frontiers | Frontiers in Sustainable Food Systems

REVIEW
published: 19 July 2022
doi: 10.3389/fsufs.2022.891417

Spittlebugs (Hemiptera: Cercopidae): Integrated Pest Management on Gramineous Crops in the Neotropical Ecozone

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Spittlebug (Hemiptera: Cercopidae) species cause large economic losses on gramineous crops (Poaceae) in tropical and subtropical America. These insects are key pests of sugarcane and forages, crops that experienced a quick expansion in extensive monocultures in Brazil, Colombia, and Mexico. Mobilization toward sustainable crop and livestock systems to supply the growing demand of meat, milk, and sugar in Latin America and the Caribbean region implies developing sustainable and feasible strategies of integrated pest management to control spittlebugs. This review combines information on Cercopidae taxonomy, geographical distribution, insect biology, and control strategies to contribute to the development of integrated pest management in grasses and sugarcane in the Neotropics.

Keywords: *Brachiaria*, sugarcane, *Urochloa*, integrated pest management, salivazo de los pastos, cigarrinhas das pastagens

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Specialty section:
This article was submitted to
Crop Biology and Sustainability,
a section of the journal
Frontiers in Sustainable Food Systems

Received: 07 March 2022
Accepted: 21 June 2022
Published: 19 July 2022

Citation:
Espitia Buitrago PA, Manzano MR and
Hernández LM (2022) Spittlebugs
(Hemiptera: Cercopidae): Integrated
Pest Management on Gramineous
Crops in the Neotropical Ecozone.
Front. Sustain. Food Syst. 6:891417.
doi: 10.3389/fsufs.2022.891417

INTRODUCTION

Crop and livestock production are expected to grow in Latin America and the Caribbean at least 15% by 2028 (OECD and FAO, 2021). For sugar and meat, projections show an increase particularly in developing countries, being Brazil one of the largest producer and exporter in the world for these two commodities (OECD and FAO, 2021). In this scenario, it is necessary to develop and adopt strategies to move toward sugarcane and livestock sustainable intensive systems, avoiding the expansion of the agricultural frontier in the region (Jusys, 2017). This includes the implementation of efficient integrated pest management (IPM) programs in these traditionally monocultural extensive systems.

Spittlebugs (Hemiptera: Cercopidae) are the main limitation of economically important cash crops in the Neotropical ecozone. Different species are key pests of *Brachiaria* grasses (*Urochloa* spp., syn.: *Brachiaria* spp.; Holmann and Peck, 2002) and sugarcane (*Sacharum officinarum* L.; Rossato et al., 2019). Also are occasional pests of maize (*Zea mays* L.) and rice (*Oryza sativa* L.) (Thompson, 2004; Carvalho and Webb, 2005; Cruz et al., 2009; Heinrichs and Muniappan, 2017). These xylem-feeders have several common names in different countries as follow: spittlebugs (United States of America), froghoppers (Australia and United Kingdom), salivazo or mion (Colombia), salivita (Cuba and Nicaragua), baba de culebra (Central America), candelilla (Venezuela), mosca pinta (Mexico) and cigarrinhas (Brasil). The damage caused by this group in tropical and subtropical America has a large impact on livestock and sugar value chains for the negative effect on production, productivity and the industrial processing of these commodities. Studies to understand the taxonomy, biology, behavior, damage, and control methods of these insects are available. However, this information is scattered. This review summarizes the current studies about Cercopidae taxonomy, geographical distribution and biology, and links it with the IPM strategies available in grasses and sugarcane to provide clear information for spittlebug's control.

TAXONOMY

Hemiptera comprises many bugs grouped in three suborders: xylem feeders Auchenorrhyncha (cicadas, spittlebugs, leafhoppers, treehoppers, and planthoppers), phloem feeders Sternorrhyncha (jumping plant lice, whiteflies, aphids, and scale), and true bugs Prosorrhyncha (Heteroptera and Coleorrhyncha) (Dietrich, 2009). The suborder Auchenorrhyncha contains the superfamilies, Cicadoidea (cicadas), Membracoidea (leafhoppers and treehoppers), Fulgoroidea (planthoppers), and the monophyletic superfamily Cercopoidea (spittlebugs), with the families Aphrophoridae, Clastopteridae, Machaerotidae, Epipygidae, and Cercopidae (Paladini et al., 2018). Evidence to support the monophyly of this suborder was provided in molecular analyses (Cryan and Urban, 2012; Misof et al., 2014; Johnson et al., 2018; Skinner et al., 2020) and the presence of a bacterial endosymbiont (Koga and Moran, 2014).

Cercopidae includes the paraphyletic Cercopinae (old world), and the monophyletic Ischnorhininae (new world) subfamilies (Cryan and Svenson, 2010). Fennah (1968) divided the new world species into four tribes: Tomaspidini, Ischnorhinini, Hyboscartini, and Neaenini, and proposed a classification scheme based on morphological characters. From this classification and subsequent updates, the morphological characters describing Cercopoidea superfamily includes head with frontoclypeus inflated; median ocellus absent; ocelli on crown distant from margin; pronotum extended to scutellar suture; body clothed with fine setae; hind coxae conical, tibia without rows of setae but often with one or more conspicuous spines; male subgenital plate present (Carvalho and Webb, 2005; Dietrich, 2005, 2009). For Cercopidae, the descriptive characters are colorful patterns in tegmina, convex postclypeus anterior or laterally compressed, hexagonal pronotum with posterior margin reticulated (Paladini and Cryan, 2012). The main difference with Aphrophoridae family is having the eyes slightly longer than wide and the posterior margin of the pronotum straight (instead of emarginate) (Dietrich, 2009). Machaerotidae and Clastopteridae differ from the other families in having a developed appendix on the forewing, in which Machaerotidae has two or more r-m crossveins in the forewing and lacks an outer fork on the radial vein of the hind wing (Dietrich, 2009).

An illustrated key of new world spittlebugs based on characters as color patterns, styles, plates, and aedeagus of male genitalia was reviewed by Carvalho and Webb (2005). However, the classification of some species is complex for their body similarity, color patterns, and male-genitalia intra-specific variation, the absence of specific accurate descriptors and taxonomic keys, and the lack of diagnostic keys for identification in immature individuals (Cryan and Svenson, 2010; Paladini and Cryan, 2012).

Some inconsistencies in diagnostic characters indicate the lack of reliable evidence for defining major lineages, leading to the rejection of the monophyly of Ischnorhinini and Tomaspidini, and taxonomic instability (Paladini et al., 2015, 2018). For this reason, some authors opted to exclude this tribal-level classification including all the Neotropical cercopids in the Ischnorhininae subfamily, with 62 genera and 438 species (Carvalho and Webb, 2005; Paladini and Cryan, 2012; Paladini et al., 2015; Paladini and Cavichioli, 2017; Castro et al., 2018; Castro et al., 2020).

The main genuses reported attacking gramineous crops in tropical and subtropical America are *Aeneolamia* Fennah, *Deois* Fennah, *Isozulia* Fennah, *Kanaima* Distant, *Mahanarva* Distant, *Maxantonia* Schmidt, *Notozulia* Fennah, *Prosapia* Fennah, *Sphenorhina* Amyot and Serville, *Tunaima* Fennah, and *Zulia* Fennah (**Table 1**).

