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The Status of Research for the Management of the Banana Weevil, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae) in Sub-Saharan Africa

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ABSTRACT

The banana weevil *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae] is a major pest of East African highland bananas and plantains. Its larvae bore in corm tissue damaging the root system, disrupting nutrient and water uptake, compromising plant anchorage, reducing yield, and shortening plantation life. Yield losses in bananas and plantains may exceed 50%. Available technologies for the management of the pest include cultural control, biological control, and chemical control. These methods may be costly, labor intensive, or ecologically unsustainable. Such effects, together with developed pesticide resistance, have led to various efforts searching for sustainable alternatives. To achieve this, there is a need to understand the biology of the pest and the currently available management options which includes use of cultural practices, resistant banana varieties, biological and microbial control, pheromone trapping and chemical and botanical insecticides. This article reviews the research status concerning *C. sordidus* biology, distribution, management options, including current innovations such as genome editing, and suggests future research directions for the management of the pest. Research findings suggest that no single control strategy will provide complete control. The integration of appropriate conventional *C. sordidus* management options with genetic engineering and other ecologically friendly methods such as use of botanicals and infochemicals will manage the pest and sustainably increase banana production.

Keywords: Conventional breeding, *Cosmopolites sordidus*, genetic engineering, host resistance, IPM.

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I. INTRODUCTION

Bananas and plantains are the most important staple and cash crops for more than 50 million mostly smallholder farmers in East and Central Africa. Annual production is worth US $4.3 billion or 5% of the region’s gross domestic product [1]. In Uganda, over 20 million people depend on banana as an important component of their food security while government revenues exceed $440 million per annum [2]. Bananas and plantains are planted in low-input, small scale systems for local markets and household consumption. Farmers employ numerous cultivars, including cooking, roasting, brewing, and dessert types, in different cropping associations under diverse ecological conditions and levels of management.

Despite the key role of banana in the food security of the region, the smallholder farming communities engaged in its production derive inadequate income from it. This has been attributed to a range of biotic, abiotic and socioeconomic constraints including pests, diseases, declining soil fertility, low yields and market-related issues [3], [4]. One of the most important pests is the banana weevil (*Cosmopolites sordidus*, (Germar), Curculionidae: Coleoptera). *Cosmopolites sordidus* is narrowly oligophagous attacking wild and cultivated clones in the related genera *Musa* (banana, plantain, abaca) and *Ensete*.

Bananas are tall herbaceous plants that typically grow 1 to several meters high. A mat consists of an underground corm from which one or more suckers (plants) emerge. These suckers form ratoon crops and may serve as planting material that may be detached from the corm and planted elsewhere. The pseudostem is composed of leaf sheaths. A single true stem bearing the flower and subsequent fruits emerges after leaf production has ceased. Banana bunches can weigh 20 or more kilograms creating a top-heavy plant that is susceptible to toppling and snapping, particularly under conditions of pest attack on the corm and root system.

Cosmopolites sordidus larvae tunnel in the banana corm and pseudostem affecting anchorage, weakening the stem, and interfering with nutrient and water uptake. The attack can result in stunting, delayed maturation, reduced bunch sizes, snapping, premature death of affected plants and reduced stand life [5], [6]. Pest status may vary with ecological conditions (soil type and fertility, temperatures, rainfall, banana cultivar selected, cropping systems, and agronomic /management practices). Damage effects may be exacerbated by a complex of root nematodes (*Radopholus similis*, *Helicootylenchus multicinctus*, *Pratylenchus goodeyi* and

Meloidogyne spp) that also affect anchorage and interfere with nutrient and water uptake [4], [7]. These pests are most severe at altitudes below 1500m, offsetting investments in soil fertility and water management and causing yield losses of more than 50% [8].

Research findings suggest that no single control strategy will provide complete control for *C. sordidus* [9]. An Integrated pest management (IPM) strategy that includes cultural control (habitat management), biological control combined with the use of infochemicals, the use of resistant cultivars and genetic engineering (host plant resistance), and botanical insecticides options can be used to reduce *C. sordidus* damage [4], [9]. Some of the options have been validated to control and reduce damages caused by *C. sordidus*, while others appear to be effective only under controlled laboratory and screen house conditions but not in the field. Interventions that require labor or other investments on the part of the farmer (e.g., pseudo stem trapping, crop sanitation) may have limited adoption.

There has been therefore increased search for innovations within conventional breeding, soma clonal selection, genetic engineering, microbial controls, and enhanced pheromone trapping for sustainable *C. sordidus* management. The integration of appropriate conventional *C. sordidus* management options with genetic engineering and other ecologically friendly methods such as use of botanicals and infochemicals will manage the pest and sustainably increase banana production. In this review, we, discuss the research status of *C. sordidus* concerning its biology, distribution, host range, pest status and management options. This review also discusses how previous and current management options inform and improve *C. sordidus* control and suggest future research directions of the pest.

II. DISTRIBUTION AND HOST RANGE

Cosmopolites sordidus originated within the Indo-Malayan region [10], coincident with the area of origin of bananas. The adults rarely fly and spread primarily through the movement of immature stages in infested planting material. The pest is currently found throughout Asia, Oceana, Australia, sub-Saharan Africa, and the Americas [11]. It is unclear how long the *C. sordidus* has been present in most areas.

Plantains and East African highland bananas tend to be more susceptible than other banana groups. *Cosmopolites sordidus* damage on Cavendish varies in different regions with higher levels observed in South Africa and South America than in Central America [9], [12]. For example, recommended action thresholds on Cavendish banana vary from 2 adults/trap in Brazil to 15 to 25 adults/trap in Central America [12]. Night *et al*. [13] found that larvae survived in the laboratory on excised corm of field-resistant East African highland banana clones. In Uganda, the cultivar Kisubi (AB, Ney Poovan subgroup) is resistant to *C. sordidus* attack, yet high levels of damage may be found in crop residues more so on prostrate rather than standing stems [14]. Kiggundu *et al.* [15] suggested that damage on residues of resistant clones reflect larval success rather than ovipositional preferences. This would imply the breakdown of biochemical (antibiotic) defenses following harvest [16].

III. *COSMOPOLITES SORDIDUS* BIOLOGY, BEHAVIOR, AND DYNAMICS

A. *Biology and Life Cycle*

Studies in East Africa in the 1980s and early 1990s revealed *C. sordidus* to be an important production constraint and a primary cause of the disappearance of highland banana from central Uganda [3]. At the time, little was known about the pest. As a result, a series of studies were undertaken to investigate the biology of the pest including life cycle, behavior, population dynamics, and host plant-pest relationships [ecology]. These studies served as a foundation for the development of effective control strategies [3], [4], [15], [17].

