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Soil Sickness in Fruit Orchards: Causes and Management

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CONTENTS

ABSTRACT

Soil sickness is a serious problem to establish new fruit orchards at the old orchard site. It is a complex soil sickness syndrome that reduces the plant growth, survival and yield of replanted trees. Various factors are responsible for soil sickness viz., (i) biotic factors i.e. rhizospheric microflora (bacteria, fungi, actinomycetes, nematodes and their interactions) and

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(ii) abiotic factors (phytotoxins, nutrient imbalance, low or high pH, soil structure and lack of excess soil moisture). In many cases, autotoxins may enhance soil-borne diseases by predisposing the roots to infection by soil-borne pathogens through direct biochemical and physiological effects. It is not easy to prevent the soil sickness problem because of its exact etiology and complex nature of problem and different biotic and abiotic factors are associated with it. The nature and intensity of incidence are variable from region to region and country to country and there is a lack of quick diagnostic methods. It cannot be controlled with one method and require integrated management practices. This review outlines the current knowledge on methods to reduce the negative effects of soil sickness in fruit orchards, which may be a promising strategy to improve the growth and yield of fruit trees in sick soils.

Keywords: Allelopathy, autotoxicity, detrimental microbes, microbial community, rhizosphere, root exudates, soil health, soil borne pathogens, soil-legacy effects, suppressive soil

1. INTRODUCTION

Continuous cultivation of the same fruit tree or related fruit trees on the same soil in orchards over a long period often reduces the growth, yield and quality of many fruit trees (Fig. 1). It is strongly species-specific, i.e. mainly affecting individuals of the same species. Plant-soil legacy-effects, the influences of all positive and negative interactions between plant and soil organisms, have received increasing attention in the soil sickness phenomena (84). Plants influence the soil organisms via supply of organic matter, or rhizodeposition these can alter the plant performance through mutualistic interactions, nutritients availability, or pathogenic activity, etc. In ecosystems, plants can modify the soil by root exudation, root deposition and susceptibility to pathogens and symbionts. These changes can increase or decrease the subsequent plant growth, as positive and negative plant-soil feedback, respectively (42).

Figure 1. Declining/Replant apple orchards

Meanwhile, aboveground and belowground microflora of preceding plants induces changes in the soil biota, which greatly influence secondary metabolites accumulation, biomass and aboveground multitrophic interactions of succeeding plants (41). Soil sickness in orchards is a prevalence of soil-borne diseases, which reduces the fruit yield when the same fruit trees or its related species are cultivated on the same soil successively. The problem of soil sickness dates to the beginning of fruit production (7,66-Fig. 1)**.**

Theophrastus (ca. 300 BC), the father of Botany, wrote of how chickpea "exhausts" the soil and destroys weeds in his botanical works. In an ancient Chinese book, Jiminyaoshu (ca. 540) gave a detailed description of the importance of cropping sequencing for high crop productivity. Later, many agriculturists and biologists investigated the involvement of autotoxic substances in cropping systems (29). However, scientific work was not initiated until the beginning of the 20th century. Pioneering work by Schreiner and Reed (72), Russell and Petherbridge (68) revealed the involvement of phytotoxins and detrimental microbes in soil sickness (7). Later (1950s-60s and 1980s-2010s), many biologists and agronomists attempted to isolate phytotoxic substances from plant tissues, root exudates, and soils. Many phytotoxic substances involved in soil sickness have now been isolated from plants, soils and the rhizosphere. At present, soil sickness becomes prevalent in the production of many annual crops with intensive monocropping, and it also affects trees and shrubs in orchards (apple, pear, stone fruits, citrus, grapes etc.), coffee and tea plantations (Fig. 2), where it causes replant problems for fruit trees and regeneration problems in natural forests (10).

Figure 2. Peach plant showing symptoms of replant problem

Generally, replant disease of fruit trees is mainly caused by allelopathy, autotoxicity and the imbalance of both soil physical-biochemical properties and soil microflora. Replant disease has been reported in several horticultural crops (Apples, peaches and cherries) in nurseries and orchards the world over (80,81,61,95). This review mainly outlines the current knowledge on mitigation methods for reducing the harmful effects of soil sickness in fruit orchards, which is important to improve the growth and yield of fruit trees in sick soils.

3. CAUSES OF SOIL SICKNESS

Soil sickness is caused by various biotic (fungi, bacteria, actinomycetes, nematodes, and their interactions) and abiotic (phytotoxins, nutrient imbalance, soil pH, soil structure and deficit or excess of soil moisture) factors which vary from region to region or even orchard to orchard.