GEOGRAPHIC DISTRIBUTION

Cercopidae (Hemiptera: Auchenorrhyncha: Cicadomorpha: Cercopoidea) is the most speciose spittlebug family distributed worldwide, being found in most terrestrial ecosystems (Thompson, 2004). Cercopids of gramineous crops occur in the neotropics from the southern United States to northern Argentina (Paladini et al., 2018). The species may vary or coincide in each country (**Table 1**). For example, the predominant species in Brazil are of the genera *Mahanarva*, *Deois*, and *Notozulia*, while in Colombia the most representative species are from *Aeneolamia*, *Prosapia*, and *Zulia* (Hernandez et al., 2021).

Ecological niche studies modeling the potential distribution under different climate change scenarios, show various current suitable habitats for spittlebugs across Central and South America. Besides, depending on the species, a long-term change in the distribution is estimated particularly due to changes in abiotic factors like precipitations (Schöbel and Carvalho, 2020; Hernandez et al., 2021). These results suggest that they have little ability to quickly adapt to changing environments with a high dependence on climate factors. This tendency was reported in Aphrophoridae, where climate change led to warmer and dryer environments in California, decreasing *Philaenus spumarius* populations on *Erigeron glaucus* Ker. (Karban and Huntzinger, 2018).

In the global network database, Global Biodiversity Information Facility (GBIF), 58570 occurrences for Cercopidae

TABLE 1 | Reported economically important cercopid species in gramineous crops in the Neotropical ecozone.

Genera	Species	Host	Country	References
Aeneolamia	*A. albofasciata*	Sugarcane	Costa Rica Guatemala Mexico	Thompson and González, 2005; Castillo, 2006; Parada Domínguez et al., 2019
	A. colon	Grasses	Brazil	Hernandez et al., 2017
	A. flavilatera	Sugarcane	Colombia Guyana Surinam	Wiedijk, 1982; Hernandez et al., 2017
	A. contigua	Grasses Sugarcane	Costa Rica Mexico Guatemala	Thompson and González, 2005; Olán-Hernández et al., 2016; Hernandez et al., 2017
	A. lepidior	Grasses	Costa Rica Colombia Panama Venezuela	Peck et al., 2002; Thompson and González, 2005
	A. occidentalis	Grasses	Mexico	Cardona et al., 2004
	A. postica	Grasses Sugarcane	Mexico	Cardona et al., 2004; Herrera-Huerta et al., 2004
	A. reducta	Grasses Sugarcane	Costa Rica Colombia Panama Venezuela	Peck et al., 2002; Thompson and González, 2005
	A. varia	Grasses Sugarcane	Colombia	Castro et al., 2005; Cuarán, 2012
Deois	*D. flexuosa*	Rice	Brazil	
	D. flavopicta	Grasses Maize Rice Sugarcane	Brazil	Rosseto et al., 1978; Ferreira et al., 2003
	D. incompleta	Grasses	Brazil	Rosseto et al., 1978; Sujii et al., 2001; Cruz et al., 2009; Gusmão et al., 2016
	D. knoblauchii	Proposis Sugarcane	Argentina	Valério and Koller, 1993; Vasconcelos et al., 2018
	D. schach	Grasses Rice	Brazil	Foieri and de Remes, 2019
	D. mourei	Grasses Rice Corn	Argentina	Rosseto et al., 1978; Auad et al., 2010
Mahanarva	*M. andigena*	Sugarcane	Ecuador	Peck, 2002
	M. bipars	Sugarcane	Colombia	Peck et al., 2004
	M. fimbriolata	Grasses Rice Sugarcane	Brazil	Gómez, 2007
	M. indentata	Grasses Sugarcane	Brazil	Ferreira et al., 2003; Dinardo-Miranda et al., 2014
	M. liturata	Grasses Sugarcane	Brazil	
	M. mura	Grasses	Brazil	Chaves et al., 2014; Schöbel and Carvalho, 2020
	M. posticata	Grasses Sugarcane	Brazil	Alves and Carvalho, 2014; Schöbel and Carvalho, 2020
	M. spectabilis	Grasses Sugarcane	Bolivia Brazil Paraguay	Vasconcelos et al., 2018
	M. tristis	Grasses	Brazil	Chaves et al., 2014; Schöbel and Carvalho, 2020
Notozulia	*N. entreriana*	Grasses	Brazil Argentina	Resende et al., 2014; Schöbel and Carvalho, 2020
Prosapia	*P. plagiata*	Grasses	Costa Rica	Vasconcelos et al., 2018
	P. simulans	Grasses Sugarcane	Colombia Costa Rica Guatemala Honduras México Nicaragua Panama	Vasconcelos et al., 2018
Zulia	*Z. carbonaria*	Grasses Sugarcane	Colombia	Peck, 2002
	Z. entreriana	Grasses Rice	Brazil	Thompson and González, 2005; Hernandez et al., 2017
	Z. pubescens	Grasses	Colombia	Thompson and González, 2005; Castillo, 2006
	Z. vilior	Grasses	Costa Rica	Chalarca et al., 2002; Cuarán, 2012

are registered. Most of them reported in Costa Rica, the United States, Germany, France, and The Netherlands (GBIF.org., 2022). However, the tropics are the most diverse zones with 70% of the 1,360 described species of this family, considering that approximately 475 are mostly distributed in the American tropics and subtropics (Peck and Thompson, 2008; Dietrich, 2009; Cryan and Svenson, 2010; Hamilton, 2013; Paladini et al., 2018). Thus, more efforts should be made to report cercopid occurrences in biodiversity global networks, prompting research in other fields like phylogenetics, taxonomy, and ecology.

BIOLOGY AND BEHAVIOR

Spittlebugs have hemimetabolous metamorphosis (**Figures 1**, **2**). The duration of each stage varies among species, sites, and climate conditions (**Table 2**).

Eggs

Eggs are laid on soil (1–2 cm of the top of the soil), near to stalks, on litter, and on plant tissues (de la Cruz-Zapata et al., 2016). Northern hemisphere species lay ∼35 eggs (Hamilton and Morales, 1992) and tropical species lay between 40 and 100 eggs in 3–10 days (Sotelo and Cardona, 2001). The four egg stages are completed in 2 to 3 weeks (S1–S4; **Figure 2**) (Peck, 2002; Peck and Thompson, 2008; Dietrich, 2009). Eggs are elongate (1 mm of length and 0.3 mm of width), light-yellow in the first stages, changing to dark-yellow or orange with two reddish spots in the anterior part corresponding to eyes, and other two lighter marks in the posterior part corresponding to the abdomen in the final stage (**Figure 2**; Valério et al., 2001; Parsa et al., 2011; Peixoto, 2016). In some species, egg diapause is expressed to avoid adverse climate conditions, i.e., dry seasons, taking up to 530 days to hatch (Peck et al., 2002; Peck and Thompson, 2008; Auad et al., 2011). The mechanism that activates diapause is not completely elucidated.