Cosmopolites sordidus manifests a ‘K’ selected life cycle with a long-life span of 2 to 4 years and low fecundity [3]. The immature stages are cryptic with the eggs, larvae, and pupa hidden in plant tissue (Figure 1). Upon mating, females deposit eggs singularly in notches created with rostrum at the collar of the plant corm around ground level. The white, oval eggs hatch in 5 to 8 days. The creamy-white larvae take 30 to 50 days to develop through 5 or 6 instar stages[3], [18] The pre-pupal and pupal stages last 6-8 days [16].

Thus, in East Africa, the development time from egg to adult is 40-70 days [3], [15], [17]. Temperature plays an important role in both egg and larval development [18], while resistant clones affect larvae development and survivorship rates [13].

Fig. 1. *C. sordidus* adult, eggs, and larvae [Picture by Cliff Gold, Uganda].

B. *Cosmopolites Sordidus Behavior*

Adult *C. sordidus* are free-living, negatively phototropic, thigmotactic, strongly hygroscopic, gregarious, and display death mimicry [19], [20]. Although the *C. sordidus* are differentially attracted to banana cultivars [17], [21], *Cosmopolites sordidus* exhibits restricted feeding habits, with adults feeding on dead plant material, while larvae feed and develop mainly on corms and pseudostem [9]. Adult *C. sordidus* have been widely reported to favor crop residues and moist environments, including in or under newly cut or rotting pseudostems, decaying stalks, cut or damaged corms, moist trash and under the soil surface [5], [22]. The adults can also penetrate the soil to depths of 50 to 70 cm [23]. Treverrow *et al*. [22] observed adults to be closely associated with the banana mat, being primarily in the leaf sheaths, around the roots, under loose fibers surrounding the base of the plant, and occasionally in larval galleries. This kind of life cycle and behavior undermines most conventional control methods.

Ovipositing females are differently attracted to banana cultivars [17], [21]. *Cosmopolites sordidus* is a cryptic pest. Eggs are inserted in the plant corm and pseudostem often at or below the soil surface. The larvae tunnel in the corm and lower pseudostem and are the damaging stage. Pupation is within the plant. Data suggest that host plant resistance is more a function of larval survivorship than oviposition preferences [24].

C. Cosmopolites Sordidus Activity Dynamics and Dispersal

Cosmopolites sordidus adults are nocturnally active with the greatest activity between 2100 and 0400 hours [25]. A substantial proportion of the population may be inactive for extended periods and remain sedentary during daylight hours. The nocturnal habit of the *C. sordidus* has largely precluded direct observations on *C. sordidus* flight under field conditions. Although the *C. sordidus* has functional wings, they rarely fly [26].

Seasonal differences in trap captures of adult *C. sordidus* have been reported [16]. Trap captures may reflect activity patterns, but do not provide meaningful estimates of population density which require mark and recapture methods [14], [27]. Higher trap captures in dry seasons and rainy seasons or unrelated to climatic factors have been reported [28]. These conflicting results provide an unclear picture of when adults are most active and, hence, most vulnerable to control interventions.

D. Dispersal and Movement

Dispersal of the *C. sordidus* maybe by walking, occasional flight, and dissemination of infected planting material. The maximum observed distance moved by walking was 35 m in 3 days and 60 m in 5 months [14]. Gold *et al*. [3] found only a small percentage of *C. sordidus* moved > 25 m in 6 months. This suggests that dispersal by walking may contribute to invasion of neighboring fields but not much beyond. The *C. sordidus* narrow host range and limited dispersal capability mitigate against immigration of adults into isolated or newly planted banana stands by walking or flying [3]. It has been widely recognized that dispersal of *C. sordidus* is primarily through infected planting material [26]. Banana suckers may contain adults in the leaf sheaths or immature stages within the corm. This suggests that the use of clean planting material is an important factor in establishing healthy banana stands.

IV. Pest Status and Yield Loss

The pest status of *C. sordidus* may be affected by region, agro-ecological zone, elevation (temperature), rainfall, soil types, cultivars, cropping systems, presence of other pests and diseases, and management practices. Yield loss estimates ranging from 0 to 100% [12], [16]. The combined attack of *C. sordidus* and root parasitic nematodes have caused yield declines of more than 50% and contributed to the disappearance of East African highland banana from traditional growing zones in central Uganda [16].

Cosmopolities sordidus damage and related yield loss tends to increase over time, likely reflecting its slow population buildup. In a field trial with East African highland bananas, Rukazambuga *et al*. [6] found yield losses to increase from 5% in the plant crop cycle to 44% in the third ratoon. In a 7 year field trial with East African highland bananas, Gold *et al*. [3] found high levels of *C. sordidus* attack resulted in reduced bunch weights, plant loss, mat disappearance and fewer harvested bunches, with estimated yield losses averaging 42% over the final 4th year of the trial. These results supported farmer observations that *C. sordidus* contributes to shortened plantation life. In addition, a 34 to 40% sucker mortality of cooking bananas was reported when the pest free suckers were planted in fields previously infested with *C. sordidus* [16]. In addition, larval galleries may be secondarily invaded by disease agents including *Pseudomonas (Ralstonia] solanacearum* (Moko disease) [9] and banana Xanthomonas wilt [29].

Cosmopolites sordidus damage is commonly estimated by visual observations of peripheral tunnels on pared corms (percentage coefficient of infestation or PCI) and cortex and central cylinder damage estimated from cross sections of banana corms [30]. Peripheral (cortex) corm damage (Fig. 2) disrupts existing and emerging roots which interfere with normal nutrient and water uptake. This in turn leads to yellowing of leaves, snapping of the plants during windy weather due to damage at the coral and disappearance of mats over time [30]. Damage in the central cylinder affects the vascular system which may stunt the plant growth, delay flowering, compromise fruit fill which in turn results in small bunches. Gold *et al*. [30] concluded that damage to the central cylinder had a greater impact on yield than damage to the corm cortex.

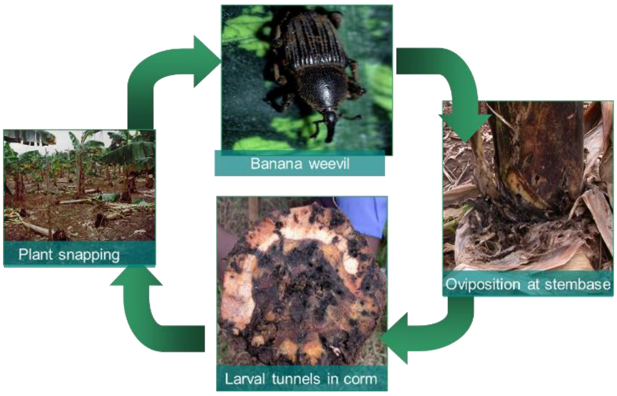

Fig. 2. *C. sordidus* and its damage (pictures by Cliff Gold, Uganda).

