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Review Paper

Plant Parasitic Nematodes, Serious but Most Trivialized Biotic Challenge against Food Security: A spotlight on their Management for Sustainable Agriculture and Public Health

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ABSTRACT: Though the majority of soil dwelling nematodes are free living organisms, agricultural land use or farming systems, such as continuous cropping and monocultures, can disrupt soil health and lead to the accumulation of plant parasitic nematodes (PPNs) in soils. The activities of these tiny, parasitic, soil-dwelling organisms typically interfere with the anatomy and physiology of affected organs in a wide range of susceptible crops. Unsuspecting farmers usually attribute symptoms of such attacks, such as chlorosis, stunted growth, wilting and tipping-over and so on - to other biotic and abiotic causes. Large losses of valuable nutrient elements including protein, carbohydrates, potassium, calcium, phosphorus, zinc, iron, and gross yield associated with the damaged crop are also misrepresented or attributed to other factors. These declines in biomass accumulation and nutrient composition, taken combined, contributed significantly to increases in both hidden and visible hunger, which remains a serious public health issue in tropical landscapes, particularly in Sub-Saharan Africa. Simple crop and soil management techniques in low-input agriculture, such as crop rotation, the use of resistant root stocks or varieties, biological and phytochemical control approaches, the use of agro-waste, and so on, are discussed in this paper in order to reduce or keep PPNs populations below damage thresholds for sustainable food production and environmental health.

Keywords: Plant parasitic nematodes, sustainable agriculture, environmental health, hidden hunger, crop rotation, integrated nematode management

INTRODUCTION

Nematodes are microscopic, smooth-bodied, non-segmented, multicellular, and bilaterally symmetrical roundworms; found in virtually all marine and edaphic habitats (Williams *et al*., 2021). They constitute the most abundant zoological organisms on earth (Hodda, 2021); estimated as numbering over 400 quintillion (Ishak, 2019). The majority of soil-dwelling nematode species are beneficial free-living microbes that contribute to soil microbial population balance, ecological health, and soil fertility by decomposing organic wastes and releasing ammonium ions (NH4+) for plant life (Currel, 2013). A variety of free-living nematodes consume bacteria, protozoa, and fungi. For example, *Heterorrhabditis* and the mole cricket nematode *Steinnernema* spp. feed on insects and are used as lethal bio-insecticides to combat soil-dwelling insect pests.

Table 1: Plant parasitic nematodes, their host ranges and damage symptoms on affected crop plants Pin nematode *Paratylenchus* sp. Carrot, celery, sugar beet Stunted root system, reduced root pigmentation

Nematode species	Scientific name	Host range (usually wide)	Signs and Symptoms
Lesion nematode	*Practylenchus spp.*	Onion, corn, grape, wheat, potato	Kills feeder roots, chlorosis, dieback, stunting and deaths
Bulb/stem	*Ditylenchus spp*.	Alfalfa, onion, garlic, maize, tobacco, rye, potato	Swelling, blistered and bloated leaves, breakdown of middle lamella, rots of bulbs, tubers etc.
Foliar nematode	*Aphelenchoides spp.*	Strawberry, chrysanthemum	Leaf crinkling and discoloration, distortion, dwarfing and stunting
Dagger nematode	*Xiphinema spp.*	Tomato and solanaceous plants	Root tip swellings, and damage, transmits 13 viruses
Root knot nematode	*Meloidogyne spp.*	cowpea, onion, potato, cotton	Excessive root branching, root galls or enlarged knots on tubers
Lance nematodes	*Hopolaimus spp.*	Pea, bean, wheat, grasses, lawns, sweet potato	Reduced plant vigour, chlorosis
Citrus nematodes	*Tylenchus spp.*	Citrus, apple and other tree crop	Symptoms similar to nutrient deficiency diseases
Spiral nematode	*Heliocotylenchus spp.*	Tobacco, potato, soybean, corn	Stressed appearance on crops
Ring nematode Stunt nematode	*Criconemoides spp.* *Tylenchus spp.*	Peach and other tress	
Stubby root nematode	*Trichodorus spp. Paratrichodorus spp.*	Potato and solanaceous crops	Spraing, vectors tobacco rattle virus
Cyst nematode	*Heterodera spp.*	Legumes and a host of crops	Chlorosis, stunting, reduced root system, reduced nodulation in legumes
Pin nematode	*paratylenchus sp.*	Carrot, celery, sugar beet	Stunted root system, reduced root pigmentation
Needle nematode	*Longidorus spp.*	Various crops	Root tip swelling,, root proliferation and stunting

Sources: Wheeler *et al*. (2018); CSU (2021).