2.1 Autotoxicity

Autotoxicity is a specific type of intraspecific allelopathy, where a plant speciesinhibits the growth of its own spp. and not of other spp. through the release of toxic chemicals into the environment (9,10). Allelochemicals are released into the environment through volatilization, leaf leachate, root exudates of living plants and decomposition of dead plant tissues (67). Autotoxicity has been observed in both natural and managed ecosystems. In the agroecosystems, autotoxicity causes losses in fruit tree yields and replant problem in orchards. It is prevalent in perennial fruit plants [strawberry, apple, peach, citrus, grapes, cherries, ginseng, and roses (67)]. Plant extracts, root exudates and sometimes the soil extracts after planting these plants causes autotoxicity i.e. 20-50 % decrease in plant growth (67). The autotoxic potential of many plants is species-dependent and is influenced by genotypes, light and nutrition levels in many plants (64,104).

Many allelopathic compounds from plants, root exudates and soils have been identified as autotoxins. These chemicals include simple water-soluble organic acids, aliphatic aldehydes, lactones, long-chain fatty acids, naphthoquinones, anthraquinones, phenols (benzoic and cinnamic acids), coumarins, tannins, terpenoids, steroids, alkaloids, cyanohydrins, sulfides, soil glycosides, purines etc. (46). Several autotoxins have been isolated from nutrient solutions in hydroponic culture using the adsorbents such as Amberlite XAD or activated charcoal. The benzoic and cinnamic acids Autotoxins, inhibits the plants' growth but are easily degraded in soil (101).

2.2 Soil Microbes

Soil contains a vast diversity of microorganisms; these are involved in many biological, chemical and physical processes in terrestrial ecosystems. Microbial diversity is important for soil quality and is influenced by soil type, planting history and agricultural practices (fertilization and pesticide use). Bacteria are the most abundant and diverse group of organisms in the soil (39). In the past, microbial communities were monitored by traditional culture-dependent methods. Now modern methods such as fatty acid analysis (FAME and PLFA) and nucleic acid analysis (PCR-DGGE), are used to estimates the bacterial diversity (43,84). The autotoxins such as cinnamic acids significantly decreased the soil microbial community functional diversity and genetic diversity (as indicated by RAPD markers) (99). Most recently, pyrosequencing of the bacterial 16S ribosomal RNA gene is used to characterize the bacterial community in the soil rhizosphere and roots (9).

Root exudates vary with plant species, leading to changes in the soil microbial community. Roots of apple and peach exude strigolactones and benzoxazinoids that stimulates the AM fungi and also attracts the *Pseudomonas putida*, beneficial to plants in the rhizosphere (59) On the other hand, monocropping together with extensive applications of chemicals decreases the soil biota and increased plant diseases (11). Changes in soil biota influence plant growth because soil biota~~s~~ are involved in many processes like nutrient's availability. In many cases, continuous monoculture reduces the microbial competition in the root zone by lowering the biodiversity of root-associated fungi and bacteria, thus enabling the development of pathogenic populations and increasing the disease incidence and subsequent yield losses (40). Monocropping also simplifies the microbial structure, decreasing the population of fluorescent *Pseudomonas*, which produces the antifungal metabolite 2,4-diacetylphloroglucinol (93). In healthy soils > 60 % were *Pseudomonas* sp., while in sick soils 58 % were *Bacillus* sp., which produce HCN *in-vitro* (3). Accordingly, yield decline in monoculture of a single fruit species is related to the accumulation of non-pathogenic, harmful rhizobacteria (70).

2.3 Interactions between autotoxins and microbes

Soil sickness may be also caused by the interactions of autotoxins, microbes and others increasing the soil-borne diseases and thereby inhibiting the growth (46). Plant-microbe interactions extend over time, space and substrate (56). In addition, antagonism also occurs between microbes. The presence of deleterious rhizobacteria (DRB) increases the plant susceptibility to other pathogens (26). The roles of autotoxins have been observed in many sick soils depending on the soil types and responses of different plants to specific autotoxins.

Autotoxicity in peach plants is attributed to amygdalin, which is broken down in the soil by microbes into toxic cyanide substances, causing injury to the roots of young peach seedlings (62). A similar phenomenon has also been observed in walnut with juglone as the autotoxin (85). In contrast, many allelochemicals or autotoxins are easily degraded by microbes, for example, benzoic and cinnamic acids (6,97). Autotoxins alters the soil microbial ecology and accordingly affects plant growth due to the accumulation of allelochemicals in the soil (33). Autotoxins can modify the prevalence of many soil-borne diseases.

4. SOIL SICKNESS CONTROL MEASURES IN ORCHARDS

Soil sickness may be controlled with the application of broad-spectrum fumigants, but environmental concerns necessitate a search for alternative organic compounds. Since the problem develops mainly through changes in the soil microbial population, hence, the integration of biological soil amendments may shift the microbe's population to a more beneficial microbial community. Various control measures, found effective, are discussed below:

3.1. Solar sterilization: Solar sterilization, an environmentally friendly method, is increasingly used to control many soil-borne diseases, although its influence on autotoxins degradation is unknown. It can kill both pathogens and beneficial microbes in the soils.