Farmers are aware that *C. sordidus* damage is more important in older stands. This has been confirmed by on-station trials that have shown damage and yield losses increasing over time [31], [32]. The pest's importance may be influenced by the banana type, and management system. In general, plantains and East Africa Highland bananas (EAHBs) are considered among the most susceptible types [33]. *Cosmopolites sordidus* damage tends to be greater in smallholder farms characterized by poor soil nutrient status, poor agronomic practices, and poor phytosanitary measures than in commercial farms with good management practices [16]. For example, recommended action thresholds on Cavendish banana vary from 2 weevils/trap in Brazil to 15 to 25 weevils/trap in Central America [12].

Yield losses to *C. sordidus* have been associated with sucker mortality, plant loss, reduced bunch weights, mat disappearance and shorter stand life [32]. Newly planted stands in or near previously infested fields may suffer high levels of plant loss [27] as a sucker can be killed by a single larva if it attacks the growing point. Moreover, ovipositing *C.*

sordidus are attracted to cut corms, making newly detached suckers especially susceptible to attack. Toppling is often attributed to plant-parasitic nematodes that attack the root system, thereby reducing anchorage [34]. However, it appears likely that *C. sordidus* damage reduces root number and can also contribute to toppling. For example, in Ugandan field trials, Rukazambuga [31] found extensive toppling in mats with high levels of *C. sordidus* attack and low levels of nematode damage. Snapping (i.e. breaking of the corm) may also occur on plants with severe *C. sordidus* damage [34]. In central Uganda, *C. sordidus* has contributed to a decline in stand life from > 30 years to less than 4 years [32].

Cosmopolites sordidus pressure has been widely associated with management practices and ecological factors. Poor management of the plantation; bad drainage, acid or low fertility soils, weedy fields, inadequate sanitation, extended droughts, and nematode infestations [12], [34] exacerbate *C. sordidus* damage to the crop. In Uganda, higher levels of *C. sordidus* have been attributed to reduced crop sanitation and other management practices [35]. In Ghana, low levels of *C. sordidus* damage in plantain may result from the short crop cycle (1-2 ratoons) before replanting [36]. In contrast, Rukazambuga *et al*. [37] found the percentages of yield loss of 27% in stressed (i.e. intercropped with finger millet) and more than twice in vigorous (i.e. mulched monoculture) growing banana. This translated into a 2.5 ton/ha loss in the intercrop and a loss of 6.3 ton/ha in the mulched field. These data suggest that *C. sordidus* can be an important constraint even in well-managed banana stands.

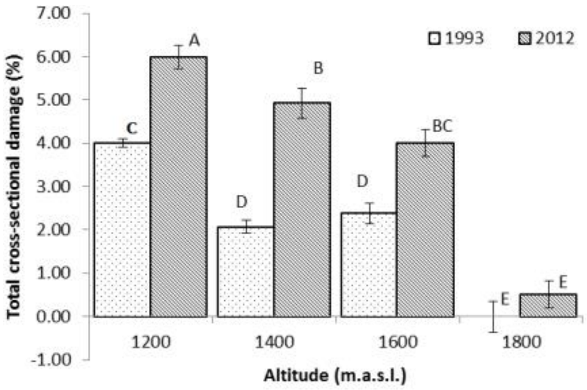

Fig. 3. Proportions for total cross-sectional C. sordidus damage (%) at a different altitude in 1993 and in 2012 (Figure reproduced with permission from the authors, [39]).

Ecologically, *C. sordidus* tends to be absent or in low numbers above 1600 masl [38]. As a result, it is unimportant in much of the Ensete growing regions of Ethiopia and part of the highland banana-growing region of eastern Africa. In Uganda, most severe *C. sordidus* damage was found between 1000 and 1400 masl [7]. However, increased levels of damage have been reported (Figure 3) at 1600 masl in banana stands [39]. These changes may be associated to the climate change and increased temperatures at higher elevation. The *C. sordidus* thrive best at high humidity with temperature ranges of 23-26 °C [16]. Lower temparatures (< 23 °C) restrain the *C. sordidus* development cycle while higher temperatures (> 32 °C) cause *C. sordidus* desiccation. Therefore, it is argued to incorporate management technology that considers the effects of climate change and other factors that encourages *C. sordidus* damage at higher elevations.

V. MONITORING: POPULATION AND DENSITIES DAMAGE ASSESSMENT

To understand the pest status and the impact of interventions, there is need for an accurate assessment of *C. sordidus* population levels and damage. The pest biology makes assessment and control difficult. Adult weevils are often monitored using traps from corms or pseudostem residues, although interpretation of trap captures is difficult. This is because several factors such as trap material, size, number, age, location and weather, influence trap catches. Bakyalire and Latigo [17] suggested use of a sandwich trap using banana psusdostems as an attractant. A maximum of 10 weevils per trap per week have been captured using banana pseudostem disc traps, although the number of weevils collected at these traps was consistently low to accurately assess weevil density [17]. Studies conducted on different trap designs and the response of adults to semiochemicals demonstrated that weevil counts increased with combinations of host plant kairomones with the aggregation pheromone cosmolure+, compared with the use of any compound alone [40]. Studies on the male produced aggregation pheromones and host kairomone compounds have identified the trap designs and protocols that can be used for enhanced monitoring of weevil populations in the field [41].

In addition, adult populations can be estimated through mark and recapture methods using pseudostem traps [27] and such estimates often do not correlate well with plant damage [35]. It was observed that adult population estimates in Ntungamo District, Uganda showed enormous variability between neighboring farms growing highland banana clones (range 1600 to 149000; median 9300 adults/ha) [14]. The within site variability of weevil numbers suggests that management plays a great role in influencing weevil populations. The weevil numbers are also widely believed to be associated with low fertility soils, bad drainage, inadequate sanitation, weedy fields, nematode infestation, and drought.

Estimates of larval damage in the corm require destructive methods and can give a single point estimate for a plant. As a rule, damage estimates are done as soon after harvest as possible. Assessment methods in Uganda entailed cutting the corm in cross sections at and 5-10 cm below the plant collar depending on size of the corm. Visual estimates were made on the area consumed by *C. sordidus* larvae (i.e., area taken in galleries) in the central cylinder and outer cortex for each cross section. Such estimates, however, provide little information on the timing of attack which, in turn, can affect plant development and yield. Still Gold *et al*. [30] was able to demonstrate that yield loss was most closely related to damage levels in the central cylinder

VI. MANAGEMENT OPTIONS FOR *C. SORDIDUS*

Research on interventions for the management of *C. sordidus* suggests that there no single strategy for the management of the pest. Using an integrated pest management (IPM) approach that combines two or more methods can provide the best option for successful management of the pest. The IPM program would include cultural control (habitat management), biological control, host plant resistance (including genetic engineering and somaclonal selection), chemical control, botanical control, and use of semio-chemicals.