Plant parasitic nematodes, on the other hand, account for about 10% of soil nematodes (CSU, 2021). According to recent scientific reports, 2,500-4,100 plant parasitic nematode (PPN) species have been identified thus far (Poveda *et al*., 2020; Nicol, 2021). PPNs are obligate parasites of agricultural crop tissues (Table 1). The majority of these plant parasitic nematodes, such as root knot, lance, lesion, needle, sting, and stunt nematodes (Figure 1), have hypodermic needle-like structures called Stylets that they use to puncture, penetrate and sap crop nutrients (Figure 1: top right). Male nematodes are typically sterile and free-living, whereas female juveniles and adults are parasitic and destructive (Warmer and Bird, 2000; Williams *et al*., 2021). Plant parasitic nematodes like *Meloidogyne spp., Heterodera* spp., and *Pratylenchus* spp. have been named among the top ten most damaging pests to farm economies and scientifically significant nematode species (Table 2;

Figure 1: Some plant parasitic nematodes associated with tropical and subtropical agriculture
Top from left. *Practylenchus penetrans, P. penetrans* (adult), *Meloidogyne incognita, Meloidogyne* sp. (adult), RKN penetrating root tissues. **Bottom from left:** RKN galls on a plant root, *Criconemoides spp., Heliocotylenchus spp,* Soybean cyst nematode, *Aphelencoides sp.* **Sources**: WUR, CSU. Ohionline.

Table 2: Top 10 plant parasitic nematodes in molecular plant pathology.

Nematode grouping	Nematode genera/species
Root knot nematodes	*Meloidogyne spp.*
Cyst nematodes	*Heterodera spp., Globodera spp.*
Root lesion nematodes	*Pratylenchus spp.*
Burrowing nematodes	*Radopholus similis*
Root/Stem feeding nemadode	*Ditylenchus dipsaci*
Pine wilt nematode	*Busaphelenchus xylophillus*
Reniform nematodes	*Rotylenchus reniformis*
Dagger nematode	*Xiphenema index*
Root knot nematode	*Nacobbus aberrans*
Leaf and flower nematodes	*Aphenecoides besseyi*

*Source: Jones *et al*. (2013)

Subramaniam *et al*., 2020). They can be endo-, ecto-, or semi-endo-parasites. Some are shallow feeders, while others are deep feeders that delve deep into soils. PPNs feed on the meristematic tips of plant feeder roots, underground storage roots and stems, young buds, flowers, and leaves of susceptible plants, causing severe anatomical and physiological damage to such crop tissues. Symptoms on affected plants include disrupted xylem and phloem functions (Asawalam and Adesanya, 2001), galls or knots, multilaterally branched (Figure 1: bottom left) and stunted roots with delayed pigmentation, and unsightly tubers, among other things. Chlorotic, blistered, and bloated leaves, as well as bulb rot, occur on shoot systems (Figure 2). Overall, their actions result in weakened plant anchorage, decreased produce vitality, quality, yield, and marketable values. As such, they are undeniably important contributors to both visible and hidden hunger, both of which pose serious public health challenges, particularly in Sub-Saharan Africa (Enyiukwu *et al*., 2020). Consider nematodes if you've noticed a drop in crop yield, vitality, or quality without clear explanation (PSE, 2021). Many plant parasitic nematode species have short life cycle and undergo multiple generations per growing season (2 weeks to 2 years) and this thus exacerbates their damaging impacts on crop production and makes their control difficult to a very large extent. In infested soils, eggs of the golden nematodes are projected to remain viable for up to 30 years, making their control an uneasy and daunting task (Ishak, 2019). Juveniles that hatch from its eggs attack crop roots, sucking their growth factors and stunting crop growth, making it the most damaging pest of the crop than any insect or pathogen (Ishak, 2019). RKN alone affects between 300 and 2000 plant species.