3.2. Chemical control

Both physical and chemical sterilization approaches are now available. Instead of using methyl bromide, many alternatives are being developed to control the soil-borne pathogens. The sensitivity of soil microbes to chemical sterilants such as calcium cyanamide varies with microbial species and many microbes recover faster than pathogens (74). The use of plastic mulch against replant problem was as effective as fumigation with methyl bromide, chloropicrin or formalin (37, Fig. 3).

Figure 3. Soil fumigation using plastic mulch

3.3. Soil Fumigation

Soil fumigation greatly increased the growth of apple trees at the replanting site (66,79). Oehl (60) reported that pre-planting fumigation of apple replanting soil with chloropicrin @ 281 l ha^{-1} in increased the shoot numbers, trunk girth and total yield**.** The growth of an apple tree can be significantly improved by effective control of replant disease with chloropicrin (69). Sewell and White (73) obtained the effective control of apple replant problem using pre-planting soil treatments with chloropicrin, propylene oxide, steam or formalin. Line *et al*. (48) compared the efficacy of Telone C35 (chloropicrin), Basamid (dazomet) and the standard methyl bromide at apple replant sites and reported significant control of replant problem with methyl bromide and Telone C35 than control and the Basamid. Application of formalin @ 150 ml/m^2 soil provides an economical and less hazardous alternative to chloropicrin to control apple replant problem (Fig 4.). Control of replant disease has typically relied on the pre-plant application of broad-spectrum soil fumigants (53). Brown and Schimanski (8) recommended the use of Basamid (dazomet) for soil fumigation to control the replant disease.

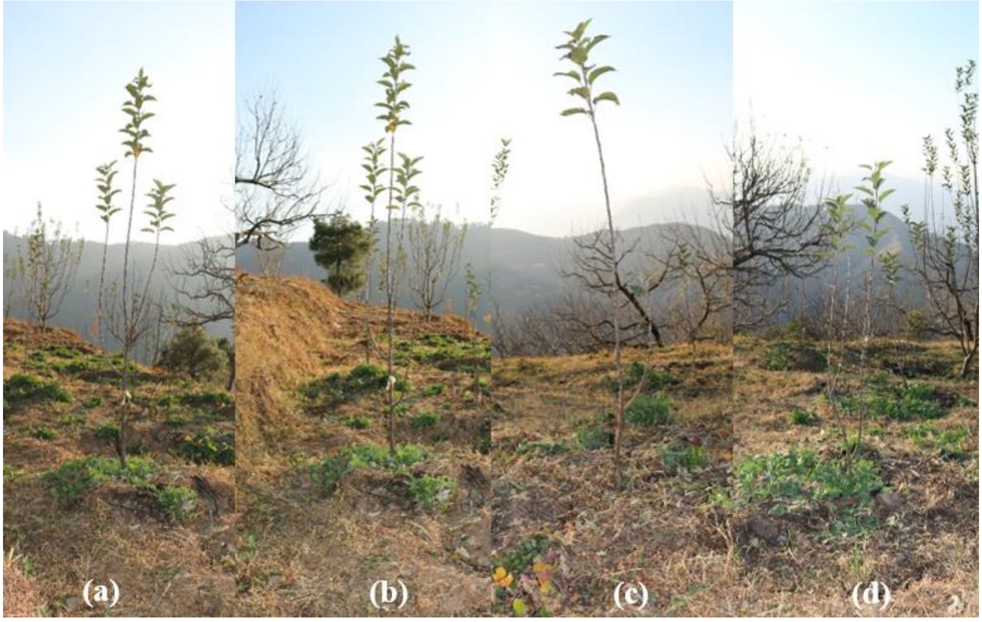

Figure 4. Growth of apple 'Super Chief' on (a) M.793 (b) MM.111 (c) M.7 (d) Seedling Rootstocks after response to soil fumigation with Formaldehyde under replant site

Application of the fungicides difenoconazole or metalaxyl enhanced the growth of apple plants in replant soils (51). Bavistin (0.2 %), Jkstein (0.2 %) and Dithane Z-78 also improve the growth of apple plants in replant soils but are not as effective as formalin.

3.4 Cultural practices

Costante (17) had suggested cultural practices to reduce losses due to diseases at apple replanting sites. As soil sickness has been recognized as a soil-borne problem, hence, we need to modify the cultural practices such as (i) digging the pit slightly away from the old one, (ii) take out old roots before replanting and destroy them, (iii) removal of hardpan at sub-soil level and (iv) avoid waterlogging.