A. *Cultural Control (Habitat Management)*

Cultural control (habitat management) options for the management of *C. sordidus* include the use of clean planting material, crop sanitation, mulching, trapping with crop residues and enhanced trapping with infochemicals (Table I). Cultural techniques create an environment that reduces pest movement, promotes host plant tolerance of pest attack, and/or is unfavorable to pest build-up [20]. For *C. sordidus*, cultural control methods are the oldest techniques used in its management though many were at one time abandoned in favor of chemical pesticides. The commonly practiced cultural methods include:

1) *Clean planting material (CPM)*

Infected suckers are major entry points of weevils into newly planted fields. The use of CPM prohibits the introduction and the initial *C. sordidus* population build-up which lowers damage to 5% in the 1st ratoon of the newly planted plantations [6]. The effectiveness of this technology depends on the ability to eliminate *C. sordidus* eggs and larvae, and to avoid re-infestation from nearby plantations with a history of *C. sordidus*. Elimination of *C. sordidus* eggs and larvae has been done through the use of tissue cultured plants, selection of clean suckers, paring of corms, and hot water treatment (52-55 °C) for 20 min to kill cryptic *C. sordidus* eggs and larvae. Paring, or removal of the outer surface of the corm, has also been widely recommended [42]. Paring can expose *C. sordidus* galleries and allow the farmer to reject heavily damaged suckers. Removal of all the leaf sheaths and paring of the entire corm will eliminate most *C. sordidus* eggs and first instar larvae. Many later instar larvae are likely to be deeper within the corm and not removed by paring. Paring the corms and dipping them in a solution of a chemical insecticide, Dursban (a solution of 1.5 cc of Dursban per litre of water for 1 hour) have observed to kill weevil eggs and larvae within the corm [43]. The use of tissue culture plantlets for *C. sordidus* control are recommended possibly because plants are 100% free of *C. sordidus* and nematodes at the time of planting. However, tissue culture plantlets are not universally available or affordable. Tissue culture corms are too small and therefore not many weevil larvae are required to cause significant damage.

2) *Field sanitation*

Following harvest, crop residues may serve as shelters for adults and oviposition sites [3]. For example, Gold *et al*. [32] found > 35% of adult *C. sordidus* to be associated with crop residues. *Cosmopolites sordidus* readily oviposit on residues for extended periods after harvest [8]. For some clones, attack on residues may be more extensive than that on growing plants (e.g., Gros Michel in Ecuador; Cavendish in Australia and Latin America, Ney Poovan in Uganda) [14], [44]. Crop sanitation for example destruction of crop residues, has been widely recommended to eliminate *C. sordidus* refuges and breeding sites [45]. The methods include cutting residues at or below the soil surface and chopping or splitting harvested corms and pseudostems to quicken the desiccation. This does not only destroy immature *C. sordidus* growth stages but also the most preferred breeding sites in susceptible clones [46].

The value of sanitation as a means of *C. sordidus* control has been disputed. Treverrow *et al*. [22] suggest that crop hygiene (i.e. sanitation) is the long-term key to *C. sordidus* control and that without it all other control measures are pointless. Nanne and Klink [47] report that sanitation can drastically reduce *C. sordidus* populations. Farmers in central Uganda felt that abandonment of sanitation practices was an important factor in increasing *C. sordidus* problems on their farms [32]. Gold [5] suggested that crop residues might act as “trap crops” drawing gravid female *C. sordidus* away from growing plants. In contrast, Blomme *et al*. [11] reviewed that sanitation required too much labor and competes for time with other crop activities. In farmer participatory trials in Ntugamo District, Uganda, Masanza *et al*. [35], [46] found that increases in crop sanitation levels (i.e. destruction of banana residues after harvest) significantly reduced adult *C. sordidus* adult populations, lowered corm damage, increased plant maturation rates and increased yields. However, in an on-station trial, Masanza *et al*. [48] found that crop sanitation reduced *C. sordidus* adult populations but did not affect damage or yield levels during the duration of the trial. In Tanzania, Rannestad *et al*. [49] found that crop sanitation combined with trapping reduced *C. sordidus* populations by 33 to 74%. Despite the labor intensity associated with crop sanitation in reduction in the yield loss due to *C. sordidus* damage, it remains a reliable technology to promote to affect banana farming community.

TABLE I: STUDIES THAT INVESTIGATED *C. SORDIDUS* CULTURAL CONTROL STRATEGIES

Cultural strategy	Result on the measured parameter	Experiment	Significance	*Reference*
Weeding, de-suckling and manuring	Population increased by 2.25 folds	Field	-	[6]
Trapping by farmers and scientist	Reduced corm damage and C. sordidus population by 61% and 53%	Field	+	[52]
Cover crop, Paspalum notatum	Abundance and damage	Field	+/-	[50]
Manure + mulching, Manuring, millet intercrop	*C. sordidus* densities and corm damage was the same	Field	-	[53]
Pseudostem trapping	Corm damage and *C. sordidus* density reduction	Field	+	[52,54]
Pseudostem, pheromone trapping & Insecticide-treated pseudostem traps	*C. sordidus* density reduction and Corm damage assessment (-)	Field	+/-	[55]
Pseudostem and pheromone trapping	*C. sordidus* densities reduction	Field	+	[56]
Kairomone of Fermenting tissue + Pheromone trap	A combination had an additive attraction in the laboratory but with no significant effect in the field	Laboratory /Field	-	[40]
Kairomone 2R,5S-theaspirane of senesced banana leaves	Number of adult *C. sordidus* attracted	Laboratory	+	[57]
Clean planting material	*C. sordidus densities (+) and Corm damage assessment*	*Field*	+/-	[5]

(+) The study reported a significant effect on *C. sordidus* population and or damage, (-) study reported non-significant results, (-/+). Significant results on one of the tested technologies and insignificant on another in the same experiment.

