

A 100 years of biological control of sugarcane pests in India: review and perspective

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Abstract

Insect pests constitute a major biotic stress in sugarcane in India as they attack the crop from the time of planting until almost harvest, inflicting yield and sugar losses. Biological control has always received a prominent position among the pest management tools, facilitated by the unique semi-perennial crop habitat and low pesticide usage. Biocontrol research of the early 1930s and 40s was characterized by surveys focusing on identification and studies on the basic biology of natural enemies. Conservation and re-distribution, and introduction and colonization of predominant parasitoids was practiced very early, and even in the recent past, with remarkable success. Mass multiplication and field evaluation that began in the early decades continue today, as is demonstrated by the use of the most exploited parasitoid *Trichogramma chilonis*. Several parasitoids and predators of borers and sucking pests were investigated systematically when the need arose. Among entomopathogens, granulosis viruses and fungi received considerable attention; a simple formulation of *Beauveria brongniartii* reached commercial production for the control of the white grub *Holotrichia serrata*. In recent years, isolates of *Bacillus thuringiensis* from sugarcane soil have been examined and a scarabaeid-specific *cry* gene has been identified. Preliminary studies of kairomonal principles from borers as attractants to the larval parasitoid *Cotesia flavipes* have been carried out. Organizational support to the cause of biological control includes coordinated research efforts from government agencies, production of biocontrol agents by commercial insectaries and promotion of technologies by the sugar industry. In this review, we chronicle the major research findings over the past eight decades, portray an overview of their significance and project the prospects and priorities for biological control research and promotion in the country.

Keywords: Sugarcane, Biological control, Historical progress, Organizational support, Sugar industry, Research priorities, Technology transfer

Review Methodology: In this review, we present a snapshot account of the decade-wise significant research findings over the last century and an overview of biological control in sugarcane in India. We examined the assortment of literature shown in the section Introduction and also investigated the relevant references in these publications. Further, we searched CAB Abstracts and CAB Abstracts Archives using general keywords such as sugarcane, natural enemies, parasitoids, predators, entomopathogens, biological control, etc. We also used scientific names of individual pests known to occur in the country to obtain abstracts from the CAB databases and searched further within the saved sets of abstracts using terms related to biological control. We also requested and obtained latest publications from colleagues working on sugarcane biological control at our own institute as well as other organizations.

Introduction

Sugarcane crop

As an important commercial crop of Indian agriculture, sugarcane provides raw material to sugar industry, the

second largest agro-based industry after textiles. Sugarcane also supports two important rural and cottage industries, namely jaggery and *khandsari* (unrefined raw white) sugar. In addition, some by-products of sugar industry, such as molasses, bagasse and press-mud, serve as raw material for alcohol-based industry, power generation and organic

fertilizers, respectively. Sugarcane area, production and productivity figures have steadily increased over the decades alongside the growth of sugar industry. All India estimates for 2013–14 indicated a crop area of 4.99 M ha with average cane yield of 70.50 t/ha and sugar recovery of 10.23%. The number of functional sugar mills in the country went up from 29 during 1930–31 to 513 during 2013–14 [1]. Cultivated in two broad agro-climatic regions of the country, namely tropics and subtropics characterized by moderate or ideal and extremes of climatic conditions, accounting for 45 and 55% area, respectively [2], sugarcane will continue to remain a major agro-industrial crop of the country despite several limitations.

Insect pest scenario

The significant growth in the sugar industry and the expansion of sugarcane cultivation brought in their wake biotic stresses. Amongst these, insect pests, though ranking behind diseases, inflict considerable losses in terms of cane yield as well as sugar output. Sugarcane displays different pest profiles in subtropical and tropical India, albeit with considerable overlap (Table 1). The hostile climate characterized by seasonal extremities in subtropical India supports moderate crop growth but high pest abundance. In contrast, the moderate climate in tropical India favours good crop growth but low pest levels [3]. Insect pests attack sugarcane from planting to harvest and these include borers, sucking pests, defoliators and subterranean pests. David and Nandagopal [4] provide an exhaustive list of sugarcane pests, together with notes on their distribution and keys for identification based on damage symptoms, gross morphology and feeding habits. David *et al.* [5] compiled the sugarcane entomology work conducted in the country and Varma [6] gave a detailed account of pest problems in subtropical India with notes on their management. Additional records of pests have been documented subsequently [7].