3.4.1. Soil amendments and fertilizers

The organic manures (*viz.* farmyard manure, vermicompost, mushroom compost etc.) promotes plant growth by slowly releasing the plant's nutrients (avoiding their leaching) and improving the physical condition of the soil. The manures application reduces the soil moisture stress and replant problem by providing congenial conditions for plant growth and development (75). The composts also have disease-suppressive effects (19,82) mainly due to their microbial activities (65). Compost or vermicompost added to the planting holes of replanted apples considerably increased the growth (31). Organic substances modify the composition of microflora in rhizosphere soil (83). Szczygiel and Zepp (83) suggested that activated charcoal controls replant disease to some extent. The adding of activated charcoal to the soil or by soil fumigation with methyl bromide reduced the ethylene content in the soil and root environment of replanted apple plants (31). The addition of slow-release fertilizers, compost and mulch extracts significantly increased the growth parameters and survival of apple seedlings in replant soil (71).

In general, the biological activity of the soil is stimulated by the addition of available carbon sources (49) and soils with diverse beneficial microorganisms suppress the disease development (44). Mazzola *et al*. (55) suggested the use of *Brassica napus* seed meal amendments for the management of apple replant disease (*Rhizoctonia* species) as this amendment controlled the disease by the production of glucosinolate hydrolysis products. Growing apple plants for 4-weeks in a soil-less potting mix before transplanting them into pasteurized replant soil or amended with organic matter proved more effective than planting directly into replanting soil (98). Applications of compost and compost extracts proved promising to manage the replant disease. In pot trials, the application of sterilized or unsterilized compost extracts to apple replanting soil significantly increases the growth of apple seedlings (71). Application of peat and drip irrigation enhances the shoot growth in replant soils (21).

Fertilizers: Hudska *et al.* (35) recorded 2.17-folds higher growth with liquid fertilizer and 1.76-fold higher growth with potassium sulphate at replant sites and suggested the soil acidification and sulphuric acid treatment of old orchard soils to control the replant disease. Fertilization with mono ammonium phosphate corrected the stunting effect and effectively promoted the growth of apple plants at replanting sites (89). Utkhede and Smith (91) recorded a significant increase in seedling height with the application of N and P fertilizers in soil infested with fungi and bacteria causing replant disease. They further reported that N and P promoted the growth of bacteria and antagonistic organisms associated with replant disease. Mono ammonium phosphate was found more effective than *Bacillus subtilis* and formalin in increasing total shoot length and trunk cross-sectional area of 2-year-old McIntosh plant on M.26 rootstock (90). Szczygiel and Zepp (83) recommended the use of bio-humus amendment at 10-20 per cent and mono ammonium phosphate at 2 g/litre of soil for effective control of apple replant problem.

Engel *et al.* (24) recommended the planting of 2-year-old nursery plants than 1-year-old plants in replant disease affected soils for higher growth and vigour. Leinfelder and Merwin, (45) studied the effects of planting site on tree growth and reported that trees planted in old grass lanes perform better than those in the old tree rows. According to Rumberger *et al.* (67), avoiding replanting into the old tree rows coupled with the use of tolerant rootstocks appeared to be the best strategy for reducing apple replant problem.

3.4.2 Rotation and Intercropping

To mitigate continuous replant disease, reasonable crop rotations, intercropping and inter-planting are often used in the field to increase the total amount of soil microbes as well as the bacterial/fungal ratio to overcome the continuous cropping disease (50). Proper rotation can decrease the pathogen populations and also minimize the autotoxic effects of the crops. The residues of crops like Brassicaceae and marigolds suppresses the soil-borne pathogens and nematodes (16). Furthermore, the allelopathic properties of cover, smother and green-manure crops or crops grown in rotation can be useful for pest management (25,76). Most of the fruit crops exude nematicidal and antimicrobial substances. Rotation with cereal crops such as sorghum and maize suppresses the incidence of nematode and other root diseases in tomato and cucumber (unpublished data). It remains to be determined, however, that whether strigolactones and benzoxazinoids in the root exudates of maize contribute to their beneficial effects. It is, therefore, apparent that plant diversity is an important factor for successful plant growth in agroecosystems.

Antagonistic activity of marigold and grasses like red fescue and the red top has been recorded against *Pratylenchus penetrans* (86). Intercropping or rotation with Chinese chive (*Allium tuberosum*) decreases the occurrence of bacterial wilt caused by *Pseudomonas solanacearum.* Because the root exudates of Chinese chive plants strongly inhibits the bacterial pathogen (103). Intercropping with herbaceous crops greatly improves apple seedling growth in replanting soils (96). Brassicacae crops like mustard, radish, cabbage etc are effective in controlling soil-borne pathogens. These crops release volatile allelochemicals as gases, which effectively controls the soil-borne pathogens (27). Edwards *et al.* (23) conducted field trials to test the effectiveness of antagonistic plants on the populations of *Pratylenchus penetrans* and *Pythium* species in replant soils and found that marigold (*Tagetes patula*, cv. Harmony), creeping red fescue (*Festuca rubra*), as well as red top (*Agrostis alba*), substantially decreased the population of *Pratylenchus penetrans* and *Pythium* species. The microbial community in a wheat field soil suppresses the components of the microbial complex that incites apple replant problem (52). Wheat cultivation before planting modified the genetic and species composition of the *Fluorescent pseudomonas* population in orchard soil and substantially enhances the apple seedling growth (30).