3) *Selected cropping system*

Insect immigration rates, increasing host plant location, and emigration rates are often influenced by mixed cropping systems. However, weevils are sedentary insects that live in perennial systems with abundant supply of hosts. Coffee intercrops and residues (e.g., husks) may repel weevils but this remains to be investigated. Live (green manures) and dead mulches have also been used in an attempt to manage pests and diseases. Among live mulches, legumes like *Mucuna pruriens*, and *Canavalia ensiformis* were used in the banana plantation as cover crops but did not reduce *C. sordidus* densities or crop damage [20]. *Paspalum notatum* also was used as a cover crop, and it did reduce *C. sordidus* densities but not damage [50]. On the other hand, organic mulch (slashed grass, straw, wood ash, sawdust, plant residues, and compost manure) when used they favor crop growth and yield more than managing *C. sordidus* and their damages. These mulches attract beneficial soil-dwelling macro and micro-organisms that aid in the breakdown of the mulch to release nutrients needed for crop growth and yield. *C. sordidus* prefer moist/ dump places, for they are highly susceptible to dissection. This suggests that mulching creates a suitable micro-environment for them to multiply and cause damage to a challenge that may be reduced by mulching away from the mat [51].

4) *Trapping*

This involves trapping adults using split pseudostem and discs-on- stump traps] [46], [52], and pheromone-baited traps [41], [56]. Pest reductions due to trapping have been reported [58], [59]. Studies indicated that pseudostem trapping reduced *C. sordidus* population by 38%, and corm damage by 49% [54]. However, pseudostem trapping has low adoption among farmers, possibly due to being laborious, immigration of *C. sordidu*s from poorly managed neighboring fields, and the inability to trap the cryptic larvae. Pseudostem traps are good for monitoring weevil populations and can be applied to two weeks before replacing with new ones.

Pheromone traps have been reported to be far better, 5-10 and up to 18 times compared with pseudostem traps in Costa Rica and Uganda respectively [55]. Trapping using pheromone and kairomones, in the management *C. sordidus* population has been recommended [57]. Pitfall-pheromone based traps, at a rate of 4 traps /hectare reduced weevil damage by over 60% and increased bunch weight by 20% in Costa Rica [59]. However, when tried in farmers' fields in Uganda at the recommended pheromone trap density of 4 traps per hectare, did not effectively reduce weevil densities and plant damage [60]. Other than male-produced pheromone, many semiochemicals have been reported to attract *C. sordidu*s and can be used to enhance *C. sordidus* trapping. For example, Uzakah *et al*. [61] provided evidence for the presence of female produced sex pheromone, though it is active within a short-range and serves for the mating purpose only, unlike sordidine. Nonetheless, *C. sordidus* are attracted to kairomones such as 1,8-Cineole an electrophysiologically active compound got from susceptible, but not ß-Phellandrene of resistant banana cultivars [62]. It was further established that, *C. sordidus* is highly attracted to a volatile kairomone 2R,5S-theaspirane from **s**enesced banana leaves [57]. This organic compound is comparable to pheromone and can serve as an alternative in the management of *C. sordidus* population.

Enhanced trapping which involves integration of pheromone traps with and entomopathogen such as Beauveria bassiana has been suggested [57], [63]. Similarly, Braimah, Tinzaara *et al*.[64], [65] showed that the use of pseudostem traps enhanced with or combined with other compatible control methods (e.g., entomopathogens) was key to *C. sordidus* control (Fig. 4). In Costa Rica, for example, baiting pseudostem traps with male *C. sordidus* aggregation pheromone significantly increased adult *C. sordidus* trapped, though its adoption was limited by cost [66]. Addition of 7 days fermented 'Mbwazirume' AAA-EA plant tissue, increased the efficiency of pheromone baited traps by 50% compared to pheromone traps alone [40]. Gokool *et al*. [55] on the other hand observed that treating pseudostem traps with an insecticide like Confidor 200 SL (imidachloprid) at 2 ml/L would do away with the regular checking of the traps for it kills the trapped *C. sordidus* which saved on labor. Despite the above enhancement to improve on the low weevil captures of pheromone-based traps, further considerations should be made on trap parameters; trap placement (position), trap color, size, and frequency of collections among others. For instance, Reddy *et al*. [67] observed that mahogany brown ground-based traps of 40 X25 cm were more effective than pitfall yellow traps.

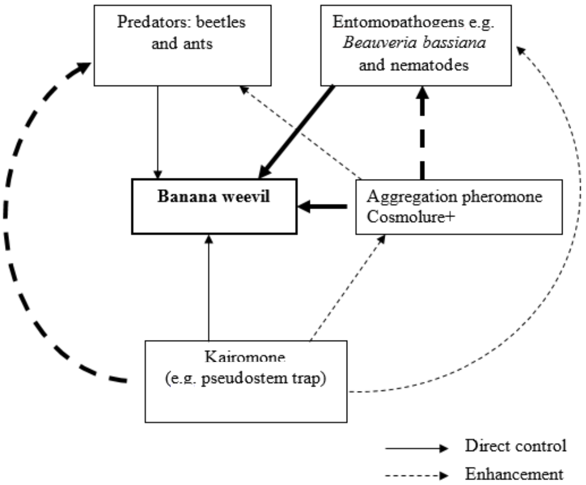

Fig. 4. The aggregation pheromone Cosmolure+ as a component in the integrated management of the Cosmopolites sordidus. The thickness of the lines represents the relative importance of the indicated effect, source: [68].

B. *Biological Control*

Several biological agents have been evaluated for the management of *C. Sordidus* (Table II). Several predacious beetles feeding on *C. sordidus* adult, and its larvae were found effective in South East Asia, a region of the pest origin. Their effectiveness was however lost when introduced in banana growing region for example East Africa. This led to a search into endemic biological control agents in the region [69]. These, however, were more effective in the laboratory than under field condition whereas others were stage specific, something that limited their commercialization. For instance, predators and parasitoids identified in Western Kenya were only effective on eggs, larvae, and pupae, but not adult *C. sordidus* [69]. A survey conducted in Uganda [70] about the natural enemies associated with the *C. sordidus* found

Euborellia sp., *Labia* sp. and *Thyreceophalus* sp. as potential predators targeting *C. sordidus* eggs, larvae and pupae. The myrmicine ants *Tetramorium guinense* and *Pheidole megacephala*, successfully controlled *C. sordidus* in Cuba, however, when tried in Uganda were infective [71]. Cane toads also potentially reduce *C. sordidus* population, hence a need to search into its potential under field conditions.

