,* among broadleaf are the common weeds in cashew [39, 40]. Infestation of *Acanthus montanus* (Nees) T. Anderson, *Axonopus compressus, Chromolaena odorata, Commelina nudiflora* L., *Euphorbia heterophylla* L., *Fleurya aestuans* (L.) Gaudich., and *Tridax procumbens* has been reported in eastern Nigeria [41].

Cocoa

The predominant weed species in cocoa fields are *Chromolaena odorata, Cyperus* sp., *F. aestuans, I. cylindrica*, *L. camara, Monstera* sp., *P. repens, Setaria barbata* (Lam.) Kunth, and *Talinum triangulare* (Jacq.) Willd. Other common weeds in the cocoa fields are *Alternanthera sessilis* Br., *D. cordata, Panicum laxum,* and *Paspalum conjugatum* [42]. Mistletoes are plant parasites that live on other plants to obtain food, water, and support. At least six different species have been found on cocoa across the growing regions worldwide. Infestation of mistletoes may lead to the loss of vigor, reduced pod yield, and eventually death of the branch or the tree [43]. Two species of mistletoes, *Phragmanthera incana* (Schumach.) Balle and *Tapinanthus bangwensis* (Engl. & K. Krause) Danser are very common in West Africa [44, 45]. In Ghana, the cocoa farms are also extensively affected by *T. bangwensis* [45]. In cocoa, the young seedling and establishment stages are critical for weed control [46]. In Brazil, the competition of weeds with cocoa in agroforestry systems is severe during the winter months (June to November) [47].

Rubber

The weeds commonly found in the rubber plantations in Southeast Asian countries are *Asystasia intrusa, Axonopus* sp., *Borreria* sp., *Chromolaena odorata, Cynodon dactylon, Cyperus rotundus, I. cylindrica, Lantana aculeata* L., *Mikania micrantha, Mimosa pudica, Panicum repens, Paspalum* sp., and *Pennisetum* sp. Some ferns (e.g., *Adiantum, Nephrolepis,* and *Gleichenia linearis* (Burm. f.) C.B. Clarke) were also reported in rubber plantations in Sri Lanka [48].

Losses Caused

Tea

In tea plantations in India, the period of rainy season crop coincides with the period of active weed growth and infestation, necessitating more deployment of labor for plucking and weeding. In the nursery, the environmental conditions are congenial for plant growth, which facilitate rapid weed growth, competing with tea plants. It calls for extra labor for the nursery success. Weed infestation at the peak flowering stage causes maximum reduction in growth of tea plants [49].

In the newly planted tea in India, weed control during summer and rainy seasons (April–September) is essential for the establishment of the plants. The weed competition during this period has been reported to cause nearly 50 % reduction in the number of primary branches and about 3.5 times decrease in the yield in the 2nd year [50]. Weeds also retard the efficiency of farm workers. Certain weeds, such as *B. pilosa* and *Rubus* sp., often reduce the plucking efficiency of workers. In the heavily infested tea sections, shoots of weeds are inadvertently harvested along with tea shoots, which adversely affects the quality of processed tea.

Coffee

In Brazil, Alcantara and Ferreira [51] reported reduction in the yield of processed beans to the extent of 178 kg/ha. At the young stage, coffee plants are sensitive to weed infestation as weeds cause reduction in the nutrient content in the coffee plant [52]. Dias et al. [53] reported that the foliar area and dry biomass of leaves were the most affected attributes in coffee by weed infestation in summer, while in winter, leaf number and dry stem biomass were significantly reduced. The critical periods of weed interference were 15–88 and 22–38 days after coffee seedling transplanting, during winter and summer, respectively. Weeds, including *Bidens pilosa, Brachiaria decumbens* Stapf, *Commelina diffusa* Burm. f., *Leonurus sibiricus* L., and *Richardia brasiliensis* Gomes, caused severe reduction in growth, mainly with increasing weed plant densities [54]. Weeds reduced root dry matter of coffee plants by 47–52 % as compared to the weed-free treatment, regardless of the weed density. Crop and weed nutrient concentrations as well as competition degrees greatly varied, depending on both weed species and densities [55]. Weed competition during the dry period from November to April reduced parameters of coffee growth to a much greater extent than competition at any other time of the year. Of the parameters measured, stem diameter and the length of non woody branches were the best indicators of weed competition during the vegetative and generative stages of growth. Weed control between the rows using a rotary cultivator was more effective than mowing; however, the possible long-term damage to the soil due to the cultivator should also be taken into consideration [56].