3.5 Use of resistant/tolerant rootstocks

Grafting is often used to overcome replant disease because disease-resistant rootstocks in fruits trees possess better root development and greater capacity to produce endogenous hormones and antioxidants to enhance soil-borne disease resistance (34). Rootstock selection and row re-positioning are more beneficial than soil fumigation or compost amendments to control apple replant problem. Development of resistant

Table 1. Effects of Galaxy and Fuji Suprema apple (*Malus* × *domestica*) scion cultivars grafted on different rootstocks on growth and yield in the sixth year in replanted soil

Apple Genotypes	Crop Season: 2009/2010 to 2014/2015			2013/2014 Crop Season	
	Suckers/ Plant	Burr knots/ Plant	Cumulative Yield (kg/plant)	Trunk Cross Sectional Area (cm^2)	Yield Efficiency (kg cm^{-2})
Rootstocks					
G.056	3.41b	0.71b	85.56b	43.74b	1.99a
G.202	1.09c	0.38b	77.30b	38.75c	2.14a
G.213	0.46c	0.19b	56.07c	27.24d	2.13a
G.814	0.83c	0.44b	124.97a	52.30a	2.41a
G.896	0.55c	0.54b	112.20a	58.92a	1.93a
G.969	0.42c	0.17b	39.03c	25.71d	1.61b
M.-9*	1.43c	1.46a	66.04b	37.99c	1.74b
Marubakaido+M.-9**	23.01a	1.26a	68.99b	47.07b	1.51b
Scion Cultivars					
Galaxy	-	-	71.67b	34.28b	2.09a
Fuji Suprema	-	-	85.87a	48.65a	1.77b

Source : (20) *Obtained using data annual evaluation, when the highest incidence for each trait was observed. Burr knots were counted on the M.-9 interstem grafted on the Marubakaido rootstock.
** Marubakaido rootstock combined with M.-9 interstem.

Table 2. Effects of Galaxy and Fuji Suprema apple (*Malus* × *domestica*) scion cultivars on different rootstocks on fruit yield on replanting soil

Apple Genotypes	Annual Fruit Yield (Kg/Plant)						Mean
	2009/2010	2010/2011	2011/2012	2012/2013	2013/2014	2014/2015	
Rootstocks							
G.056	5.12aD	27.05aB	13.84bC	12.58aC	26.98bB	44.40bA	21.66
G.202	6.76aC	23.32aB	13.72bC	12.09aC	21.42cB	37.38bA	19.12
G.213	6.84aB	19.46bA	8.60bB	5.65bB	15.53dA	21.69cA	12.95
G.814	11.39aE	31.66aC	24.38aD	16.96aE	40.58aB	53.29aA	29.71
G.896	10.19aD	29.52aB	23.57aC	17.14aC	31.79bB	44.10bA	26.05
G.969	5.97aB	11.35cB	7.15bB	5.14bB	9.41dB	18.91cA	9.66
M.-9*	5.86aC	17.31bB	11.32bC	9.82bC	21.72cB	39.40bA	17.57
Marubakaido +M.-9*	8.16aC	20.17bB	12.50bC	7.49bC	20.68cB	39.18bA	18.03
Scion Cultivars							
Galaxy	8.63aC	21.60aB	11.12bC	11.70aC	18.63bB	28.13bA	16.64
Fuji Suprema	6.44aF	23.35aC	17.65aD	10.02aE	28.40aB	46.46aA	22.05
Average (season)	7.54D	2.48B	14.38C	10.86D	23.52B	37.30A	16.01
CV (%)	85.69	28.74	44.93	59.49	27.47	17.32	-

Source : 20

* Marubakaido rootstock combined with M.-9 interstem.

rootstocks for apple is a slow and lengthy process and sometimes the obtained resistance is lost by the time plant comes into productive stage. In replant apple soils, Ryan (69) suggested the use of M.-12 rootstock for sites susceptible to root diseases, MM.115 and M.-793 for lighter soils and M.-793 for heavier soils with chloropicrin fumigation. Costante *et al.* (18) reported that apple rootstock MM.-111 roots in clay had fewer *Pratylenchus penetrans* than MM.-106 roots. Rootstock genotypes modify their rhizosphere environments, which differed significantly in their bacterial, *Pseudomonas*, fungal and oomycetes communities. Although none of the apple accessions was found completely resistant to replant disease in test soil, however, seedlings of *Malus sieversii* and *Malus kirghisorum* had some tolerance and 3-clonal rootstock accessions (viz., CG.65, CG.6210 and CG.30) and 4-clones viz., *Malus baccata* 1883, *Malus xanthocarpa* Xan, *Malus spectabilis* PI 589404 and *Malus mandshurica* 364 had good tolerance (36). Rootstock genotypes had the dominant influence on root lifespan and distribution, whereas, pre-plant soil fumigation, compost amendments and replanting positions had little impact on root characteristics despite their influence on aboveground tree growth and yield (77,100).