Nymphs

Nymphs have five instars (**Figure 2**) that may last from 4 to 9 weeks (**Table 2**) (Hamilton and Morales, 1992; Peck and Thompson, 2008). Nymphs usually feed gregariously on the xylem sap of plant roots, leaves, branches, and crowns (Pires et al., 2000; Sujii et al., 2002; Cid-Muñoz et al., 2020). Young nymphs have weak motility; however, they can move short distances to choose feeding sites (Pires et al., 2000). Hagley and Blackman (1966) and Garcia et al. (2007) found that on roots, nymphs ingest parenchyma cells in the cortex during their first instars, while third, fourth, and fifth instar nymphs reach the xylem vessels and, occasionally, sieve-tube elements of the primary phloem (**Figure 3**). In this stage, nymphs cover themselves with a foam composed of excreted semi-digested plant fluid, fatty acids (palmitic and stearic acid), carbohydrates, along with mucopolysaccharides and proteins produced by Malpighian tubules (Rakitov, 2002; Tonelli et al., 2018). Each of these components plays a vital role in the stability, viscosity, and elasticity of the foam, functioning as a microhabitat protecting the nymph from desiccation, predation, parasitism, and solar radiation (Martin et al., 2002; Carvalho and Webb, 2005; Chen et al., 2018).

Adults

Longevity ranges between 1 and 3 weeks, exhibiting a plethora of color patterns presenting intraspecific polymorphism (Peck and Thompson, 2008, **Figure 2**) and have two stout, thorn-like spurs in the hind tibiae, which end in a broadly flared double row of black-tipped spines (Hamilton and Morales, 1992). Males are distinguished from females by genitalia and size, females are larger. Adults have two strategies to avoid possible predators: long jump (115 times their body length; Burrows, 2006; Burrows et al., 2007) and reflex bleeding (Peck, 2000a). The latter consists in emitting odoriferous orange hemolymph from the pretarsal pads as a startle stimulus linked to the jumping ability (Peck, 2000b). As nymphs, adults feed by inserting the stylets through the stomata, passing through the chlorophyll-bearing and parenchyma to reach the metaxylem or vascular bundles (Hagley and Blackman, 1966; Garcia et al., 2007) on the shoots injecting saliva to aid digestion and prevent clogging of the stylet (Crews et al., 1998; Dietrich, 2009).

Mating starts when males emit a call based on vibration through the stems and leaves of the host (Lopez et al., 2001). This call is emitted by tymbals located on the first abdominal segment and is transmitted through the host plant, and it is usually inaudible (Peck and Thompson, 2008; Dietrich, 2009). Copulation occurs during the photophase and, depending on the species, may last from a second to several hours. Females usually mate only once, and males mate several times (Dietrich, 2009).

FEEDING HABIT

The xylem feeding habit is thought to be a constraint for managing the strong negative pressure of the xylem sap generated by transpiration (Novotny and Wilson, 1997). High rates of this unbalanced food is needed to meet the nutritional requirements since it is composed of diluted amino acids, simple organic acids, and various sugars (Redak et al., 2004). Other diet supplements are provided by intracellular symbiotic microorganisms to synthesize other nutrients (Douglas, 1989). An obligate dependent symbiosis with multiple organisms living in specialized cells, bacteriocytes, or tissues, bacteriomes, vertically transmitted through host generations *via* ovarial passage was identified in Auchenorrhyncha (Moran et al., 2005; Koga et al., 2012). Depending on the species, spittlebugs contain at least two symbionts that provides essential amino acids: the *Candidatus Sulcia muelleri* A. (Bacteroidetes) as a common organism in various species usually complemented with the *Betaproteobacteria Zinderia insecticola* or the *Enterobacteriaceae Sodalis glossinidius* Dale and Maudlin (1999) (Koga et al., 2013; Koga and Moran, 2014). These paired symbionts show a complementary set of genes related to the 10 essential amino acids required for animals. In *Clastoptera arizonana* Doering (1929), *Sulcia* presented the genes involved in the production of leucine, isoleucine, valine, threonine, lysine,

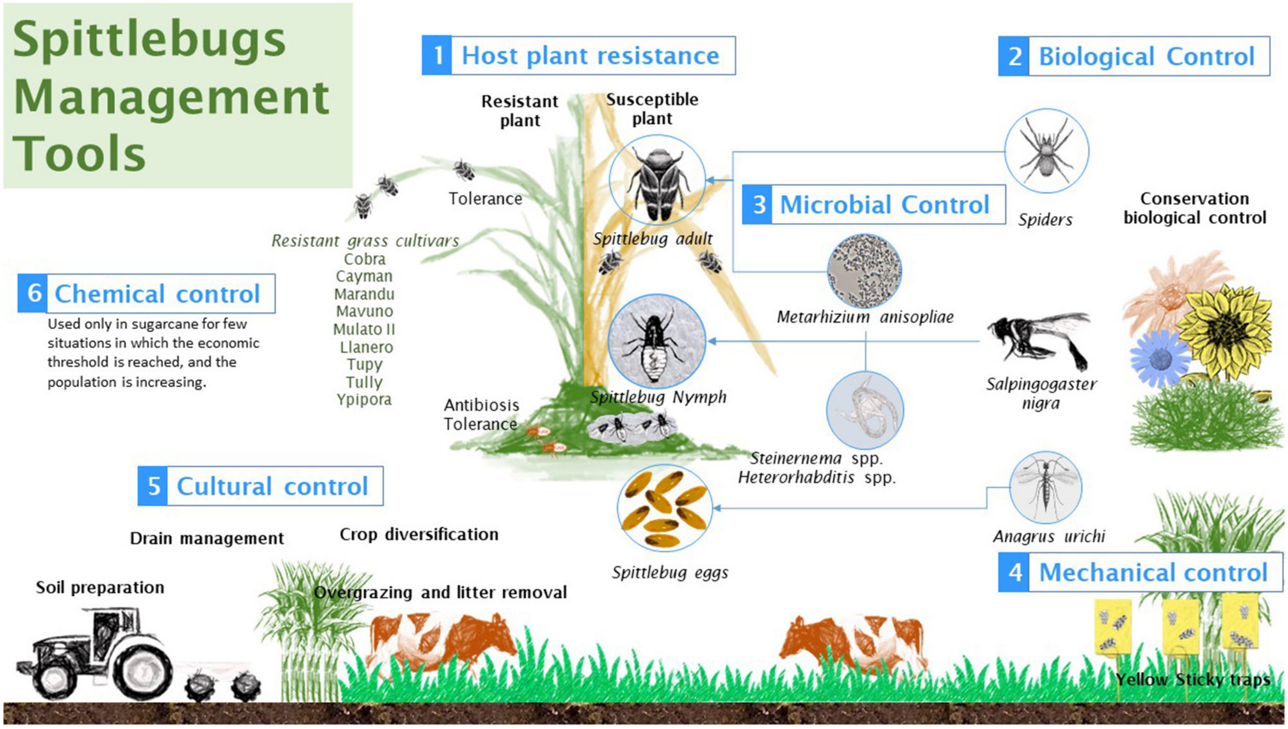

FIGURE 1 | Main tools used in integrated spittlebugs management program.