Biological control

An array of control tools, including resistant cultivars [8] and chemical control [9], is in vogue in sugarcane pest management. Nonetheless, biological control occupies a prominent position, both in theory [10] and practice [11], owing to several unique features of the crop-pest system. These include long crop duration, staggered planting in synchrony with the crushing schedule of sugar mills, and regenerative ability of the crop that enhances economic thresholds and multitude of pests occurring sequentially through the crop phenology supporting the natural enemy continuum, all of which confer on the crop the status of a semi-perennial system. Interestingly, key natural enemies, besides the pests themselves, appear to exhibit diverse reproductive strategies in tropical and subtropical India [12]. The relatively shorter favourable period available from summer to winter in the subtropical zone induces the two

trophic levels to adopt a strategy of maximizing their reproductive rate (*r* selection). In contrast, the more uniform climatic and favourable crop growth conditions prevalent throughout the year in the tropical zone apparently govern both the pests and natural enemies to maintain their populations at what can be akin to the carrying capacity of the environment (*K* selection). Besides, the inclement crop canopy in the grand growth period disallows insecticide applications thereby rendering the semi-perennial habitat conducive for both natural and applied biological control. Organizational support from government and industry also plays an important role in making biological control an implementable reality in sugarcane.

The historical roots of biological control in the country date back to 1919 when Misra [13] made some preliminary observations on the parasitoids of pyrilla *Pyrilla perpusilla* (Hemiptera: Lophopidae) and whiteflies (*Aleurolobus barodensis* and *Neomaskellia bergii*; Hemiptera: Aleyrodidae). Mass multiplication of *Trichogramma chilonis* (= *evanescens minutum*) on the factitious host *Corcyra cephalonica* was started in the 1930s [14] for use against shoot borer *Chilo infuscatellus* (Lepidoptera: Crambidae) in the inundative release mode. During 1958–64, *Isotima javensis* was successfully established in peninsular India against top borer *Scirpophaga excerptalis* (Lepidoptera: Crambidae) [15]. Similarly, *Encarsia flavoscutellum* introduced from north-eastern India [16] established in tropical India and prevented yield and quality losses due to woolly aphid *Ceratovacuna lanigera* (Homoptera: Aphididae) [17]. While the biological control attempts against top borer with *I. javensis*, pyrilla using *Epiricania melanoleuca* [18] and woolly aphid with *E. flavoscutellum* are classic examples of successful introduction and colonization within the country, *T. chilonis* has become synonymous with augmentative use of a mass-produced parasitoid. The progress of biological control research in sugarcane in the country has been documented as, for example, research publications in periodicals, annual reports of the All India Coordinated Research Project (AICRP) on Biological Control of Crop Pests and Weeds, books [5, 10, 11] and bibliographies [19, 20]. Recently, sugarcane entomology work – including biological control – at the Sugarcane Breeding Institute, Coimbatore, Tamil Nadu State, southern India, over the last century was compiled in the centenary commemorative publication of the institute [21]. The issues and strategies in sugarcane pest management, with emphasis on biological control, have been delineated in yet another centenary publication [22].

Decade-wise progress

Prior to 1930

Entomological work prior to 1930 composed mainly of descriptive symptomatology and bioecology of major and minor pests with preliminary observations on natural enemies, especially parasitoids and predators.

Table 1. Major pests of sugarcane in India

Pest	Order: family	Scientific name	Geographical distribution
I. Borers			
Early shoot borer	Lepidoptera: Crambidae	<i>Chilo infuscatellus</i>	T, ST
Internode borer	Lepidoptera: Crambidae	<i>Chilo sacchariphagus indicus</i>	T
Top borer	Lepidoptera: Crambidae	<i>Scirpophaga excerptalis</i>	T, ST
Stalk borer	Lepidoptera: Crambidae	<i>Chilo auricilius</i>	ST
Root borer	Lepidoptera: Pyralidae	<i>Polyocha depressella</i>	T, ST
Gurdaspur borer	Lepidoptera: Crambidae	<i>Acigona steniellus</i>	ST
Plassey borer	Lepidoptera: Crambidae	<i>Chilo tumidicostalis</i>	ST
II. Sucking pests			
a. Foliage feeders			
Pyrilla	Hemiptera: Lophopidae	<i>Pyrilla perpusilla</i>	T, ST
Woolly aphid	Hemiptera: Aphididae	<i>Ceratovacuna lanigera</i>	T
Whiteflies	Hemiptera: Aleyrodidae	<i>Aleurolobus barodensis</i>	T, ST
		<i>Neomaskellia bergii</i>	T, ST
b. Cane colonizers			
Scale insect	Hemiptera: Diaspididae	<i>Melanaspis glomerata</i>	T, ST
Pink mealybug	Hemiptera: Pseudococcidae	<i>Saccharicoccus sacchari</i>	T, ST
III. Subterranean pests			
Termite			
	Isoptera: Termitidae	<i>Odontotermes obesus</i>	T, ST
		<i>Microtermes obesi</i>	T, ST
White grub	Coleoptera: Scarabaeidae	<i>Holotrichia serrata</i>	T
		<i>Holotrichia consanguinea</i>	ST

T, tropical; ST, subtropical.
Compiled from [4–6].