Among the microbial agents are the entomopathogenic fungi (EPF) e.g., *Beauveria bassiana* and *Metarhizium anisopliae*. Other EPF have also been screened against adult *C. sordidus* and larvae with > 90% mortality in the laboratory bioassays [72] – [75]. Kaaya *et al*. [76] also reported *B. bassiana* and *M. anisopliae* to have caused 98-100% *C. sordidus* instar larvae and 63-97% adult mortalities in laboratory bioassays. Moreover, Bakaze *et al*. [73] isolated other fungal strain like *Curvularia senegalensis* and *Fusarium verticillioides*, whose mortality was > 80% for eggs and larvae, and 60-75% for adult which compares to *B. bassiana* G41. Inconsistence with laboratory trial mortality may be a result of geographical isolation point of the strain, stage of insect development, formulation of EPF. This limits their use in banana fields, thus a need for a study to harmonize such variations. Performance of candidate strains under field condition, have varied efficacy that is greater than that observed in the laboratory trials. For instance, *B. bassiana* which showed 100% *C. sordidus* adult mortality under laboratory trial, showed field mortality with oil formulation of 66% in Uganda [77] and 75% in Ghana [78]. This limited efficacy is possibly a result of inefficient delivery system and formulation that target both adult and the cryptic larvae stage.

Use of endophytic fungi may greatly reduce the stringency needed when delivering EPF. Endophytes are heterotrophic microorganisms that are either pathogenic or nonpathogenic which live inside the plant roots or vascular tissue primarily for reproduction, nutrition, or protection. The idea of exploring endophytic technology was that *C. sordidus* resistant banana genotypes were reported with high levels of endophytes compared to susceptible ones [79], [80]. Therefore, many susceptible cultivars were evaluated with strains like *B. bassiana* [81], *Fusarium oxysporum* V5w2 [82] and *Beauveria* G41 [83]. This strategy, however, had limited success under field conditions and strain like *F. oxysporum* V5w2 reduced the growth performance of treated plants [83]. Nonetheless, endophyte use would reduce on the EPF subsequent delivery cost and their formulation.

Entomopathogenic nematodes (EPN), *Steinernema* and *Heterorhabditis* species have been evaluated in Australia and Tonga to attack both *C. sordidus* adults and its larvae [84]. These EPNs have a wide host range with good host finding abilities, fast host killing and tolerance to temperature range (2-35 °C), and can be conventionally applied with other agrochemicals [84]. Strains that were promising were: *Heterorhabditis zealandica*, *Heterorhabditis Dl*, *Steinernema carpocapsae* and *S, carpocapsae* BW. *Steinernema carpocapsae* BW caused 85% and *S. carpocapsae* caused 45% adult mortality in the laboratory. When *S. carpocapsae BW* was tested under field conditions it caused 63% larvae mortality and 0 -79% for adult mortality [44]. This limited efficacy on adult *C. sordidus* may be due to hard cuticle, lack of efficient dispensing method with baits to aggregate *C. sordidu*s at the treated site, and seasonal variations. The costs involved in production and refrigeration may also limit their economic use under rural setting. Entomogenous bacteria such as *Serratia marcescens* were reported effective against *C. sordidus* larvae (LT50 2.8 days) but not adults under laboratory conditions [76].

Microbial control agents integrate well with other technologies. For example, pheromone baited traps with *B. bassiana*, increased *C. sordidus* mortality through autodissemination of the pathogen by trapped *C. sordidus* that exit the trap to the field [85]. Despite of the ability of microbial agents to self-propagate, they may require repeated applications as bio pesticides. Although they lack the toxic side effects of chemical insecticides, the periodic application may levee costs on the part of the farmer. Nonetheless, adaptive research, mass production, and delivery means to farmers for adoption should further be investigated.

TABLE II: STUDIES THAT INVESTIGATED BIOLOGICAL CONTROL AGENTS OF *C. SORDIDUS*

Biological strategy	The result on the measured parameter	Experiment	Significance	Reference
Predators and parasitoids	Inventory of natural enemies	Field survey	+	[70]
Endophyte *Beauveria bassiana* on tissue plants	Reduced survival by 24 – 89 Reduced corm damage by 42-86.7%	Screen house	+	[86]
Nematode strains; *Heterorhabditis zealandica*, *Heterorhabditis bacteriophora*, *Steinernema carpocapsae*	Reduced damage *S. carpocapsae* caused 63% larvae and 0-70% adult mortality	Field & laboratory	-/+	[44]
Beauveria bassiana [IMI331094] in planting holes	75% *C. sordidus* mortality in 60 days	Field	+	[78]
Bacteria: *Serratia marcescens*; fungi: *Beauveria bassiana* and *Metarhizium anisopliae*	98 –100% Larvae mortality in 9 days for all *B. bassiana* 63–97% in 35 days	Laboratory	+	[76]
Volatile organic compounds of *B. bassiana*, 3-cyclohepten-1-one and Pochonia chlamydosporia 1,3-dimethoxy-benzene	*C. sordidus* repellence	Laboratory	+	[87]

(+) A study reported significant effect on *C. sordidus* population and or damage, (-) study reported non-significant results, (-/+) Significant results on one of the tested technologies and insignificant on another in the same experiment.

C. Host Plant Resistance

This is the collective heritable characteristics by which a plant species, race, clone, or individual may reduce the possibility of successful utilization of that plant as a host by herbivorous insects and pathogens. Painter [88], divided host resistance into three categories; antixenosis, antibiosis and tolerance. Antixenosis is the non-preference reaction of pests toward the host to oviposit, feed, or shelter. Banana clones with "A" genome (Yangambi-KM5 (AAA), Culcuta-4 (AA), commonly used in breeding (Table 4) possess an antixenosis resistance, for they lack sufficient stimulant compounds like 1, 8 Cineole and phenolic glucoside salicin [62]. For example, 1,8 Cineole (C10H18O) is a rhizosphere volatile aromatic component of many plants that have allelopathic and deterrent activities. Such compound is used by herbivores to assess host plant quality as well as searching cue [89]. Instead, "A" banana genome have compounds that repel weevils from ovipositing or feeding [90].

Antibiosis refers to plant properties that adversely affect the physiology of attacking pests e.g. absence of essential nutrient inhibit insect development [91]. Banana cultivars with a "B" genome such as Kayinja / Pisang Awak (ABB), predominantly have an antibiosis mechanism of resistance [62]. Antibiosis has been suggested as a factor responsible for low *C. sordidus* population build-up that is, high oviposition but above 80% of eggs and larvae die prematurely [8]. Tolerance in banana cultivars is attributed to growth vigor, and to a lesser extent corm hardness [91], [92] and relatively large corms. For example, Gross Michel, Cavendish (AAA), and Pisang Awak (ABB) cultivars [93], permit larvae to complete their instar cycle in outer corm cortex, thus less effect on yield. Using laboratory trials, Night *et al*. [24] found that resistant components do not break down in excised tissue to leave only those that support development, rather resistance lies in food consumption and utilization efficiency.