3.5.1 Breeding resistant varieties

With the development of molecular techniques in horticultural plants, genetic engineering and breeding technology have become important fields to enhance the tolerance to replant disease (57). Lin (47) analyzed the changes of proteomics in continuous cropping of heterophylla (*Pseudostellaria heterophylla* Miq. ‘Zheshen No. 2 Pax’) in replant versus non-replant soil. They found that the expression level of several proteins of leaves related to cell division and protein synthesis under replant soil was decreased, which decreased the number of soil bacteria and bacterial species diversity. These results showed that breeding for high expression of relevant proteins (e.g., pathogenesis-related proteins) in plants is a major pathway to overcome the replant disease. Duan *et al.* (22) proposed that varieties resistant to replant disease should have no self-toxicity, little autotoxicity, production of beneficial allelochemicals and root exudates. Wild horticultural plant species generally show better resistance than cultivated cultivars, because rhizospheric allelochemicals and effective microorganisms decrease the pathogens due to antagonistic reactions. Thereby, in continuous cropping conditions, the inclusion of wild ancestors into breeding programmes may enhance plant trees resistance to replant disease.

3.6 Biological control

Biotic factors play an important role in autotoxicity and pathogenesis. Beneficial microbes can be used to degrade phytotoxins, autotoxins and microbial toxins (15). Inoculation of apple seedlings and rootstocks with *Trichoderma viride* improved the growth of apple plants grown in soil with replant problem (82, Fig. 5). Microbes can also be developed for biological control. Many beneficial microbes with fungicidal potential have been identified from suppressive soils (4). Similarly, many isolates from suppressive soils can degrade autotoxins in the rhizosphere of continuously cropped plants (15). We found that inoculation with *Fusarium flocciferum* and *Cephalosporium acremonium* overcome the autotoxicity induced by phenolic acids in cucumber.

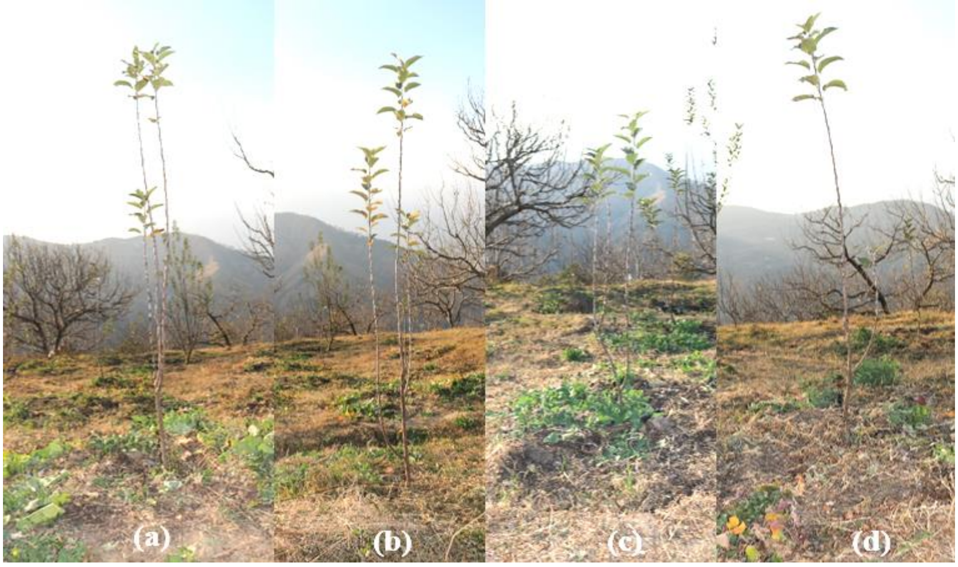

Figure 5. Growth of apple ‘Super Chief’ on (a) M.793 (b) MM.111 (c) M.7 (d) Seedling Rootstocks after response to *Trichoderma viride* under replant site

Although soil fumigation and chemicals are easy to control the replant problem they disturb the natural equilibrium between pathogen and antagonistic microorganisms in the soil. Utkhede and Smith (91) reported an increase in the growth of apple trees in the replanting site of apple replant problem by soil drenching with *Bacillus subtilis* and

Agrobacterium radiobacter (14). The post-planting drench application of strain EB-4 of *Bacillus subtilis* alone or with formalin fumigation effectively increased the trunk cross-sectional area, shoot growth and fruit yield of apple, which showed the potential of *B. subtilis* for biological control of replant disease (32,88). Mycorrhizal fungus *Glomus mosseae* used alone or with *Enterobacter aerogenes* + peat significantly increased the growth of replanted apple in sick soil and effectively overcome the replant problem (92).