Trichogramma chilonis (= *Trichogramma minutum*) was observed to parasitise eggs of borers with maximum parasitism rates (60–80%) during August and September [23]. *Aleurolobus barodensis* caused considerable damage in Tharsa district, Maharashtra State, but attempts to discover parasitoids of this pest were unsuccessful [24]. *Neomaskellia bergii* occurred along with *A. barodensis* and was often found devoured by *Scymnus* sp. [13]. As many as 44% of pyrilla eggs were parasitised by encyrtids during September–October. Adults of the nymphal parasitoid *Dryinus pyrillae* were active from the middle of March to December. Cocoons of the parasitoid were observed on the leaves of sugarcane and sorghum throughout the year; the parasitoid was almost exclusively in the pupal stage from January to the middle of March and adults emerged from the middle of March to the end of April [25].

1930–40

Two species of *Trichogramma* were observed on *C. infuscatellus* and sorghum stem borer *Chilo partellus* (Lepidoptera: Crambidae). Life cycle and temperature requirements of the two *Trichogramma* species were studied in the laboratory on different hosts [26] and superparasitism in *T. chilonis* was observed [27]. Mass multiplication of *T. chilonis* using *C. cephalonica* as a factitious host was initiated in 1930 to target shoot borer [14]. The various steps involved in the mass rearing of the host and the materials needed for *Trichogramma* production were described [28, 29]. After reviewing the efforts made towards the biological control of sugarcane pests, Narayanan

[30] recommended extensive releases of *Trichogramma* in sugarcane fields at the time of borer outbreaks.

The pupal parasitoid *Tetrastichus howardi* (= *Tetrastichus ayyari*) was observed on *C. infuscatellus*, internode borer *Chilo sacchariphagus indicus* (Lepidoptera: Crambidae), *C. partellus* and pink borer *Sesamia inferens* (Lepidoptera: Noctuidae); the parasitoid was multiplied on pupae of a number of other hosts in the laboratory [31].

1941–50

Borers

The egg parasitoids *Telenomus beneficiens* on top borer [32] and *Trichogrammatoidea nana* on shoot borer [33] were reported. Larval parasitoids, such as *Bracon hebetor* [34], *Myosoma* (= *Bracon*=*Microbracon*) *chinensis* [35], *Rhaconotus scirpophagae*, *Stenobracon deesae* [36, 37], etc., were recorded on sugarcane borers.

Seasonal occurrence and temperature requirement studies of *S. deesae* [38], *Goniozus indicus* [39] and *I. javensis* [40] on top borer revealed the diversity and role of natural enemies in the natural regulation of the pest. In Punjab State, parasitism levels of *I. javensis* reached 35–40% during August–October [40]. The parasitoid showed 40% incidence, did not harbour hyperparasitoids, and was amenable to laboratory multiplication [41].

In *Trichogramma* rearing, wheat bran was substituted for sorghum in *Corcyra* diet [42] and vitamin B was found to be important for its growth [43]. *Trichogramma chilonis* releases against shoot borer produced encouraging results in Sagauli, Bihar State [44] and Karnataka State [45]. Mass

releases enhanced parasitism rates of shoot borer and internode borer eggs from 0–13% to 90% and increased cane yield by 3 t/ac in 1938 in Mandya, Karnataka. The parasitoid was also sent to Orissa State and Bihar during 1937–39 [45]. The release of 30 million *T. chilonis* during 1944–55 in Karnal, Haryana State, increased egg parasitism from 7.4 to 23.4% [46]. The egg parasitoid *T. beneficiens* gave considerable control of top borer [44].

Sucking pests

Biological control work on pyrilla was initiated by placing parasitised egg masses of pyrilla in wooden cages fitted with wire gauge in sugarcane fields in Karnal [47]. Muliyl and Lakshmanan [48] also suggested the use of this method as the egg parasitoids *Tetrastichus pyrillae*, *Ageniaspis pyrillae* and *Cheiloneurus pyrillae* caused over 60% parasitism, and their conservation using field cages enhanced parasitism levels. The nymphal and adult parasitoid *E. melanoleuca* showed 69–95% natural parasitism of pyrilla [49]. The parasitoid completed its life cycle in 10–13 days and 19–22 days in summer and winter, respectively, in Bengal State [50]. Two other parasitoids, namely *Coniopteryx pusana* from eggs [51] and *Pseudogonatopus pyrillae* from nymphs [52] were reported on pyrilla.