Coconut

Based on the cumulative average yield of coconut for three consecutive years in Sri Lanka, Samarajeewa et al. [57] concluded that weed infestation may cause up to 54 % reduction in nut yield as compared to the weed-free conditions.

Cocoa

Adverse effects of weeds on the cocoa production are expected to be higher at the initial stages. Proper weed control is always beneficial for the growth and establishment of seedlings. Oppong et al. [58] reported favorable increment in seedling girth due to weed-free conditions over a long period. Weeds often climb up and twine around the plant and prevent it from unfolding.

Rubber

Weeds hinder the cultural operations, such as tapping, spraying, irrigation, and fertilizer application in rubber plantation. The cost of weed control operations in the young rubber plantations may be about 34 % of the total cost of cultivation [59].

Weed Management

Physical and Mechanical Methods

Tea

At the nursery stage, use of black polyethylene mulch provided satisfactory weed control [60]. Similarly, Singh et al. [61] concluded that in young China hybrid tea planted on slope, low-density polyethylene (LDPE) mulch totally suppressed weeds in the interrow spaces. LDPE mulch also enhanced plant growth and yield of tea compared to no mulch.

In northeast India, cultivation with a deep hoe on heavy soil on a flat terrain during the intermittent dormancy in June and winter dormancy in December provided higher average annual yield, while weed control throughout the year by cutting with a sickle provided the lowest yield [62].

Coffee

In Cuba, weed cover for 77 days in the nursery under shade improved the growth and development of coffee; however, in the open fields, the nursery could be left weedy only for 48 days without affecting its growth [63]. In Uganda, hoeing once a month reduced 75 % of weed seeds in the coffee field soils as compared to only 30 % reduction with slash weeding [64]. In Kerala, India, deep digging was done annually in winter season (October–November) for soil and moisture conservation measures, which was found injurious, particularly to the feeder roots, accelerated soil moisture loss, and was cost-ineffective [65]. On the other hand, scraping of soil with incorporation of weeds was the most beneficial for plant growth. It was therefore suggested that deep digging should be practiced only once in new clearings, and not annually. The combination of partial slashing and application of herbicides in patches was more effective in reducing the unwanted weed biomass and enhancing spread of the ground cover legumes, whereas the use of partial slashing enhanced spread of the grass weed *Oplismenus burmannii* (Retz.) P. Beauv. [66].

In the coffee plantations in Cuba, regular mowing between the rows encouraged low-growing grasses, particularly *Brachiaria subquadriparia,* while rotary cultivation favored the development of *C. rotundus* and broad-leaved species, such as *A. dubius, L. virginicum,* and *P. oleracea* [67].

Cardamom

Mulching around plants has been found to reduce weed infestation in large cardamom [68]. In small cardamom, sickle weeding during summer (May) and sickle weeding + forking + mulching during winter (October and January) provided the highest numbers of young tillers, mature tillers, and panicles, and the highest yield (270 kg/ha), as compared to the yield in non-treated control plots when averaged 161 kg/ha [69].

Coconut

A study in Sri Lanka reveals that manual weeding in coconut was not as effective as the chemical method [70]. Though plowing and harrowing operations in coconut reduces weed seed bank by burying them to deeper soil profiles, they lead to high seedling emergence from seeds brought from deeper to shallow depths [71]. Thus, slashing weeds with a tractor three times a year was less effective than establishing cover crop with *P. phaseoloides* and buffalo grazing once a month [38].

Cashew

In young cashew plantation, manual hoeing is done within 1.5–2.0-m diameter around trees followed by slashing the remaining weeds in the interspaces to ground level. Hand pulling of annual and perennial grasses and sickling of tall and perennial grasses particularly before application of herbicides are adopted wherever labor is available [39, 40].

In India, mechanical hoeing is recommended along the planted strip up to a width of about 4 m, with precautions to avoid root injury by leaving a strip of 2 m on both sides. Whereas in the new plantations where sufficient space exists, hoeing, plowing, and mowing may be adopted [39]. However, the mechanical hoeing, harrowing, or mowing cannot be as sustainable as those methods that promote soil covering through leguminous species or spontaneous vegetation in improving soil organic content [72]. Besides, these practices cause intense soil mobilization and fragmentation of biomass of cover plants and favor degradation of physical and chemical properties, resulting in the reduction of the soil quality [73].

Cocoa

In the cocoa plantation with wide row spacing and without shade trees, weeds are effectively controlled by tillage. However, deep tillage should be avoided to prevent damage to feeder roots. Hand weeding with hoe and sickle is recommended during the initial 6 months after planting when the plants are small. Weeding within 1-m radius around the trees by machete (a large cleaver-like knife) is commonly practiced in most of the cocoa plantations. Strip weeding 1 m each side of the trees in the row is also practiced. Small machines are used for mowing down weeds in the cocoa field where sufficient space is available between the rows for allowing the mower to pass. For mowing operations, the cocoa fields should be free from stone and boulders.