A radiobacter may affect the plants by changing the composition of rhizosphere microflora and by reducing the number of colony-forming units of phytotoxic micromycetes contributing to replant disease (13). Inoculation of apple seedlings and rootstocks with *Agrobacterium radiobacter* improved the growth of apple plants grown in replant problem soil (14)]. Similarly, inoculation with the vesicular-arbuscular mycorrhizal fungus *Glomus etunicatum* successfully controls the apple replant problem. Inoculation of apple-tree seedlings with *Glomus fasciculatum* and *Glomus macrocarpum* reduces the Apple replant problem (12), which showed that the use of some VAM fungi could replace chemical treatments of apple replant problem sick soil. The strain EBW4 of *Bacillus subtilis* has the potential for biological control of the apple replant problem (90). Singh *et al.* (79) recorded an increase in tree growth of apple in the replanting site by soil drenching with *Bacillus licheniformis* CK-1 improves the growth of apple plants grown in apple replant problem sick soil at farmer field (Fig. 6).

Figure 6. Growth of apple ‘Super Chief’ on (a) M.-793 (b) MM.-111 (c) M.-7 (d) Seedling Rootstocks after response to *Bacillus licheniformis* CK-1 under replant site

The development of fungal and pseudomonas communities in the rhizosphere of different rootstock genotypes affects the tree growth and yield at apple replant sites (100).

Raj and Sharma, (64) tested four isolates of VAM and two isolates of *Azotobacter chrococcum* on seeds and seedlings of Golden Delicious apple against *Dematophora necatrix* (root rot of apple) and found that AZUHF1 isolates of *A. chrococcum* and AMUHF1 (*Glomus fasciculatum*) increased the shoot and root length.

3.7. Thermal control

Soil steaming at 60 °C or above for 45-60 min removes the growth-inhibiting agents from sick soil. Soil steaming temperatures up to 50 ºC did not alter the growth suppression induced by replant disease, whereas, 60°C steaming improved the shoot growth and 70 ºC permitted normal growth of plants (101). According to Moyls *et al.* (58), steaming of soil reduced the effects of apple replant disease and steam for 1 min showed 68 % better growth while steaming for 2 min showed 120 % growth improvement. Mazzola (51) reported that soil pasteurization enhanced the growth of apple plants and changed the composition of the fungal community.

3.8. Integrated management

The exact cause of the replant problem is difficult to investigate as it varies from region to region. Therefore, it is difficult to control the soil sickness/replant disease problem with only one method, hence, integrated management may be an effective tool to overcome the replant problem. Baxter (2) reported that soil treatment with Vertafume and mulching with sawdust or plastic markedly increased tree growth (total shoot length and trunk cross-sectional area) at replanting sites. Utkhede and Li (87) suggested the use of bacterial strain B8 in combination with mono-ammonium phosphate and lime + fumigation and bacterial strains (EBW-4 of *B. subtilis* and strain B8 of *Enterobacter aerogenes*) for effective control of replant disease. Utkhede and Smith, (89) reported that although the application of mono-ammonium phosphate alone may be sufficient to alleviate the replant problem, however, the addition of *Bacillus subtilis* strains BACT-1 or EBW-4, or *Enterobacter aerogenes* strain B-8 to this treatment may increase the tree growth. Granatstein and Mazzola (28) advocated the integration of cultural and biological methods to control the apple replant problem.

The use of topsoil + P + formalin drenches effectively controlled the apple replant problem (5) in Kullu valley of Himachal Pradesh, India. Soil fumigants control apple replant problem, when applied with biological and cultural practices (1). Wheat cropping controlled apple replant problem and enhanced fruit yield, whereas, *Brassica napus* seed meal amendment with post-plant mefenoxam soil drench was found equivalent to soil fumigation to improve the growth and yield (54). Avoiding replanting into the old tree rows coupled with the use of tolerant rootstocks is the best strategy to reduce replant problem in apple orchards (67). Kandula *et al.* (38) reported improvement in the growth of apple in the replant site with commercial *Trichoderma* formulations with NPK supplements. According to Singh and Sharma, (78) soil fumigation with Formaldehyde × *Bacillus licheniformis* CK-1 × *Trichoderma viride* × Merton 793 rootstock proved effective, but due to the complex nature of the problem, the combined use of chemical, cultural and biological methods is beneficial in controlling this problem (Fig. 7).