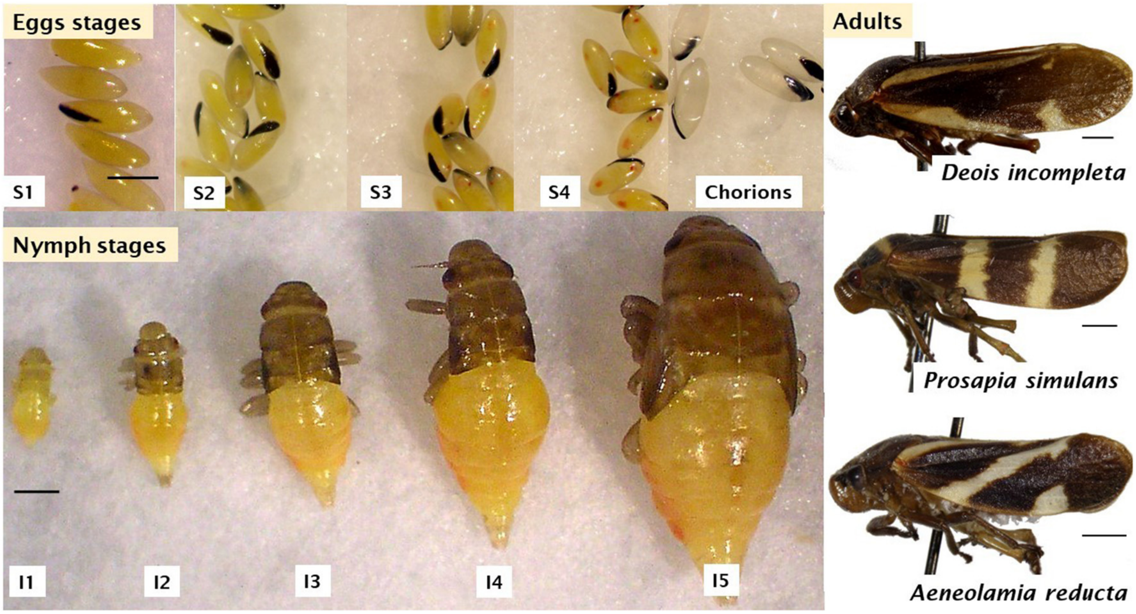

FIGURE 2 | Different stages of spittlebug: Eggs (*Aeneolamia varia*), nymph (*Prosapia simulans*), and adults. Scale bar represents a 1 mm. Pictures taken from the archive of the forage entomology laboratory – CIAT.

arginine, and phenylalanine, *Zinderia* presented those for tryptophan, methionine, and histidine (McCutcheon and Moran, 2010). Foieri et al. (2022) reported *Candidatus sulcia muelleri* in the new world *Notozulia entreriana* (Berg, 1879), *Deois mourei* (Cavichioli and Sakakibara, 1993), and *Deois knoblauchii* (Berg, 1879).

TABLE 2 | Duration of life cycle of different spittlebug species.

Species	Egg	N1	N2	N3	N4	N5	Adult	Total	References
Aeneolamia lepidior	27.7 ± 0.7	6.6 ± 0.1	7.3 ± 0.3	6.7 ± 0.2	6.7 ± 0.1	8.2 ± 0.2	6.3 ± 0.1	52.7	Peck et al., 2002
Aeneolamia reducta	15.8 ± 0.1	5.9 ± 0.1	5.4 ± 0.1	5.3 ± 0.1	4.8 ± 0.1	4.5 ± 0.1	6.6 ± 0.1	45.2	Peck et al., 2002
Deois mourei	12.1 ± 0.7	5.3 ± 1.3	7.3 ± 1.4	8.3 ± 3.1	6.2 ± 1.3	9.1 ± 0.9	11.9 ± 1.4	58.5	Foieri et al., 2016a
Mahanarva fimbriolata	20–22	36–39					10–15	66–76	Grisoto et al., 2018
Mahanarva andigena	16.4	6.3 ± 1.03	8.6 ± 1.1	8.18 ± 1.3	10.1 ± 1.5	15.0 ± 3.8	21.4	75.5	Rodríguez and Peck, 2007
Mahanarva indentata	36.4 ± 1	12	9	9	11	21	15 ± 0.8	99 ± 1.7	Chaves et al., 2014
Notozulia entreriana	15.3 ± 0.5	5.9 ± 0.8	5.9 ± 0.9	4.4 ± 0.6	5.3 ± 0.7	4.3 ± 0.9	7.6 ± 0.9	47.5	Foieri et al., 2016b
Prosapia bicincta	19	8	8	10	14	12	21	92	Fagan and Kuitert, 1969
Prosapia simulans	17.9 ± 1.2	6.7 ± 1.1	7.5 ± 2.1	9.3 ± 2.7	10.0 ± 2.3	13.1 ± 2.7	16.5	71.9	Rodríguez et al., 2003
Zulia carbonaria	17.4 ± 0.9	7.4 ± 0.9	7.2 ± 1.5	6.4 ± 1.3	8.3 ± 1.1	12.9 ± 1.2	19.6	69.6	Chalarca et al., 2002
Zulia pubescens	14.34 ± 0.5	6.6 ± 0.7	6.3 ± 1.2	5.9 ± 0.9	7.0 ± 1.4	12.2 ± 1.6	18.4	61.5	Chalarca et al., 2002

POPULATION DYNAMICS

Abiotic factors play a vital role in population dynamics, characterized by high fluctuations and synchrony (Peck and Thompson, 2008). A peak favoring egg hatching and reducing nymph mortality was observed during the rainy season (Sujii et al., 2002). Thus, in humid zones, the insects achieve up to 6 generations per year (Sotelo and Cardona, 2001). This seasonal dynamic was reported for *Zulia carbonaria* (Lallemand, 1924) and *Aeneolamia reducta* (Lallemand, 1924) in colombian pasture systems for bimodal and monomodal rainfall patterns respectively (Peck et al., 2002; Castro et al., 2005), and *Aeneolamia contigua* (Walker, 1851) in sugarcane crops in Mexico, having a higher abundance of nymphs and adults after the rainy season started (Olán-Hernández et al., 2016). Additionally, Herrera-Huerta et al. (2004) found that high humidity rates increase the egg hatching and survival rate of *Aeneolamia postica* (Walker, 1858) collected from sugarcane in Mexico in laboratory conditions.