Figure 2: Some crops parts of agricultural crops affected and damaged by nematodes infestation. From Left: Yam, Carrot, radish and lastly dry bean root on the right. Sources: Wikipedia.org

The costs of nematode attacks outweigh those of insect pests (Singh *et al*., 2021). In addition to direct injury, nematode lesions serve as entry points for pathogenic diseases and predispose crops to cold, frost injury, and the negative effects of hydrogenium potentials. Some nematodes even vector viruses; in fact, nematodes can transmit up to 13 different phytopathogenic viruses. PPNs in general cause significant crop losses around the world (Tian *et al*., 2007).

It has been reported that Pratylenchus spp. infestation has resulted in a 70% yield reduction in spring wheat. On a global scale, Singh and Singh (2015) and Forghani and Hajihassani (2021) estimated that nematode attacks cause 12.30 percent of total global crop yield reductions, amounting to USD 157 billion annually; and damages are most severe in moisture and nutrient-poor, coarse sandy soils (CSU, 2021).

Crop loss estimates of 40-92 percent, 30-85 percent, and 20-75 percent in wheat have been documented in Saudi Arabia, Australia, and the United States, respectively, due to cyst, lesion, and root knot nematodes (Nicol, 2021).

The annual cost of damage caused by root knot nematodes in Australian agriculture is estimated to be more than USD 300 million (Stirling *et al*., 1992; Hodda, 2021). Because disease symptoms are similar and generally confusing, nematode-induced losses are likely to be greater; however, a good portion of nematode-incited damages are likely misdiagnosed and attributed to other biotic or abiotic causes (Coyne *et al*., 2018). *Meloidogyne* spp., and *Rotylenchus* sp., *Tylenchus* sp., *Heterodera glycines, Ditylenchus* sp., *Aphelenchoides besseyi* and *Belonolaimus longicandatus* are reported as one of the most limiting bio-factors in the production of cotton, citrus, soybean, alfalfa, rice and other crops respectively (Wheeler *et al*., 2018). *Scutellonema bradys, Meloidogyne enterolobii, M. arerania, M. incognita and M. javanica* affect yams in the field, reducing their yield on the one hand and making their tubers unsightly (Figure 2). Nematodes hence, pose serious threat to crop production (Subramaniam *et al*., 2020), but often times, this threat is most trivialized or overlooked (Coyne *et al*., 2018; PSE, 2018). The aim of this paper was to highlight the importance of good nematode management for sustainable agricultural productivity in low-input agricultural systems of the humid tropics and sub-tropics.

METHODOLOGY

Data generation and consideration

The information presented in this work is apriority. They were generated by conducting searches on the subject matter in the databases of ResearchGate, Google, and Google Scholar based on the methodology used by Mgbeahuruike *et al*. (2017; 2018), as appropriately modified. The search terms included economic importance of nematodes in agriculture, plant parasitic nematodes and public health, nematode control methods in agriculture, nematicides used in plant protection, biotechnology's role in nematode control in Nigeria, sustainable management of plant parasitic nematodes, integrated nematode management, and so on. Papers published on *in vitro* and *in vivo* studies, as well as other useful materials presented on some URLs between 1992 and 2021, were considered for inclusion in this work for review. However, prior to the above timeframe, papers and other materials written in languages other than English were excluded from consideration.

The question is how do we curtail attacks/damage by nematodes on crops?

Chemical control measures

Nematodes remain a significantly significant threat to agricultural production and food security around the world (Ishak, 2019; Nishanthi *et al*., 2020; Subramaniam *et al*., 2020). One of the most effective ways of ameliorating the impacts of nematodes on crop production that easily comes to mind over the years has been use of chemical nematicides. Modern intensive agriculture so mulch relies on the use of these toxic nematicides to control damaging populations of PPNs (Page and Bridge, 1993). These fast acting soil-applied agro-chemicals (non-volatile, non-gas-forming medium-spectrum fumigants and volatile, gas-forming, broad-spectrum fumigant nematicides) have contributed immensely to increases in yields of agricultural crops.