Rubber

Around 4–5 hand weedings are required during the initial 2 years of the crop. The hand weeding is generally done in strips 1.5–2.0 m wide along the rows or in a circle of about 1-m radius around the tree. This method is also recommended for selective weeding in the area where the cover crop has been established. However, much disturbance with heavy hoes is not recommended. Mowing in rubber plantation is recommended only for uniform land and the fields free from rocks. Burning is the traditional practice to control *I. cylindrica* in rubber plantations. However, this practice should not be continued because of concerns over environmental pollution.

Oil Palm

Rambe et al. [74] in Indonesia adopted circle weeding, initially with a radius of 1.6 m, which was increased to 2.0 m for the succeeding weeding operations done manually as well as mechanically. Compared with manual weeding, the motorized grass cutter resulted in a three times higher number of weeded circles.

Chemical Method

Tea

The common herbicides used in tea plantations are paraquat, glyphosate, simazine, 2,4-D sodium, 2,4-D amine, diuron, and dalapon. Linuron, methazole, metribuzin, dichlormate, dinoseb, oxadiazon, butachlor, and fluchloralin herbicides were also used in tea; however, they were trivial in performance. Though most of the herbicides approved are safe to tea, phytotoxicity on tea may occur due to reasons [4] including application of herbicides at rates higher than the recommended doses, improper or nontargeted spraying, spray drift, leaching of preemergence herbicides by heavy rains, and age of the tea bush. In tea nursery, simazine, atrazine, fluchloralin, oxadiazon, and methazole are recommended to be applied at the rate of 2 kg/ha in April, about 3 weeks before planting of clonal cuttings. Treatments may be repeated after hand weeding when weed cover exceeds 50 %. Mixtures of simazine or atrazine with oxadiazon or fluchloralin were found more effective.

Chemical weed control in young tea is distinct from that in mature tea, as young tea plants are relatively more susceptible to herbicide treatments and the weed flora is more diverse and intense. Ghosh and Ramakrishnan [75] observed that in young tea, oxyfluorfen at 0.125 kg/ha applied preemergence in May followed by oxyfluorfen (0.06 kg/ha) + either paraquat (0.24 kg/ha) or 2,4-D (0.8 kg/ha) as postemergence application using shield controlled most of the problem weeds throughout the season. The presence of moisture on the soil surface improves the bioefficacy of preemergence herbicides, in general. It is normally advised that young tea plants should be shielded from the herbicide spray since they are more likely to be adversely affected than older plants. Also, the application of dalapon and diuron in tea younger than 3 years is not recommended [4]. In Sri Lanka, oxyfluorfen at 0.29 kg/ha + paraquat at 0.17 kg/ha or glyphosate at 0.99 kg/ha + kaolin at 3.42 kg/ha provided better weed control than hand weeding in young tea [76]. Also, a combination of interrow mulching and the aforementioned herbicides followed by hand weeding at least every 6–8 weeks was found to be the most appropriate weed management system for young tea [76].

In mature tea, oxyfluorfen at 0.25 kg/ha provided effective control of broadleaf weeds without any phytotoxicity when it was applied to the clean soil or to growing weeds. Oxyfluorfen was comparable to simazine or diuron, each at 2 kg/ha [77]. Pendimethalin 0.75 kg/ha, oxyfluorfen 0.44 kg/ha, simazine 1.25 kg/ha, or atrazine 1.25 kg/ha were more effective preemergence treatments for suppressing seed-borne weeds [78, 79]. Subsequent weed growth in either of the cases could be controlled with spot treatments of 2,4-D and/or paraquat [80].

Kabir et al. [81] observed that glyphosate 0.92 or 1.23 kg/ha provided effective weed control in tea of the Darjeeling area in India. The United Planters' Association of Southern India (UPASI) [82] concluded that glyphosate is a promising herbicide against hardy perennial grasses and deep-rooted broadleaf weeds, and is not toxic to tea bushes even when sprayed directly on the bushes at a rate of 1.68 kg/ha [83].

However, studies at the Institute of Himalayan Bioresource Technology (IHBT), Palampur, India, had indicated that in case of seed-raised China hybrid tea plantations, use of glyphosate even at the rate of 1.03 kg/ha may cause phytotoxicity. The susceptible tea bushes showed loss of crop for one to two pluckings. Glyphosate was also found effective in controlling brush weeds like *L. camara*—a troublesome weed in tea plantations in Himachal Pradesh and Uttarakhand, India [84].