DAMAGE SYMPTOMS AND ECONOMIC LOSS

Plant damage depends on the insect stage and host. For grasses, the first four nymphal stages, the visual damage is usually imperceptible. When nymphs reach the fifth stage, ascendant acropetal chlorosis is observed (**Figure 4**), and, under a severe attack, the entire aboveground portion of the plant appears dry and dead (Valério et al., 2001). Specifically, for adults the damage is first observed in young leaves, where whitish-chlorotic spots appear around suction points due to parenchyma tissue dilution for the caustic substances present in saliva (Valério et al., 2001, **Figure 4**). Next, the spots tend to coalesce in chlorotic lesions from the tip to the base of the leaf, and, with high populations, the leaves appear entirely yellow or necrotic (Sotelo and Cardona, 2001; Thompson and González, 2005). Reddish streaks can follow the chlorotic lesions in some genotypes (Lopez et al., 2009). In pasture systems, the quality of the forage is reduced affecting its growth, dry matter production, *in-vitro* digestibility, protein, phosphorus, magnesium, calcium, and potassium content; palatability, establishment, and persistence (Valério and Nakano, 1988; Peck and Thompson, 2008). Holmann and Peck (2002) discovered that small populations of 10 adults/m^2 can cause stunted growth and a decrease in production, as well as 2–8 percent reduction in forage carrying capacity. With larger populations, 25 to 50 adults/m^2, the stocking rate may decrease 26–33 percent. Hence, milk and meat production are affected even in low infestations of spittlebugs in forages cultivation. Congio et al. (2020) showed that *Mahanarva* sp. can decrease beef productivity up to 74% and herbage yield varying from 31 to 43% (depending on level of fertilization and grazing severity of Marandú).

In sugarcane, Dinardo-Miranda et al. (2008) and Rossato et al. (2019) report that spittlebug attack decreases productivity by reducing the number of healthy stalks, yield, and sugar accumulation resulting in yield losses of 9 ton ha-1 or 8 to 50% for every 1% of spittlebug infestation (de la Cruz-Llanas et al., 2005; Dinardo-Miranda, 2008). The negative impact in industrial processing is evident for the high fiber content and dead or deteriorated stalks that act as contaminants in the milling process making sugar recovery difficult and inhibiting fermentation. High infestation levels increase sugar color, total phenolic compounds, total and volatile juice acidity, and acetaldehyde concentration in distillate. Also reduces apparent sucrose content, Brix, pH, purity, and ethanol content in wine, indicating a lower juice quality for sugar and ethanol production (Madaleno et al., 2008; Mutton et al., 2010; Ravaneli et al., 2011).

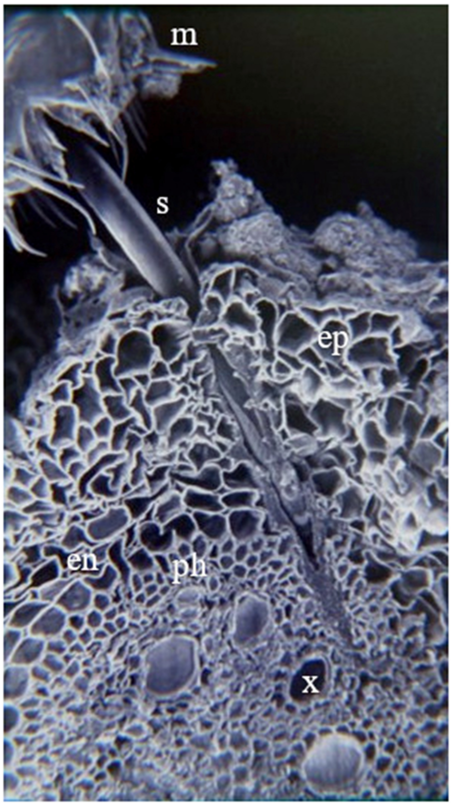

FIGURE 3 | Feeding site of *A. varia* nymph over *U. ruziziensis* root. Isect mouth (m), Stylet (s), epidermis (ep), endodermis (en), phloem (ph) and xylem (x). Picture taken from the archive of the forage entomology laboratory – CIAT.

In terms of economic losses for sugarcane and introduced pastures in the Neotropics, Holmann and Peck (2002), Thompson (2004), and Auad et al. (2010) reported estimated losses from US$ 840 to 2100 million per year.

INTEGRATED PEST MANAGEMENT (IPM)

Monitoring and Sampling

Spittlebug monitoring and sampling in sugarcane and grasses is based on visualization adults and nymph masses, and detecting chlorotic areas. Techniques for monitoring eggs and nymphs (see: Nilakhe et al., 1984b; Martín-Rivera, 1994) are considered impractical in sugarcane plantations due to high time consumption and difficulty in execution. The most reliable and efficient sampling method for monitoring grasses is to collect adults using a sweep net (Nilakhe et al., 1984a; Morente et al., 2018). The most common method for nymph sampling is to walk through a pre-determined area checking for spittle masses, which are usually on the soil or near host roots (Martín-Rivera, 1994; Pires et al., 2000). The foam can be removed with a soft brush to observe the nymphs feeding. The gregarious generalized behavior of nymphs and their low motility make it easier to locate infestation hot spots in the field for the appearance of wilted or chlorotic areas (Gutiérrez and Gómez, 2009). The most common method to monitor adults in sugarcane is sampling with yellow sticky traps in pre-established plots. Several authors proposed placing yellow traps in crops at various densities and locations (**Table 3**).

As a result, the majority of economic thresholds are based on the number of adults in a given area. Dinardo-Miranda and Gil (2007) and Dinardo-Miranda et al. (2008) set an economic injury level of 4 spittlebugs per m^2 for *Mahanarva fimbriolata*

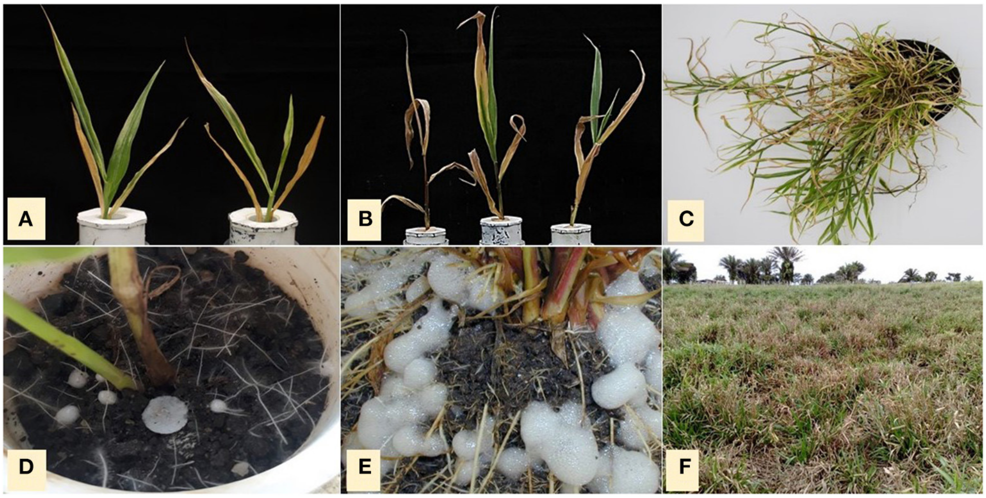

FIGURE 4 | Recognition of spittlebugs. **(A–C)**: damage characteristic caused by adult and nymph respectively; **(D,E)**: nymphs coated by their spittle and; **(F)**: damage caused in fields on grasses. Pictures taken from the archive of the forage entomology laboratory – CIAT.

TABLE 3 | Yellow sticky traps: dimension and action threshold by spittlebug species.