This they accomplished by effectively eliminating nematodes (Enyiukwu *et al*., 2014; Nishanthi *et al*., 2020). Nematicides (which include DiTera WP, DiTera EC, and Nemafos) are long-lasting broad-spectrum biocides that can eliminate both target and non-target species (Enyiukwu *et al*., 2014). Despite their efficacy, their use against cyst nematodes (Heterodera spp.) has been ineffective (Warmer and Bird, 2000). Even in effective cases, misdiagnosis leading to inappropriate or excessive applications according to many workers, has exacerbated the negative effects of nematicides (Coyne et al., 2018). Nonetheless, a plethora of new scientific evidence has linked synthetic pesticide residues, including nematicides, to ecological food chain disruption, the extinction of birds and wildlife, and mammalian toxicities leading to allergies, organ defects, cancers, and the deaths of over 0.2 million people each year (Enyiukwu et al., 2016; Defenders of Wildlife, 2021; Beyond Pesticides, 2021). Given these numerous drawbacks, the EU, for example, has imposed stricter restrictions on the use of synthetic nematicides like 3-dichloropropen-Telone II (Coyne *et al*., 2018; Poveda *et al*., 2020), while others like Methyl bromide and Aldicarb have been outright banned (Forghani and Hajihassan, 2020). Stirling *et al*. (1992) contend that, in the light of the withdrawal or outright prohibition of many widely used nematodes (due, in large part, to ecological and human health concerns), there is an urgent need to seek out and develop sustainable nematode management approaches.

How could we grow crops sustainably in the face of damaging attacks of nematodes?

We all know that land is in limited supply, but urbanization and human population growth are increasing, particularly in Sub-Saharan Africa (SSA), putting increasing pressure on agro-returns (food, fuel, fiber, and industrial raw materials) from the land. Low agricultural productivity, caused by a variety of factors including climate change and increased pest pressures, has undoubtedly reduced food and fiber per capita in SSA (Enyiukwu *et al*., 2014; Coyne *et al*., 2018). In the light of this, sustainable land management as an economic resource becomes increasingly important. Sustainable agricultural land use entails cultivating it without jeopardizing agricultural productivity or ecological health. To accomplish this, the answer to the preceding question will be integrated nematode management (INM).

This management strategy employs a combination of control strategies aimed at preventing nematode introduction and spread to nematode-free areas, and where nematodes are already present, using good agronomic practices (GAP), resistant cultivars, biological control, and soil amendments to facilitate and achieve nematode population density reductions below economic injury levels (Table 3).

INM is a comprehensive and long-term approach to nematode management. As such, Subramaniam *et al*. (2020) defined sustainable plant parasitic nematode management as the concurrent application or use of two or more compatible nematode control methods (in sequence, combination, or both) to achieve nematode population reductions below damage thresholds in order to increase crop output while taking environmental into serious consideration.

Practice avoidance

According to experts, anything that moves soils also moves nematodes (Williams *et al*., 2021). Nematodes are slow movers in nature, moving only about 6 inches per year in soils. Machines, seeds, planting stocks, run-off water, wind erosion, and floods all transport soils over long distances. In the light of this, nematode eradication is conceivably difficult and is not regarded as a viable option in sustainable crop management. This is because nematode eggs, cysts, juveniles, and adults could overwinter for a long time in soils, infected debris, and planting stocks. The most dependable management approach to nematode challenges in agriculture therefore is prevention (UC, 2021). As a result, it appears that avoiding nematode infestations is preferable to attempting to eradicate them. During farm operations, use nematode-free planting stock. Also, make certain that the equipment is clean (Warmer and Bird, 2000). Adjust planting dates in small farm ventures to only when rainfall is abundant to avoid warmth-assisted damaging nematode populations. Nematode population density is critical to crop damage and vital to initiating control. Periodic nematode monitoring becomes imperative (Table 3).

Table 3: Nematode population threshold level to initiating control.

Nematode	Threshold level in plant root or soil
Root lesion (general)	500-1000
Root lesion in dry bean	>250
Dagger nematode	50-100
Lance nematode	40-150
Ring nematode	250-600
Spiral nematode	300-500
Alfalfa stem nematode	>1000
Stunt nematode	150-300
Root knot nematode	100
Citrus nematode	10-1000

*Source: CSU, 2021

Use resistant and tolerant varieties (where available)