Glufosinate-ammonium at 0.38 kg/ha provided better weed control than paraquat dichloride at 2 weeks after spraying [85]. In an experiment conducted in Valparai, Tamil Nadu, India, napropamide at 2.0 kg/ha exhibited effective weed control only up to 60 days after the application of herbicide. Also, napropamide at 4.0 kg/ha was at par with oxyfluorfen at 0.25 kg/ha only up to 60 days [86]. Carfentrazone-ethyl at 4 and 8 g/ha combined with glyphosate at 620 or 720 g/ha exhibited 85 % weed control, while increments in the dose of carfentrazone-ethyl to 12, 15, and 20 g/ha combined with glyphosate at 620 or 720 g/ha provided total weed control and was comparable in its efficacy to the currently recommended tank mixture of glyphosate +2,4-D at 720+1120 g/ha [87]. Similar results were also reported by Rajkhowa et al. [88] with weed control up to 45 days after herbicide application.

Coffee

In Olancho, Honduras, terbuthylazine as preemergence followed by glyphosate or paraquat as postemergence treatments were more effective than terbuthylazine with weeding or weeding alone in coffee plantations [89]. Oxyfluorfen was the best treatment in maintaining the crop free of weeds for about 90 days compared to 50 days by the traditional controls [90].

In coffee plantations in Karnataka, India, glyphosate (1.25 kg/ha) provided lowest fresh weight of weeds (73 g/m^2) and significantly increased girth of the main stem by 252 %, and bush spread by 85 % [91]. Addition of urea (1 %) or ammonium sulfate (1 %) showed better weed control by glyphosate herbicides [92]. Also, addition of urea resulted in a considerable saving of glyphosate.

In young coffee from the recently transplanted stage to the 1-year-old, oryzalin and oxyfluorfen had better safety margins than simazine, atrazine, and diuron, which caused injury to young coffee at 4.5 kg/ha [93]. Oxyfluorfen, atrazine, simazine, and diuron provided better weed control than oryzalin. Oxyfluorfen failed to combat weeds of Asteraceae family, although these were totally controlled by atrazine and diuron.

In the coffee plantations in Kenya, application of paraquat alone or in combination with slashing or forking provided effective weed control [94]. In Tanzania, glyphosate at 0.729 kg/ha has been recommended for repeated applications for controlling weeds in this crop [95]. In Costa Rica, combined application of paraquat +2,4-D was not effective, which might be due to antagonism in this mixture [12]. In Brazil, ametryn plus simazine mixture applied at 2.5 and 3.0 kg/ha with glyphosate (960 g/ha) provided effective control of weeds followed by paraquat (300 g/ha). Performance of 2,4-D was not satisfactory in terms of yield of coffee beans [96].

Oil Palm

In oil palm at Selangor, Malaysia, effective control of major weeds, viz., *C. caeruleum* and *P. conjugatum* was reported with a tank-mixed application of metsulfuron and glyphosate or metsulfuron and paraquat [23]. Another study revealed that glyphosate at 720 g/ha and dicamba + glyphosate at 230 + 540 g/ha provided the most effective control of weeds [97]. Teng and Teh [24] reported that a translocative broad-spectrum herbicide Wallop, containing glyphosate 16.2 % and dicamba 8.1 %, was effective for weed control in both young and mature oil palm.

Paspalum fasciculatum Willd. ex Fluegge, the most prevalent weed in the oil palm, can be best managed with haloxyfop-methyl (Galant 240) at 100 g/ha [98]. Similarly, in Nigeria, the control of *C. odorata* in oil palm was achieved with glyphosate at 2.4 kg/ha and imazapyr at 0.5 kg/ha [25]. Bhanusri et al. [99] in India concluded that glyphosate had the highest percent of weed control efficiency on both dicots and monocots over paraquat and glufosinate ammonium. Efficiency of glyphosate can further be optimized through ammonium sulfate as surfactant [100]. Paraquat is considered to be the most effective herbicide with the fastest mode of action. In 2002, the Malaysian government banned the use of this hazardous herbicide. This led to a hunt for new effective herbicides for oil palm plantations in Malaysia. Wibawa et al. [101] evaluated the efficacy and ability of the less hazardous herbicides, viz., glufosinate ammonium and glyphosate, as an alternative to paraquat in controlling weeds in the immature oil palm (below 3 years old). The results showed that lower rates of glufosinate ammonium (200 g/ha) and glyphosate (400 g/ha) provided excellent weed control and the efficacy was much better than that of paraquat [102–104].