Dimensions	Placement	Frequency of monitoring	Threshold	Species	References
50 × 50 cm	Five traps: in the four corners and in the center of the plantation. 1-1;5 m from the soil.	Weekly		*A. contigua*	Olán-Hernández et al., 2016
40 × 60 cm	Two traps per hectare in the border of the crop. 30–50 cm from the soil.	Weekly	100 adults trap^{-1}. 0.2 adults stalk^{-1}.	*A. varia*	Cenicaña, 2019
40 × 60 cm	Two traps per hectare; located 20 m from the border; 50 m from each other. 50 cm from the soil.	Weekly	50 adults trap^{-1}.	*M. andigena*	Valle Ramirez et al., 2015

(Stal, 1854) in sugarcane in Brazil. According to Gómez (2007), the economic threshold of *Aeneolamia varia* (Fabricius, 1787) for sugarcane in Valle del Cauca, Colombia is 0.2 spittle masses or adults per stalk, or 50 adults per week per trap if yellow sticky traps are used. Resende et al. (2013) found that 8 adults of *Mahanarva spectabilis* (Distant, 1909) feeding for 6 days influences the physiological function of *Urochloa ruziziensis* Germ and Evrard in plants with an average of 80 tillers, implying this reference value for spittlebug control in these grasses. Holmann and Peck (2002) defined a low infestation as 10 adults per m^2, an intermediate infestation as 25 adults per m^2, and a high infestation as 50 adults per m^2. A host may exhibit variable levels of resistance or tolerance to different spittlebugs species (Cardona et al., 2004), making establishing an economic threshold difficult because it needs a thorough understanding of the host and its interaction with a specific species.

Cultural Control

Cultural strategies aim to make the ecosystem less suitable for the establishment and proliferation of insect populations (Zaefarian and Rezvani, 2016). In the past, a common practice was control by burning (Beck, 1963; Koller, 1987). However, new strategies aim to implement more sustainable actions based on the knowledge of insect biology. As spittlebugs are highly susceptible to humidity variations, most of the cultural practices are related to avoiding humid and hot microhabitats. These include litter removal from the field and soil mechanical preparation by tillering or discing, to expose the immature stages to desiccation and remove potential secondary hosts (Sáenz et al., 1999; Nachappa, 2004; Dietrich, 2009; Busoli et al., 2014). Lilliston equipment for tillage, identification of focal distribution patterns and removing the straw from the field after harvesting in sugarcane are feasible strategies to reduce nymph infestation for next seasons (Gómez, 2007; de Castro et al., 2019).

In grasses is recommended the diversification of crops, e.g., grasses and leguminous systems or pasture blends mixing tolerant and resistant materials to have a wider diversity in the ecosystem that promotes niches for natural enemies and reduces the feeding sources for spittlebugs (Sotelo and Cardona, 2001). Also, pasture renewal with resistant varieties adapted to local conditions to decrease spittlebug populations, avoiding extensive monocultural meadows and keeping a focal distribution of the insect (Valério and Koller, 1993). These strategies are also important to prevent resistance-breaking biotypes by offering alternative hosts to the insects (Cardona et al., 2004). In highly infested pastures, intensive grazing is also recommended to reduce the biomass through livestock feeding and nymph population for the trampling effect (Valério and Koller, 1993; Sotelo and Cardona, 2001; Thorne et al., 2017).

Other cultural strategies involve the drain management in the field reducing the soil top layer moisture, particularlly in clayey areaswith a higher water retention capacity that favors the nymph and egg survival (Figueredo et al., 2012; de Castro et al., 2019) and fertilization management. The susceptible genotype *U. ruziziensis* showed a reduced damage and high quality when a recommended dose of fertilizer was applied under *Mahanarva spectabilis* infestation (45 mg/dm^3 of urea, 255 mg/dm^3 of superphosphate, and 28 mg/dm^3 of potassium chlorate on the planting and 140 mg/dm^3 of NPK 20-5-20 on the 30th and the 60th days) (Aguiar et al., 2014). Besides, macronutrient fertilization enhances tolerance traits of grasses by improving the nutritional quality and physiological status of the plants, even if the nymphal survivorship is high (Pires et al., 2000; Valério, 2009; Alvarenga et al., 2019b).

Mechanical Control

The use of traps as a spittlebug control method has received limited attention. Yellow sticky traps, according to Sáenz et al. (1999), may reduce the first generation of adults in sugarcane spittlebugs. In that case, they recommend placing plastic yellow bags covered with a sticky layer on the stalks, depending on the threshold: 25 traps per hectare are required for a population of 0.2 adults per stalk or 0.4 nymphs per stalk; 75 traps are required for a population of 0.3 adults or 0.5 nymphs per stalk; and 100 traps are required for a population of more than 0.8 adults. This tactic should be used only for monitoring because natural enemies may also be trapped (Fernández, 2013).

Microbial Control

Metarhizium Sorokin is the most used entomopathogenic agent to control cercopids in sugar cane and pastures of Brazil, Mexico, Guatemala, Costa Rica, Panama, Venezuela, Ecuador and Colombia (Sotelo and Cardona, 2001; Badilla, 2002; Bustillo et al., 2011; García et al., 2012; Hernández-Domínguez et al., 2016). In Brazil, 1.8 million sugarcane ha are treated to control spittlebugs, being one of the most successful biological control programs in the world (Parra, 2014; Mascarin et al., 2019).

Reasons for the widespread adoption of *Metarhizium* for pest control is attributed to its worldwide distribution, its broad host range, its ability to inhabit soil or act as an entomopathogen or endophyte, the standardized production and application protocol, and the number of product registrations (Brunner-Mendoza et al., 2019; Sant et al., 2019). Persistence, virulence, and viability depend on the strain and abiotic factors, e.g., temperature, solar radiation, and humidity (Zimmermann, 2007; Ortiz-Urquiza and Keyhani, 2013). These factors influence the quality and efficiency of this agent, so it is needed to increase survivability of the conidia over the time by using registered products and applying under optimal conditions (high relative humidity, avoiding direct solar radiation and extreme temperatures, etc.) (Bustillo et al., 2011).

Despite recommended doses may vary depending on the authors, spittlebug mortality rates above 60% have been found when treated with *Metarhizium* (**Table 4**). Within the *Metarhizium* genus some species can infect many insect species, e.g., *Metarhizium robertsii* J.F.Bisch., S.A.Rehner & Humber, or can be restricted to certain hosts, e.g., *Metarhizium album* Petch to Hemiptera (Brunner-Mendoza et al., 2019). The richness and predominance of *Metarhizium* species vary among ecosystems, and identifying this ecological status allows to understand the interactions with the hosts and crops lead to better use in IPM strategies (Obando et al., 2013; Rezende et al., 2015; Brunner-Mendoza et al., 2017).