Resistant (or at least tolerant) varieties are the first major step toward a more environmentally friendly approach to pest management (Subramaniam *et al*., 2020). This is because such varieties require less pesticide input, are resistant to pest infestations, provide adequate yields at a low cost in farming systems, and are environmentally friendly (Stirling *et al*., 1992; Enyiukwu *et al*. 2014; Subramaniam *et al*., 2020). According to Williams *et al*. (2021), some sweet corn, asparagus, and cabbage are the least tolerant to RKN. Similarly, some soybean and potato varieties are resistant to cyst and golden nematodes. Tomato plants containing M-genes that are resistant to nematode (including RKN) attack have been reported. VFN (*Verticillium, Fusarium*, and Nematodes) tomato varieties are resistant to wilt fungi and nematodes (UC, 2021). However, genetically engineering these M-genes to confer resistance to a wide range of other horticultural and field crops has remained primitive (Warmer and Bird, 2000). Commercial tree root stocks Nemagold and Guardian are resistant to root knot and ring nematodes, respectively, when used to establish peach plantations. Other RKN-resistant plants include African marigold (*Tagetes* spp.), Carmella, and Oleander. Apples, apricots, cherries, plums, and pears are nematode resistant and make good choices for establishing plantations. However, nematode resistant varieties of common vegetables and field crops are scarcely available commercially, limiting their use in rural farming communities (Coyne *et al*., 2018).

Adopt and ensure good agronomic control

Good agronomic practices (GAP) is central to sustainable agriculture (Enyiukwu *et al*. 2014). The fundamental objective of GAP is to reduce target pest density or population below damaging levels field and crop sanitation. To this end preference is geared towards low-key interventions such as:

a. To establish large farm concerns, use only clean and certified seeds obtained from registered seed companies.
b. In greenhouses, seeds or planting stocks such as bulbs or sets obtained from untrustworthy sources should be subjected to a 60-120minute heat or steam treatment to attenuate or destroy infested nematodes (Warmer and Bird, 2000).
c. Flooding for two years or more in heavily infested plantain and banana plantations significantly reduces nematode population in infested soils (UC, 2021).
d. In field crop systems, fallowing for two years or more, depending on land availability, helps to reduce nematode population density in the soil.
e. Historically, farmers in small-scale agro-enterprises grew mixed or multiple crops per field or intercropped staple crops with early maturing crops rather than mono-cropping (Dixit, 2019). Allelopathic exudates from one crop are thought to interfere with nematode pest pressure and activity on another.
f. Try to include trap and allelopathic cover or green manure crops, such as Sudan grasses, Marigold (Tagetes spp.), Tangerine, Queen Sophia, and Brassica species, to trap and kill parasitic nematodes (Baker and Koening, 1998). Brassica spp. contain isothiocyanates or glucosinolates, which kill PPNs while increasing the population of beneficial free living nematodes.
g. Implement effective weed-control strategies to eliminate alternative nematode weed hosts.
h. If possible, shift planting dates to later in the season when temperatures are cooler, and ensure irrigation when planting on hotter days.
i. Deeply bury or burn susceptible thrash from the previous cropping season.
j. Where possible, practice soil solarization, in which the soil is moistened and covered with dark tarpaulins for several days in direct sunlight, causing the high underneath temperature to kill the nematodes and their juveniles (UC, 2021).
k. In a well-tailored plan, rotating non-host crops with host crops such as vegetables is a must for long-term nematode management (Stirling *et al*., 1992; Dixit, 2019;

Subramaniam *et al*., 2020).