Nuertey et al. [105] reported that glyphosate at 0.47 kg/ha mixed with either 0.23 kg/ha of sodium chloride or 0.53 kg/ha of ammonium sulfate controlled the weeds up to 3 months after treatment. However, in the next year, these weed control measures were ineffective. So it may be inferred that the herbicidal effectiveness was controlled by the prevailing weather conditions. In Malaysia, a biotype of *Eleusine indica* showed resistance to glyphosate and invaded oil palm plantations in a vast area. Control of this resistant weed may need repeated applications of glyphosate, as many as eight times in a year [106]. Jalaludin et al. [107] recorded 82 % control of *E. indica* at a vegetable farm with glufosinate-ammonium at the recommended rate, but at another location in oil palm nursery, the same rate of herbicide failed to control the weed. Mortimer and Hill [108] studied weed species shifts in response to broad-spectrum herbicide use in oil palm and found that the use of a broad-spectrum herbicide changed the composition of the weed flora.

In 1988, an ultralow-volume applicator for herbicides with a spray volume of 10–50 l/ha showed a high level of consistency in efficacy. The equipment also reduced labor requirements by half and water requirements by 90 % [109]. A low-volume technique for weeding in a circle around oil palm using a spinning disc was also adopted [110]. Leng and Maclean [111] observed that controlled droplet applicator was effective in combating *Ischaemum muticum* L. in young oil palm when glyphosate was applied at 1.5 kg/ha. The battery-operated knapsack sprayer and controlled droplet applicator were suitable for the application of herbicides for the control of several problem weeds, including *Clidemia hirta* (L.) D. Don, *Dicranopteris linearis* (Burm. f.) Underw., *Melastoma malabathricum, Mikania micrantha,* and epiphytes [112]. However, Ikuenobe [26] recorded better weed control with greater spray volume than low-volume spray (70–93 % at 200 l compared to 10–75 % at 25 l). Eng et al. [113] in Malaysia used modified knapsack sprayers fitted with two different types of constant flow valves and found it more efficient in the area coverage and safe to the operator.

Haji Mustafa [114] in Malaysia advocated the use of a circle and rentice mechanical sprayer in mature oil palm plantations. The system comprised of a tractor-mounted collapsible boom mechanical sprayer unit. One operator setup usually covers 25–28 ha in a working day of 10 h. The sprayer resulted in five to eight times labor savings over manual knapsack sprayers with the advantage of a uniform area coverage. A Malaysian university has developed an automated sprayer system, using web camera in combinations with electromechanical system, sensor system, controllers, wireless data communication, and software [115].

Areca Nut

In West Bengal, India, glyphosate (1.7 kg/ha) applied alone or in combination with 2,4-D (6.86 kg/ha) provided broad-spectrum weed control in these plantations [116].

Coconut

In Sri Lanka, glyphosate at 1.44 kg/ha resulted in a significant reduction of weed biomass, specifically of *Imperata* sp., and a 25 % increase in nut yield over the uncontrolled weedy plots [35, 57]. In the dry zone in Sri Lanka, glyphosate at 1.08 kg/ha was found to be as effective as glyphosate at 1.44 kg/ha. The growth of coconut seedlings in terms of height and girth increased significantly at this rate, applied at the end of the nursery growth period [70].

Cashew

A study on the chemical weed control in India [117] showed that paraquat at 3.0 kg/ha was the most effective in terms of weed management, crop yield, and nutrient absorption by the cashew trees, followed by oxyfluorfen at 0.50 kg/ha. In south India, the standard recommendation for an effective control of all types of weeds is the application of paraquat at 0.4 kg/ha twice at bimonthly intervals, starting from July with alternate application of glyphosate at 0.8 kg/ha [39]. In Ghana, the use of herbicides and intercropping was compared [118]. In the young plantations, intercrops provided higher yields than the chemical weed control (glyphosate), but in the mature plants, chemical weed control slightly improved cashew nut yield. In

Brazil, Xavier et al. [72] observed substantial change in the floristic composition of spontaneous weed species with the application of herbicide.

Cocoa

Paraquat is commonly used for controlling weeds in young cocoa plantations. In mature cocoa, glyphosate is the most effective herbicide. Oppong et al. [119] reported that glyphosate at reduced rates (480–960 g/ha) can be used to control weeds without an adverse effect on the crop. Adeyemi [120] reported that a formulated mixture of glyphosate and terbuthylazine (2.10 to 3.15 kg/ha) was more effective as compared to hand slashing in a mature cocoa field. The herbicides should be applied 1 month before or 4 weeks after fertilizer application.