TABLE IV: HOST RESISTANCE TO *C. SORDIDUS*

Source of resistance	Hybrids released	Resistant trait	Reference
Yangambi-Km5 (AAA)	M9, M19 and M20	*C. sordidus*, nematodes and black Sigatoka	[95]
Calcutta 4 (AA)	M11	Moderately resistant to *C. sordidus*	[96]
Yangambi-Km5 (AAA)	M3, M4, M5, M6, and M8	Highly resistant to *C. sordidus*	[96]
Long Tavoy and Calcutta 4	Banana derived diploids; TMB2×6142-1, TMB2×8075-7, TMB2×7197-2,	Highly resistant to *C. sordidus*	[33]

Host resistant breeding is valuable because it does not exclude any cryptic *C. sordidus* developmental stages like larvae whose behaviors undermine other control strategies that target adults which normally stays outside the corm. Besides that, host resistant breeding is an important component in an integrated pest management strategy for being a long term and a sustainable technology. Kiggundu *et al*. [94] in his field trials found wild diploids Calcutta-4, banana derived diploids (TMB2×6142-1, TMB2×8075-7 and TMB2×7197-2), and cultivars Yangambi-Km5 and Cavendish highly resistant to *C. sordidus* and may be an alternative sources of host resistance. However, the genetic drudge in the conventionally bred product that is 'parent' carrying traits that detestable to consumers, limit its potential. This leaves no option, but to embrace biotechnology aided breeding.

1) Soma-clonal selection

Micro-propagation aims at producing true-to-type planting material, any variation is undesirable. Variation in tissue culture regenerated plantlets is termed as a soma-clonal variation. In banana, somaclonal variants of different types may be identified morphologically by visual screening or by using molecular markers such as randomly amplified polymorphic DNA (RAPD), amplified fragment length polymorphism (AFLP), and by cytological studies [97]. In banana, somaclonal variants range from 0 to 69%, yet up to 10% variation is permitted in the commercial micro-propagation nurseries owing it to the genetic flexibility of the crop [97]. This variation is brought by several factors such as: 1) explant source used i.e., highly differentiating tissues such as roots, leaves, and stems produce more variations than explants with pre-existing meristems like axillary buds, 2) Subculture cycles > 5 and duration of culture that exceeds 5 months, enhances variability among regenerated banana plants. 3) Plant growth regulators e.g., 6-benzylaminopurine (BAP), its combination with adenine and use of kinetin, a Cytokinin at high concentration, induce a great genetic variability in micro-propagated bananas. Although somaclonal variation is undesirable in the context of micro propagation, it can be used to advantage for genetic improvement. Reported somaclonal variants includes ploidy level, growth, yield, quality, pigmentation, disease and pest resistance, and resistance to adverse soil and climatic conditions[98]. Despite of the existing positive attributes like pest resistance in somaclonal variants, no single study has been conducted to evaluate its potential against *C. sordidus*.

2) Genetic engineering

This technology has been advocated for as an eco-friendly and safer approach to managing *C. sordidus* and other biotic and abiotic plant stresses. The available technique in the development of *C. sordidus* -resistant transgenic bananas may include but are not limited to the following: Agrobacterium-mediated transformation, electroporation, and particle bombardment. Genetic transformation successfully achieved resistance against other crop pests through the expression of genes encoding insecticidal toxin for example *Bacillus thuringiensis* in cotton. In Uganda, research to identify and evaluate candidate genes like Papaya cystatin (CpCYS) and Bt. cry6A genes against *C. sordidus* and *R. similis* in the laboratory, screen house and confined field trials (CFT) is being conducted. CpCYS delayed *C. sordidus* development by 10 days by inhibiting the dietary protease enzyme cathepsin B-like [99]. Meanwhile, CpCYS and cry6A transformed bananas were > 90% protected against *C. sordidus* damages under screen-house condition. These technologies are being evaluated in the CFT. Despite this above progress, there is a need to have additional capacity building, infrastructure, appropriate equipment, and more genes that could confer resistance. Nevertheless, gene mining 'cisgenesis' and integration of conventional breeding with biotechnological approaches, e.g., introducing unique genes into elite germplasm for use in future crossing could be a sustainable intervention in *C. sordidu* management.

D. Chemical Control

Chemical pesticides have the advantage of being fast acting and can quickly knock down problematic infestations of *C. sordidus*. However, pesticides are costly, have negative effects on non-target organisms and the environment, can be toxic to humans, and can lead to pest resistance. Chemical pesticides for control of *C. sordidus* may be applied to protect planting material (through dipping of suckers or applications in planting holes) [43]. They may also be applied periodically (once to thrice per year) at the base of the mat after crop establishment, and/or applied to pseudostem traps to kill trap catches. Chemical insecticides remain an important part of *C. sordidus* control for larger-scale producers although costs often make them prohibitive for subsistence farmers.

There have been numerous studies on the relative efficacy of different insecticides under different formulations and application rates (e.g., 2 to 100 g or 1.25 to 50 mL per plant), persistence and the appearance of insecticide resistance, since the first recommendation in 1907 for the use of chemicals (i.e., Bordeau mixture) to control *C. sordidus* [100]-[102]. In 1951, the use of chemicals gained further importance with the advent of synthetic insecticides that largely replaced labor-demanding cultural controls such as trapping or sanitation [103]. As with many other pests, the introduction of chemicals such as aldrin and dieldrin in the 1950s for the control of *C. sordidus* was greeted with optimism, for it was thought to eradicate *C. sordidus* damage.

A wide range of chemicals, encompassing all major classes of insecticides, have been tested and recommended as effective for the control of *C. sordidus* [12], [16]. Although damage is caused by the larvae, most often non-systemic insecticides are applied that target the adult *C. sordidus*. Organophosphates (prothiofos, chloropyrifos (Dursban), pirimiphos-ethyl, ethoprophos (Mocap 15G), isazofos, isofenphos), carbamates (carbofuran and oxamyl), and Dieldrin are some of the pesticides applied to kill adult *C. sordidus* [102], [104]. Insecticides can achieve high levels of control in short periods. In the review of Okolle *et al*. [20], dieldrin, chlordecone, isophenfos, ethoprophos, terbufos, furadan, aldicarbe, zeta-cypermethrine, imidaclopride, thiametoxam and fipronil were reported to have excellent efficacies against *C. sordidus*. However, many once-recommended chemicals have been banned or otherwise fallen out of favor because of their high levels of mammalian toxicity, environmental concerns, and/or the development of resistance [9].

Insecticide resistance in *C. sordidus* has been documented in Australia, Latin America, and Africa as reviewed [9] for a range of chemicals including cyclodienes (aldrin, BHC, heptachlor, dieldrin], organophosphates (chlorpyrifos, ethoprophos, pirimiphos-ethyl, and prothiophos) and carbamates (carbofuran). Cross-resistance has also been demonstrated [103]. In Uganda and Tanzania, outbreaks of *C. sordidus* in the mid-1980s were attributed to pest resurgence following the development of resistance to dieldrin [103] leading to loss of confidence in chemical control by some farmers. Because of such concerns, there has been increasing advocacy for the reduction of such effects, and this led to searching and promoting the least toxic.