Adopt biological and phytochemical control

This involves the use of predatory or parasitic living organisms, as well as their exudates or metabolites, to suppress pest or pathogenic species populations. It is broadly defined as the use of a biological antagonist to reduce nematode population or damage. This method of nematode management is widely used in sustainable food production (Stirling et al., 1992; Nishanthi et al., 2020). Arthrobotrys dactyloides is a filamentous fungus that is known to voraciously parasitize PPNs in tropical soils (Currel, 2013). Okorie et al. (2011) found that Pleurotus ostraceus strongly inhibits RKN growth and development in a study. Death also befalls every PPN that comes into contact with some nematophagous bacteria genera such as Pseudomonas, Bacillus, and Pasteuria. These genera of bacteria directly parasitize or produce certain toxins and/or enzymes that incapacitate PPNs. Pasteuria penetrans, P. thornei and P. nishizawae as an instance are used as bio-control agents against Meloidogyne spp. (root knot nematodes), Pratylenchus spp. (lesion nematodes) and Heterodera and Globdera spp. (cyst nematodes) in soils (Tian et al., 2007; Currel, 2013). Several studies found that soil drenching with Trichoderma species, T. hazianum, P. ostraetus, and P. tuberregum, significantly reduced nematode populations in treated soils planted with tomato and soybean, improving their yields (Xiang and Feng, 2002; Sandaval, 2020; Poveda et al., 2020). Nematicidal activity is demonstrated by a number of plant growth promoting rhizobacteria (PGPR). CH4O, an antagonistic PGPR strain, kills juvenile and adult RKN, particularly Meloidogyne javanica. Their antagonistic mechanisms include parasitism, antibiosis, lytic enzyme synthesis, and activating or stimulating specific plant defense systems (Baker and Keoning, 1998; Poveda et al., 2020). Meloidogyne spp. were exposed to extracts of Hyptis suaveolus and Ocimum basilicum in some studies, which significantly reduced the population density of the parasites in vivo. Nnadi et al. (2019) and Ononuju et al. (2014) found that powder formulations of Delonix regia and Baphia nitida controlled Meloidogyne spp. infestation and reduced parasite damage in Okra.

Amend soils with agro-wastes, biochar and ashes

In light soils with poor nutrient status and low water-holding capacity, nematode damage is severe (UC, 2021). Many benefits have been reported for organic, animal, and agro-waste amendment of tropical soils (Stirling *et al*., 1992; Baker and Koening, 1998).

They improve soil structure, texture, and water-holding capacity, as well as soil nutrient status, and also immobilize heavy metals. Vernonia amygdalina and cassava peels facilitated the breakdown of total petroleum hydrocarbon pollutants; and encouraged the development of soil-inhabiting free-living species (Enyiukwu *et al*., 2021). Ikwunagu *et al*. (2019) and Nnadi *et al*. (2019) discovered that ash and biochars derived from *Vernonia amygdalina* and cassava peels had comparable control effects on *Meloidigyne* spp. to *carbofuran.* In pigeon pea trials, Akhtar *et al*. (1996) discovered that amending agricultural soil with *Azadirachta indica* (neem) and *Ricinus cummunis* (castor plant) effectively reduced the population of PPNs, increased the density of predatory nematodes, and improved pigeon pea growth and yield.

Phenolic compounds released from degradation of organic soil amendments strongly retards proliferation of PPNs in treated soil (Li *et al*., 2014).

Integrated nematode management (INM): The bottom line in sustainable agricultural production

No single control strategy is without flaws. Residues from Chemical strategy residues endanger environmental and consumer health, genetic resistance in some cultivars may be short-lived due to variability in pathogen genetic strains, cultural methods may fail to contain outbreaks, and bio-agents may be difficult to formulate in such a way that local farmers can use them, and they may even become pathogenic in some cases. As a result, a comprehensive approach to reducing nematode density and damage without jeopardizing ecological health is welcomed. This type of long-term management system is known as INM. Wide-ranging protection practices, such as two or more control strategies, are used in sequence or combination in this approach to reduce nematode population density and/or damage. In this system, the use of toxic synthetic nematodes is considered a last resort in order to improve food production without jeopardizing consumer health or environmental wellness.

Recommendations

(i) Obtain seeds/planting stocks from certified sources or their authorized distributors only.
(ii) Use clean seeds, planting stock and equipment to avoid spread of nematodes.
(iii) Where available, plant only tolerant/resistant cultivars.
(iv) Adopt good agronomic practices like regular weeding, burning/burying of previous crop thrash in addition to crop rotation.
(v) As much as possible practice mixed, multiple or inter-cropping as against monocultures except in large

scale commercial farms.

(vi) Check soil nematode population pre-plant or during crop growth and compare with published threshold levels (Table 3).

(vii) Imbibe the practice of amending soils with green manure, compost, ashes and agro-wastes that liberate nematode killing phenolic compounds (Li *et al*., 2014).

(viii) Use narrow spectrum, less persistent synthetic nematicides such as lambda cyhalothrin (Ononuju and Nzenwa, 2011) only as LAST RESORT, in this case invite trained experts to do so for you following proper diagnosis and determination of nematode density.

Conflict of interest

The authors declare that no commercial or financial relationships existed that could be construed as a potential conflict of interest when conducting the research.

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