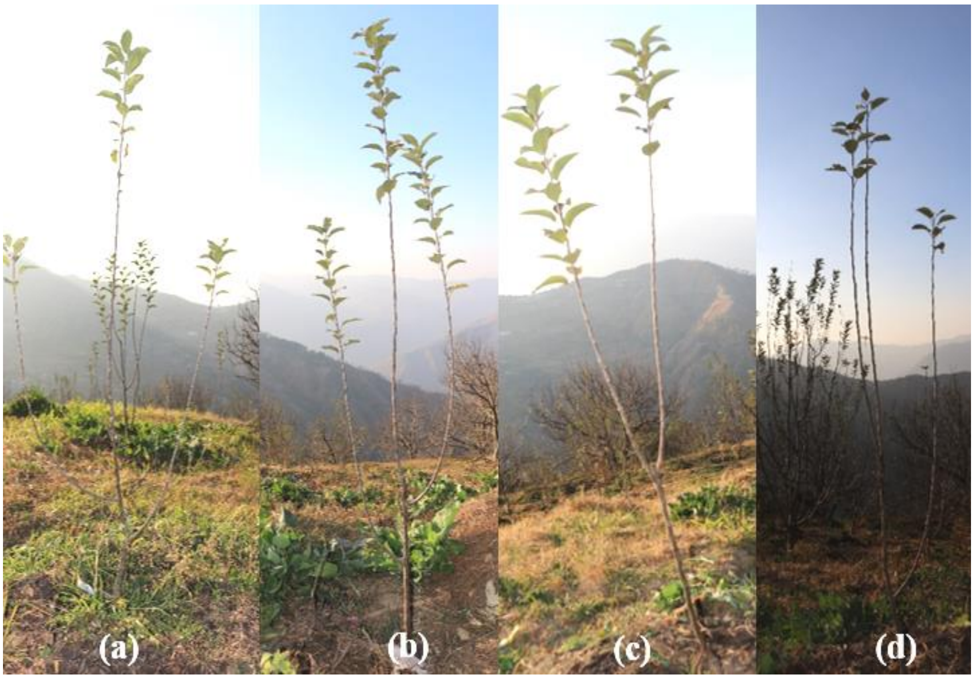

Figure 7. Growth of apple ‘Super Chief’ on (a) M.-793 (b) MM.-111 (c) M.-7 (d) Seedling Rootstocks after response to Formaldehyde × *Bacillus licheniformis* CK-1 × *Trichoderma viride* under replant site

4. SUGGESTED FUTURE AREAS OF RESEARCH

(i). The cytotoxic potential of many fruit crops has been established based on the correlation of phytotoxicity and the dose of extracts in plant tissues, without evidence for autotoxins in the rhizosphere. Until now, not enough studies have followed a criterion similar to Koch’s postulates, and genetic evidence for the involvement of autotoxicity in soil sickness. A detailed analysis of the genotypic differences in autotoxin metabolism, exudation and associated changes in knockouts plants and plant growth provides us important evidence for autotoxicity in fruit trees.

(ii). Soil is a complex matrix and many autotoxins can be easily modified by soil microbes (46). To date, only a few studies have investigated the behaviour of autotoxins in soils during monocropping. Special attention should be paid when differentiating the active autotoxins from their inactive conjugates in the orchard soils. In most cases, the concentrations of autotoxins in soils are lower than their phytotoxicity level and microbes easily degrade these autotoxins. It is, therefore, difficult to explain why a 2-7 years rotation or fallow period is necessary for these crops based on the degradation of autotoxins.

(iii). There are suppressive and conducive soils in the agroecosystems, but the underlying mechanisms are largely unknown. It is unclear whether beneficial microbes can cause Induced Systemic Resistance (ISR) in plants grown in suppressive soils. It will be interesting to compare the microbial communities and the behaviours of autotoxins in these soils.

(iv). The rhizosphere is a place with intensive interactions between root exudates, allelochemicals and microbes, leading to beneficial and detrimental impacts on plant growth and disease prevalence in the plant-soil feedbacks. Allelochemicals or autotoxins in the rhizosphere directly or indirectly affects the soil-borne pathogens or other detrimental microbes.

(v). Biodiversity in different fruit tree cropping systems is an important approach for the sustainable development of agriculture and pest control. It is important to re-examine the usefulness of traditional agricultural management methods, especially in developing countries.

5. CONCLUSIONS

Soil sickness is a complex syndrome, caused by various biotic and abiotic agents and reduced the plant population, growth and yield of young replanted plants. Soil fumigation and solarization effectively control soil sickness. However, due to the complex nature of problem, resistant/tolerant rootstocks, integrated management practices combining chemical, cultural and biological methods should be preferred to control it. Detailed research on quick and correct diagnosis of biotic and abiotic causes of the problem and its management through eco-friendly techniques is needed.

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DECLARATION

We declare that all authors of this Ms have made substantial contributions. We have not excluded any author that substantially contributed to this Ms. We have followed our ethical norms established by our respective institutions.

CONFLICT OF INTEREST

The authors announce that they have no conflict of interest.

ETHICAL APPROVAL

The authors declare that the study was carried out following scientific ethics and conduct. However, this study did not involve any use of animals, hence no ethical approval has been obtained from the concerned committee.

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