Research on the use of nematodes of the genera *Steinernema* Travassos and *Heterorhabditis* Poinar to control spittlebug nymphs increased in the last several years. The interest in these obligate parasites lies in their easy multiplication and application, broad host range, and compatibility with chemical pesticides (Bhat et al., 2020). Previous laboratory and greenhouse studies indicate that native strains of *Steinernema* and *Heterorhabditis* cause mortality rates of more than 80% in *Mahanarva fimbriolata* (Stal, 1854), *Mahanarva spectabilis* (Distanr, 1909), and *Aeneolamia varia* (Fabricius, 1787) nymphs in the fifth day after inoculation (Leite et al., 2005; Rosero-Guerrero et al., 2012; Batista et al., 2014). One of the main advantages of these agents is their capacity to move in different environments, e.g., soil or aqueous matter, and locate their hosts by chemotaxis, ambushing or an intermediate strategy between those (Lewis et al., 2006; Lortkipanidze et al., 2016). Consequently, nematodes are effective in controlling spittlebugs as they can penetrate the nymph's foam and can move through the soil to infect other individuals (de Paula Batista and Auad, 2010; Parada Domínguez et al., 2019).

The virulence of entomopathogenic nematodes varies among genera and strains. Batista et al. (2014) found that *Steinernema riobrave* (Cabanillas et al., 1994) caused greater mortality rates in *Mahanarva spectabilis* nymphs than other species for its ability to move faster on the soil. While Moreno et al. (2012) and Parada Domínguez et al. (2019) reported that nematodes of the genus *Heterorhabditis* were more virulent in *Aeneolamia varia* and *Aeneolamia albofasciata* (Lallemand, 1939) nymphs, due to the presence of a tooth that makes it easier to penetrate the host through the cuticle.

Biological Control

Predators

The nymphal predator *Salpingogaster nigra* Schiner, 1868 (Diptera: Syrphidae) is one of the most efficient agents for its high reproduction rate, high fecundity, and short life cycle that allows two or three generations per spittlebug cycle (Sotelo and Cardona, 2001). Despite this potential, this species demonstrated low larval viability in laboratory studies, implying that a mass rearing colony would be impractical (Veríssimo et al., 2018). To maintain and promote *S. nigra* populations in crops, it is recommended to use conservation biological control techniques, such as providing plants with extrafloral nectaries and available pollen (Bustillo and Castro, 2011; Pérez-Bañón et al., 2013).

Promising Natural Enemies

There are information of the occurrence of other natural enemies such as the egg parasitoids *Anagrus urichi* Pickles, 1932 and *Acmopolynema hervali* Gomes, 1948 (Hymenoptera: Mymaridae; Marques and Vilas Boas, 1985; Valério and Oliveira, 2005); the nymph predator *Pachycondyla obscuricornis* Emery, 1890 (Hymenoptera: Formicidae; Sujii et al., 2004); the adult predators *Leptrotrachelus* sp. (Coleoptera: Carabidae) and *Porasilus barbiellini* Curran, 1934 (Diptera: Asilidae; Bueno, 1987). Along with ants and Reduviidae predating immature stages, parasitic mites of adults (Acari: Erythraeidae) and spiders of Salticidae family predating nymphs and adults (Medina, 1995; Sotelo and Cardona, 2001; Castro et al., 2005). However, the use of these insects as biological control agents has not been reported.

Chemical Control

Chemical control is limited only for few situations in which the economic threshold is reached, and the population is increasing. In Colombia, Brazil, and Mexico, several authors recommend using products containing the active ingredient Thiamethoxam to control spittlebug attack (Dinardo-Miranda et al., 2004; Gómez, 2007; Madaleno et al., 2008; Pereira et al., 2010; García-González et al., 2017). Thiamethoxam is a systemic neonicotinoid from the thianicotinyl subclass that works by binding to nicotic acetylcholine receptors, which are involved in signal transmission in the insect central nervous system, causing mobility reduction and inhibiting the feeding reflex (Maienfisch et al., 2001; Thany et al., 2010). Although the doses reported may vary, some authors reported that 250 g of active ingredient per hectare for *Aeneolamia varia* (Gómez, 2007) and *Mahanarva fimbriolata* is a viable option because it has a longer residual effect, reducing spittlebug populations faster with higher productivity (Dinardo-Miranda and Gil, 2007; Pereira et al., 2010).

Other active ingredients have been tested, such as fipronil, aldicarb, carbofuran, imidacloprid (Dinardo-Miranda et al., 2004; Nakano et al., 2020). However, the use of chemical control is still a debatable because it has a low efficiency in controlling nymphs and may have an impact on the natural enemies' population and biology, measured survivorship, emergency and parasitism of *Trichogramma galloi* Zucchi, 1988 in sugarcane (e.g., triflumuron, fipronil, thiamethoxam, lambda-cyhalothrin + thiametoxam and etiprole; de Oliveira et al., 2013). As a result,

TABLE 4 | Different recommended doses of entomopathogenic fungi *Metarrhizium anisopliae* and nematodes in sugarcane and grasses to control spittlebugs.

Biological control agent	Spittlebug species	Crop	Recommended doses	References
Metarrhizium anisopliae	*Aeneolamia varia*	Sugarcane	5×10^{12} spores ha^{-1} per crop cycle low incidence 1×10^{13} spores ha^{-1} per crop cycle high incidence	Bustillo et al., 2011; Matabanchoy et al., 2012
	Mahanarva fimbriolata	Sugarcane	9×10^{8} conidia g^{-1} of rice 1 kg^{-1} of rice	Dinardo-Miranda et al., 2004
	Mahanarva fimbriolata	Sugarcane	3×10^{12} conidia ha^{-1}	Kassab et al., 2014
	Aeneolamia spp.	Sugarcane	1×10^{12} conidia ha^{-1}	Bautista-Gálvez and González-Cortes, 2005
	Mahanarva spp.	Sugarcane	5.5×10^{11} conidia ha^{-1}	Sant et al., 2019
	Aeneolamia albofasciata Prosapia simulans	*Brachiaria decumbens*	2.5×10^{12} conidia ha^{-1} two applications each 30 days	Castillo, 2006
	Mahanarva fimbriolata Deois flavopicta Notozulia entreriana Deois incompleta	*Brachiaria brizantha* cv. Marandu	1×10^{9} conidia ha^{-1} 2×10^{9} conidia ha^{-1}	Teixeira, 2010
Heterorhabditis sp.	*Maharnarva fimbriolata*	Sugarcane	3.3 × 108 infective juveniles ha^{-1}	Leite et al., 2005
Heterorhabditis bacteriophora Steinernema sp.	*Aeneolamia varia*	Sugarcane	100 infective juveniles ha^{-1}	Rosero-Guerrero et al., 2012
Heterorhabditis amazonensis Steinernema sp.	*Mahanarva spectabilis*	Sugarcane	2,000 infective juveniles ha^{-1}	Batista et al., 2014
Heterorhabditis sp. *Heterorhabditis bacteriophora*	*Aeneolamia varia*	Sugarcane	5 x 1,010 infective juveniles ha^{-1}	Moreno et al., 2012
Heterorhabditis sp. *Steinernema* sp.	*Aeneolamia albofasciata*	Sugarcane	120 infective juveniles nymph^{-1}	Grifaldo-Alcántara et al., 2019

integration with other IPM common strategies in sugarcane such parasitoid release, is hampered.

For grasses, chemical control is not usually feasible strategy as most of these systems are extensive and pastures are considered of low economic value. Thus, in a large area application would be costly and may lead to intoxication of the livestock, with residuality on meat and milk. Besides, the ecological disequilibrium that would lead to a future rise of spittlebug populations and, to long term development of resistance (Valério and Koller, 1993; Sotelo and Cardona, 2001; Castillo, 2006).