E. Botanical Control

Botanical plants used have bioactive pesticides of low toxicity to non-targeted organisms, human health and pose little or no threat to the environment, but high enough to suppress pest population through affecting their orientation and reproductive behavior [100], [101]. It was established in the surveys that farmers use biorationals to control *C. sordidus*, but without a defined efficacy [105]. This attracted researchers to evaluate some of the biorationals being used by farmers (Table 3). For example, in Uganda, Pepper, Tobacco, urine, Ash [106], Ghana, neem seed, clove buds and pepper fruit extracts [107], Kenya, [108], [109] evaluated azadirachtin content of 850ppm in neem oil, 4000 ppm seed powder, 5500 ppm kernel powder, and 5800 ppm neem cake and [20] in Cameroon also used neem seed powder. Results showed a limited knockdown effect and a short-lived effect of less than 1 month. Much of their potential lies in repellence and deterrence of adult *C. sordidus* discouraging *C. sordidus* from feeding, settling, oviposition, larvae fitness, and eclosion of the pupa. The limitation for their advancement is their need for frequent application at unstandardized dosage. However, Musabyimana *et al*. [108], [109] demonstrated great efficacy at a rate of 60 to 100 kg/ha of neem seed powder applied once every 4 months.

TABLE III: Studies that Investigated *C. sordidus* Bio-rational Control Strategies

Biorational strategy	The result on measured parameter	Experiment	Significance	Reference
Powdered neem seed or cake at 60 -100 g/mat at 4-month intervals	Reduced damage by 8 folds, increased yields from 15 to 24t/ha	Field	+	[108,109]
Neem seed Powdered at 30-100 g/mat	Reduced damage, mortality in suckers by 73-85% and 50% but did not affect *C. sordidus* density	Field	+/-	[110]
Crude extracts of chinaberry tree, mexican marigold, water hyacinth and Castor oil	Limited insecticidal properties	Laboratory	-	[111]
100g/mat of neem cake, a mixture of ash + urine + tobacco	No decline in *C. sordidus* densities and damages	Field	-	[105]
Tobacco, ash, urine, pepper and a concoction (mixture)	Tobacco, urine and concoction reduced oviposition & increased repellence	Laboratory	+	[106]
75 to 100% w/v of Neem leaves extract and 20% w/v Wood Ash	Mortality, settling and oviposition after treatment	Laboratory	+	[104]
Crude extract of dried clove buds, neem seeds and pepper fruits	A decline in *C. sordidus* densities	Field	+	[107]

(+) A study reported a significant effect on *C. sordidus* population and or damage, (-) study reported non-significant results, (-/+) Significant results on one of the tested technologies and insignificant on another in the same experiment.

VII. FUTURE RESEARCH DIRECTIONS AND INNOVATIONS

To improve the IPM approach, the farmers must be equipped with knowledge of the pest such as life cycles and ecology, as well as the cost-benefit of the control actions. This will guide the monitoring that will aid in the decision making to undertake for example refine the management strategy towards a given threats. Changes in climate in places with altitudes above 1600 masl, where *C. sordidu*s were never a problem are now registering *C. sordidus* damages. Research into resistant (conventional or genetic engineering) cultivars should consider altitude, humidity, and temperature to restrain *C. sordidus* population build-up. Nevertheless, pest status may be delayed by ecological conditions, cultivar resistance, and excellent agronomic practices. Therefore, resistant breeding and other management technology developed should consider the effect of climate changes (global warming) and other factors that would delay *C. sordidus* attaining pest status.

Biotechnology/genetic engineering; although resistance is available in wild banana, conventional breeding is not feasible. Genetic engineering as an alternative strategy to conventional breeding or in combination has been suggested for the provision of *C. sordidus* resistant banana varieties to farmers, especially with maintained taste and cultural preferences. The strategy would integrate conventional breeding with biotechnological approaches such as introducing unique genes into elite germplasm for future crossing toward sustainable *C. sordidus* management. But research to mine out and test promising genes need to be conducted.

The use of resistant banana varieties is one of the most effective ways to lessen the negative impacts of pests and pathogens on banana production. Advances in breeding that integrate genetic engineering (purposeful introduction of foreign gene(s) into banana genome to attain desired traits) have the potential to accelerate conventional breeding for pest and disease resistance. Commercialization of genetically modified (GM) products have to some extent faced with challenges of regulation in various countries. However, availability of a whole banana genome sequence has opened up a robust CRISPR/Cas9 based genome editing tool [112], [113]. Gene editing has the capability of creating precise alterations in plant genome to develop pest and pathogen resistant varieties. For example, editing the Cavendish's genome with CRISPR to boost its resilience to *Fusarium* wilt tropical race 4 (TR4), instead of inserting foreign genes. Editing does the turn on of a dormant gene in the Cavendish that confers resistance to TR4 or suppress genes that render the plant vulnerable to TR4 or edit RNA strands to silence genes in TR4. Gene-edited products may be received with open hand by regulators around the world, since no foreign gene is introduced in this case.

VIII. CONCLUSION

Several research studies have been conducted to provide bioecological information on *C. sordidus* life cycle, population dynamics and management. With this knowledge, researchers have tested different techniques to reduce pest population build up to below the economic injury status. Management options that form components of IPM and have been evaluated in laboratories, screen houses, on station and field research trials, are summarized into chemical (synthetic and botanicals), cultural (sanitation, use of clean planting materials, mulching, trapping), biological (entomopathogens, parasitoids, and predators), info-chemicals, and resistant varieties (conventional and genetic engineering). Despite the various research and development efforts conducted in the ECA region and globally, sustainable management of the pest remains elusive. Farmer adoption of the different components of IPM have been limited by being labor intensive, costly and unavailable. There is need for continued research efforts and innovative approaches to effectively mobilize all stakeholders along the banana value chain for increased banana production. Future research efforts should provide technologies that are cost effective and user friendly to the farmer and have limited impact to non-targeted organisms, environment, and human health in banana agro-ecosystems. Currently, breeding for resistance is universally accepted as the most efficient and sustainable option for management of banana pests and diseases, although consumer acceptability of resistant hybrids remains to be addressed. Conventional and transgenic breeding including genome editing can then be applied to incorporate these traits into local favorites to develop hybrids that are resistant to *C. sordidus* and meet farmers' and consumer needs.

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CONFLICT OF INTEREST

Authors declare that there is no conflict of interest

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