Rubber

In the rubber plantations, *I. cylindrica* and *P. repens* can be effectively controlled by glyphosate at 4.4 kg/ha [121]. In nursery, preemergence application of diuron at 3.0 kg/ha was found promising [48].

Biological Method

There is a conspicuous lack of efforts toward biological control of weeds deploying bio-herbicides or other biocontrol agents in plantation crops. However, there are some reports on the use of smother crops, the use of organic mulch materials, and grazing animals for weed management in these crops.

Use of Plant and Plant Materials

Tea

Slashing of intercrops or weeds (before flowering) and using them as mulch material has been reported to be effective in weed management. In young China hybrid tea planted on slopes, mulch of grassy weeds effectively controlled weeds in the interrow spaces of tea and it was statistically comparable to LDPE mulch in terms of yield [61].

Sandanam and Rajasingham [122] reported 89 and 51 t/ha soil loss with clean weeding during the 1st and 2nd years, respectively, compared with 7 and 1 t/ha with *Tripsacum laxum* Nash (Guatemala grass) mulching, and 5 and 2 t/ha with *Cymbopogon confertiflorus* (Steud.) Stapf (Mana grass) mulching, respectively. Soil loss with intercrop of *Crotalaria striata* DC. was 32 and 5 t/ha, and with intercrop of *Eragrostis curvula* (Schrad.) Nees, it was 11 and 2 t/ha as compared to 28 and 2 t/ha under selective manual weeding with minimum soil disturbance, in the 1st and 2nd year, respectively. Soil loss in the 3rd and 4th years was more than 2 t/ha with all the above treatments. It was also observed that tipping weights were highest with bare soil or selective weeding and lowest with *E. curvula*. Leaf yield in the 2nd year tended to be higher with Mana grass mulching. Mulching also increased soil moisture content. In China, intercropping with white clover and straw mulching were found to be effective ecological measures for weed control in tea plantations [123].

Coffee

In Nicaragua, Bradshaw and Lanini [124] found *Arachis pintoi* Krapov. & W.C. Gregory, *C. diffusa,* and *Desmodium ovalifolium* (Prain) Wall. ex Merr. having no potential role as long-term cover crop for smothering weeds in the coffee plantation. However, in Tanzania, in smallholder coffee plots, cut grass, sorghum, and corn residues are used as mulch material. The plant-based mulches are reported to increase growth and yield of coffee, as they control weeds, conserve soil moisture, improve soil fertility, and reduce runoff and soil losses [125]. In Puerto Rico, *Arachis kretschmeri* Krapov. & W.C. Gregory, *Axonopus compressus, Paspalum dilatatum* Poir., *P. notatum* Flugge, and *Urochloa subquadripara* (Trin.) R.D. Webster, as smother plants, showed significant reduction in weed infestation as compared to non-treated control in coffee [126]. In Ghana, raising *Canavalia ensiformis* (L.) DC., *Manihot utilissima* Pohl. (cassava), *Musa paradisiaca* L. (plantain), *Vigna unguiculata* (L.) Walp. (cowpea), and *Zea mays* L. (corn) as intercrop during the initial 2.5 years of establishment of young coffee was beneficial, though it also required 1–3 more manual weedings. In the 1st year, except the coffee + cowpea combination, intercropping provided higher net returns [127]. Cassava was not suitable as intercrop from 2nd year onward as it caused a reduction in coffee yields.

Oil Palm

In Malaysia, *C. caeruleum* and *P. phaseoloides* were used as cover crops for managing weed flora, viz., *B. latifolia, E. indica, O. nodosa,* and *P. conjugatum* in oil palm [128]. *Mucuna bracteata* DC. ex Kurz has also been evaluated as an effective cover plant for weed control [129] with potential to compete with the noxious weeds and persist until maturity stage in the oil palm plantation [130]. Besides, intercrops of soybean, corn, and cocoyam provided varying degree of success in the management of weeds in young oil palm [131]. In Monagas State, Venezuela, Barrios et al. [132] reported deployment of *Centrosema rotundifolium* Benth. and *D. ovalifolium* leguminous cover crops, in oil palm, exhibiting high covering index in the initial growth stages. Among these two species, *D. ovalifolium* showed higher competitive ability to spread and gradually displace the population of native weeds. Lee et al. [130] concluded that the leguminous cover crops can combat weeds, such as *Asystasia* and *Mikania.* Similarly, Samedani et al. [133] reported that *Axonopus compressus, Calopogonium caeruleum, Centrosema pubescens* Benth., *M. bracteata,* and *Pueraria javanica* (Benth.) Benth. were highly competitive cover crops against *Asystasia gangetica,* but none could compete against *Pennisetum polystachion.*