Nakano et al. (2020) reported the use of boric acid in 0.4% (0.4 gr of boric acid/100 ml of water) concentration to control *Deois (Acanthodeois) flavopicta* (Stal, 1854) and *Notozulia entreriana* (Berg, 1879) as an alternative to other active ingredients. Results showed the same survival rate as imidacloprid 700WG for both species. The advantages associated to the use of boric acid are economic and environmental as it is low-toxic and relatively harmless to natural enemies, along with the potential uses for mineral nutrition.

Host Plant Resistance

Breeding for resistance to spittlebug attack is the main approach to generate a sustainable and long-term control strategy being easily adopted by producers at a low cost (Valério et al., 2001; Valério, 2013; Grisoto et al., 2018). Antibiosis, tolerance, and antixenosis have been reported for grasses and sugarcane (Miles et al., 1995; Cardona et al., 2004; Dinardo-Miranda et al., 2016). Here we focused on the main advances on *Urochloa* grasses host-plant resistance to spittlebug and the next challenges in this field.

Urochloa interspecific breeding program at the International Center for Tropical Agriculture (CIAT) with a recurrent selection for specific combining ability (RS-SCA) scheme is a successful case of implementation of host-plant resistance in commercial cultivars, e.g., Mulato II, Cayman, and Cobra (Worthington and Miles, 2015). In America, the founders of these programs came from genetic banks which materials were collected in successive missions to Africa from 1950's to 1980's (Keller-Grein et al., 1996). Most of the economically important cultivars are polyploid apomicts genotypes, being that the case of the first identified unimproved source of resistance to spittlebug attack, *U. brizantha* cv. Marandu. Introduced from a volcanic region in Africa to Braziland released by EMBRAPA in 1984, it exhibited antibiosis to different American spittlebug species (Nunes et al., 1984). However, recently in central-western Brazil, Almeida et al. (2005) and Valério (2009) reported severe damage caused by nymphs and adults of *Mahanarva* spp. on cultivar Marandu. This indicates lower levels of antibiosis to this genus compared to *Deois* spp. or *Notozulia* spp., causing an increase of *Mahanarva* spp. populations in the region. Hence, it is needed to identify accessions with antibiosis to immature stages coupled with some tolerance to adult feeding damage, permitting the accumulation of genes for resistance to multiple spittlebug species of economic importance in other *Urochloa* producing localities like Brazil and Mexico (Cardona et al., 2004; Miles et al., 2006; Pabón et al., 2007).

Reliable standardized methodologies based on no-choice tests were developed to assess nymph and adult damage for obtaining resistant or tolerant materials (Cardona et al., 1999; Lopez et al., 2009; Dinardo-Miranda et al., 2014). Greenhouse screening tests are performed to classify resistant, intermediate, and susceptible genotypes based on visual scoring to measure damage severity and nymph survivorship (Cardona et al., 1999). Some authors also use other measurements such as chlorophyll content, dry mass, weight loss, and biomass weight to compare the response of each genotype (Dinardo-Miranda et al., 2014, 2016, 2018; Peixoto, 2016). More recently, high-throughput phenotyping techniques are being implemented for damage assessing in the CIAT *Urochloa* breeding program in response to the increase of resistance levels in the recurrent selection cycles to this trait. This methodology is based on the digital images analysis, in which a yellowness index is calculated from the measurement of the chlorotic shoot area in each genotype. Higher accuracy and precision were obtained through this method compared to visual scoring or chlorophyll content (SPAD units) (Hernandez et al., 2020), demonstrating the feasibility of this technique to be incorporated in the program.

In traditional pasture systems, reported antixenosis levels in *Urochloa* are not sufficiently high to be considered a true resistance mechanism. The polyphagous feeding habit of spittlebugs and the extensive monoculture systems represent lesser chances to find a strong non-preference that lead the insect to not feeding from a host (Cardona and Sotelo, 2005). However, different chemical or physical factors, e.g. volatiles from damage and undamaged plants or root exudates, mediate spittlebug choice of a host (Silva et al., 2017, 2019) determining insect behavior as it can encourage or deter feeding and oviposition (Cosenza, 1982; Bernays and Chapman, 1994). Consequently, this mechanism presents the potential use of plants that exhibit host-plant resistance in diversified or push-pull pasture arrangements, aiming to establish intensive and sustainable livestock systems.

Intra and interspecific genetic independence of resistance was reported, as levels of the main two categories of resistance (i.e., antibiosis and tolerance) vary among *Urochloa* accessions when are attacked by nymphs or adults of different spittlebug species (Cardona et al., 2004, 2010). Miles et al. (1995, 2006) suggested that the genetic basis for resistance to spittlebug attack is not complex, has more than a single major gene involved, and it improves in response to intense, recurrent selection on reliable phenotypic data obtained through screening tests. Nevertheless, mechanisms of resistance involved in antibiosis and tolerance have not been dilucidated yet. Some studies aimed to evaluate possible resistance factors using synthetic chemical inducers as it stimulates or primes the endogenous immunity of plants to tackle pathogenic attack (Zhou and Wang, 2018). Wetland and terrestrial grasses, including sugarcane, are high to medium silicon accumulators (Alhousari and Greger, 2018). This element is involved in plant regulation of resistance mechanism to pathogen and insect attacks. For sugarcane, using silicic acid in *Urochloa* grasses, *Pennisetum purpureum* Schumach, *Digitaria* sp., and two sugarcane cultivars, RB73-9735 and RB83-5486, did not show a significant effect on *Mahanarva spectabilis* biological parameters or agronomic characteristics suggesting that is not effective for triggering resistance (Auad and Resende, 2018; Alvarenga et al., 2019a).

CONCLUDING REMARKS

Spittlebugs are distributed along tropical and subtropical America, presenting differences in their life cycles, behavior, and distribution. Ecological niche models estimate a variation in current and future suitable habitats under different climate change scenarios depending on the species. Thus, invasion of new species and changes in the population dynamics of these insects may threat sugarcane and pasture productivity for Latin America and the Caribbean in the next years. The extensive nature of these systems makes necessary to use different strategies for spittlebug control, reducing unsustainable practices such as burning and pesticide applications. IPM is not only the integration of strategies but also the collaboration between the research institutes, scientific community, private industry, stakeholders, farmers, and public institutions. Consequently, the development of new cultivars by breeding programs that incorporate host plant resistance is a long term and low-cost strategy that, combined with the above mentioned cultural, mechanical, microbial, and biological control options, constitute preventive and curative measures that producers may adopt to manage this pest with an IPM approach.

AUTHOR CONTRIBUTIONS

PE, LH, and MM: conceptualization, formal analysis, and resources. PE and LH: writing the original draft and review and editing. MM: supervision. All authors contributed to the article and approved the submitted version.

FUNDING

This work was funded by the CGIAR Research Program on Livestock. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

ACKNOWLEDGMENTS

The authors express their deepest gratitude to all researchers who have generated invaluable information which has made it possible to optimize integrated spittlebug management strategies to obtain a sustainable production.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.