Coconut

Maintaining fast-growing cover crops is the other way to control competitive weeds in coconut [38, 134–137]. Cover crops are generally sown 1 year in advance to the coconut planting [134]. *Calopogonium caeruleum, Calopogonium mucunoides* Desv., *Centrosema pubescens, Moghania macrophylla* (Willd.) Kuntze, *Psophocarpus palustris* Desv., and *Pueraria phaseoloides* are suitable cover crops for different climates and soils in Indonesia [134]. The Coconut Research Institute of Sri Lanka [138] recommended *Calopogonium mucunoides, Centrosema pubescens,* and *Pueraria phaseoloides* as cover crops for wet areas; *Calopogonium mucunoides, Centrosema pubescens, Macroptilium atropurpureum* (DC.) Urb., and *Pueraria phaseoloides* for dry areas; and *Gliricidia maculata* (Kunth) Kunth or *Gliricidia sepium* (Jacq.) Kunth as bush cover crops. Broad guidelines on weed management through cultural and biological control and production of organic coconuts have also been described by Singh [139]. Growing *Crotalaria juncea* L. (sun hemp) thrice followed by hand weeding once is a better way to manage weeds in the coconut nursery. This also provided better nut germination, plant growth, and benefit-to-cost ratio [140].

Cashew

Mulching of the interrow space with straw, hay, farm wastes, weed residue, tree loppings, and sometimes coconut husk is done to smother weeds and also to conserve moisture during the dry spell [39, 40].

Cocoa

Cultural weed management includes all aspects of good crop husbandry used to minimize weed interference with crops [141]. At a young stage, a 1-m circle around each plant is cleaned and covered by 10-cm-thick mulch, viz., coconut husk, cocoa leaves, cut-bush, cut-grass, banana leaves, rice-straw, sawdust, and sugarcane bagasse. A small space of 20 cm from the trunk should be left so that the mulch does not touch the seedling. Different cover crops can be grown for weed management in the dense shade of well-established cocoa plantations. Leguminous cover plants, like *Desmodium asperum* (Poir.) Desv. and *Flemingia congesta* Roxb. ex W.T. Aiton, were extensively used in the cocoa fields for suppressing weeds and maintaining soil fertility. Fast-growing creeper legumes are potentially good for controlling the weeds that normally dominate in the thinly populated cocoa fields. However, care should be taken to ensure that they do not entangle the young cocoa plants. Also, intercropping is being adopted for weed management in cocoa plantations. Generally, sugarcane is planted in the gaps of cocoa fields to suppress weeds, but care should be taken to prevent its growth over young cocoa trees.

Rubber

For combating weeds in rubber plantations, banana, passion fruit, and pineapple can be successfully grown as intercrop without any adverse effect on the growth and yield of rubber. In addition, straw and crop residues are used as mulching material for suppressing weed growth. Planting tree legumes, such as *Flemingia, Gliricidia, Sesbania,* and *Tephrosia,* and formation of a mulch of leaf litter between planting rows by slashing and mulching is also a desirable method of weed control in the immature rubber plantations [121]. In rubber, controlled grazing by livestock such as sheep and goats has been adopted to control weeds. Wan Mohamed [142] reported that many weeds found in rubber plantations are highly nutritious and could be utilized to support sheep production. According to Tajuddin et al. [143], cost of weed management can be reduced by 18–36 % by sheep grazing.

Use of Grazing Animals

Cattle were first deployed in some oil palm plantations way back in 1987 for combating weeds and augmenting farm income [144, 145]. In Malaysia, grazing by the cattle in oil palm plantations reduced overall weeding costs by about 30 % and labor requirement by about 39 % [146]. Yusoff [147] also reported grazing as a profitable way of controlling weeds in oil palm plantations. In the coconut plantations, growers use ruminants to prevent crop–weed competition and optimize the productivity of this system as a whole [38]. Senarathne and Gunathilake [38] compared the influence of buffalo grazing and *P. phaseoloides* cover crop with slashing of weeds through tractor on weed control and nut yield in coconut plantations in Sri Lanka. These methods were significantly effective for weed biomass reduction over slashing. Similarly, Seresinhe et al. [148] reported considerable reduction in the weeding cost and a nearly double coconut yield with grazing in coconut plots when compared with un-grazed plots. However, they cautioned that animal grazing could increase soil compaction affecting soil aeration, water infiltration, and other soil physical properties and thereby reduce the growth and productivity of the coconut. Harrowing the plots put under animal grazing appeared to be the best method to overcome soil compaction problem [38].

Integrated Approach

Integrated weed management (IWM) aims to minimize the weed population to a level at which weed infestation has no effect on yield and ecological functions. IWM is a knowledge-based decision-making process that coordinates the use of environmental information, weed biology and ecology, and all the other available technologies to control weeds by the most economical means, while posing the minimum possible risk to people and environment [149]. IWM is a combination of cultural, mechanical, and biological weed control methods to deploy in an effective, economical, and ecological manner.

Coconut

Senarathne and Perera [150] reported that cover cropping with *P. phaseoloides* and application of glyphosate was significantly effective over other treatments for reduction of weed biomass. Intercrops, viz., field crops, vegetable crops, fodder crops, fruit crops, and green manure crops could also be grown for a better utilization of the open ground space between the rows of the coconuts. The selection of intercrops should be based on the climatic requirement of the inter/mixed crop, irrigation facilities, soil type, market suitability, as well as the canopy size, age, and spacing of the coconut [151].

Cashew

Weed infestation during initial years after cashew planting is the main concern for the establishment of plants. According to the Food and Agriculture Organization (FAO) [40], the principal cover crops used in different cashew-growing areas include creeping cover crops, such as *C. pubescens* and *P. phaseoloides,* bush cover crops, viz., *G. maculata, Leucaena leucocephala* (Lam.) de Wit, and nitrogen-fixing trees, such as *Acacia mangium* Willd. Further, among intercrops, banana is popular in many cashew plantations. Pineapple, papaya, pomegranate, and coconut are also used as semi-perennial and perennial intercrops in some areas. The common annual crops grown in cashew plantations are legumes (cowpea, black gram, green gram), oil crops (sesame, groundnut), and condiments, such as hot pepper and onion. Intercropping with food crops reduces weed incidence, weed biomass, and frequency of weed control, resulting in increased financial returns [152].

In Nigeria, Adeyemi [41, 153] evaluated the effect of intercropping food crops, viz., corn, cassava, cowpeas, and banana plantain with cashews. The intercropped crop mixtures reduced biomass of the weeds by about 40 % and number of hand weedings by nearly half compared to sole cashews. Also, the degree of weed succession was influenced by some crop mixtures leading to alteration in the weed sequence and their population dynamics.

In Brazil, Ribeiro et al. [73] studied change in the physicochemical attributes of soil and their effect on growth and yield of cashew, as a consequence of distinct soil management practices. Higher and more stable cashew nut yields were recorded in the systems where the weed or vegetation around the trees was not removed. This was due to building up of higher organic matter and absence of soil disturbance. Studies of Xavier et al. [72] concluded that vegetation strips in the interrows between the cashew lines are ideal from the point of weed management, improvement in soil physical and chemical properties, and to check soil erosion. However, overgrowth of the strip should be cut regularly and the practice of localized weeding should be followed.

The Sri Lanka Cashew Corporation [154] suggested growing suitable intercrops and cover crop (e.g., *C. pubescence*) and resorting to the application of suitable herbicides alone or in combination with other manual and mechanical methods for an efficient weed management in cashew. Grazing of farm animals in off-season and growing vegetation in the interrow space in the plantation have also been identified as efficient methods, appropriate for long-term managements of weeds in cashew.

Rubber

Integrating spraying of herbicides and sheep grazing has been found effective for controlling some noxious weeds, such as *A. intrusa* and *M. micrantha* in rubber [155].

Conclusion: Future Aspects of Research

In order to improve efficiency and cost-effectiveness of the weed management in plantation crops with an eco-friendly approach, research on the following aspects becomes imperative.

Information on the biology of many serious weed species may have to be generated and collected for better and integrated weed management. Weed flora succession is another aspect that needs thorough understanding to regulate rotation, combination, and dosage of the herbicide(s). Harnessing allelopathic attributes of certain plants for weed management is another aspect that needs appropriate attention. For example, in Cuba, grounded pine (*Pinus caribaea* Morelet) needles resulted in the control of weeds in the coffee fields [156]. Research on bio-herbicides needs to be strengthened.

Concept of precision agriculture should be considered and appropriately developed to encompass weed management in the plantation crops. For example, Ishak and Rahman [115] highlighted the need of an intelligent sprayer that could regulate the usage of herbicides at the optimal level and identify in the real-time environment the prevalence of the existing weeds and apply herbicides automatically and precisely. The aim is to reduce chemical wastage, economize labor, reduce application cost, and prevent environment hazards. Similarly, Ghazali et al. [157] developed an intelligent real-time system for an automatic weeding strategy in oil palm plantation using image processing to identify and discriminate weed types, viz., narrow and broad. Similarly, Ishak et al. [158] discussed development of a variable rate automated sprayer for oil palm plantation based on a camera vision with color detection mechanism.

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