The bionomics of *Adonia variegata*, *Brumus suturalis* and *Scymnus quadrillum* were studied. Among these, *B. suturalis* occurred all over the country on a variety of hosts including aphids, coccids, aleurodids, psyllids, mites and eggs of certain insects [53]. *Scymnus gracilis* was a specific predator of mites consuming as many as 50 mites in 24 h [54, 55].

1951–60

Borers

Several parasitoids and predators occurring on sugarcane pests were listed [56, 57]: the egg parasitoid *Telenomus dignoides* [58]; the larval parasitoids *Bracon famulus* [58], *Cotesia flavipes* [59], *Goniozus* sp., *Kriegeria* sp., *Listrognathus clavinervis* and *Mesostenus longicornis* [56]; and the pupal parasitoid *Tetrastichus* sp. [56] were reported on top borer in different parts of the country. *Isotima javensis* was re-described [60] and a key was provided to distinguish *Tetrastichus israeli*, a pupal parasitoid of shoot borer, from the other known Indian species [61]. The entomopathogenic nematode (EPN) *Mermis* sp. was found to infect shoot borer larvae [62].

In Punjab, *T. chilonis* parasitised 2–15% eggs of Gurdaspur borer *Acigona steniellus* (Lepidoptera: Crambidae) during July–September in two different study years [63]. In mass breeding on *Corcyra* eggs for over 4 years, the parasitoid preferred freshly laid eggs to older ones for parasitization [64]. Superparasitism studies revealed that *Trichogramma* oviposited on the same egg twice or thrice from different angles even when fresh unparasitised host eggs were available. Sometimes it laid two eggs in a host during single insertion. Further, the parasitoid was unable to distinguish

between healthy and damaged or fertilized and unfertilized eggs [65]. *Trichogramma* releases against shoot borer recommended in Bihar, Orissa, Maharashtra, Karnataka and Tamil Nadu States [66, 67] increased cane yields [68, 69]. In contrast, *Trichogramma* releases against shoot borer and root borer *Polyocha depressella* (= *Emmalocera depressella*) (Lepidoptera: Pyralidae) during April–July proved ineffective, apparently due to the adverse effect of the high temperature and low humidity prevailing during these months on parasitoid activity [70, 71]. Three factors, viz. (a) superparasitism in mass rearing resulting in emergence of no or weak progeny, (b) lack of host abundance and (c) poor ecological adaptability of the parasitoid were related to its so-called failure in the field. The parasitoid would not work well if the temperature in the target field was lower than the optimum temperature maintained in mass rearings whereas slightly higher field temperatures were favourable for its release [67]. Critical ecological studies on *Trichogramma* were recommended in view of the inconsistent results obtained at different locations [72].

The bionomics of *S. deesae* was studied [73]; two hyperparasitoids were reported and the biology of one of them was examined [74, 75]. *Cotesia flavipes* parasitism in larvae of Plassey borer *Chilo tumidicostalis* (Lepidoptera: Crambidae) was observed and the parasitoid required 25–30 days to complete its life cycle [76].

Sucking pests

Of the chalcids *T. pyrillae*, *A. pyrillae* and *C. pyrillae* observed parasitizing the eggs of pyrilla, *T. pyrillae* showed highest levels of parasitism and longest period of activity. With average life cycle duration of 10–36 days, this parasitoid completed six generations during October–February [77]. Conservation of *T. pyrillae* using wire mesh cages resulted in a higher parasitism rate of 35%; parasitism was four times higher in the eggs laid on leaves than on sheaths [78]. The green muscardine entomopathogenic fungus (EPF) *Metarhizium anisopliae* was isolated from pyrilla and its growth was studied on rice or rice mixed with an equal part of peanut hulls [79] and oat agar medium [80]; the fungus gave satisfactory control in the laboratory and field under high humidity conditions. The fungus was used to control pyrilla by other workers, too [81].

Scale insect *Melanaspis glomerata* (Hemiptera: Diaspididae) was attacked by several indigenous natural enemies, viz. *Anabrolepis bifasciata*, *Azotus chionaspidis*, *Azotus delhiensis* and *Xanthoencyrtus fullawayi* [82, 83]. *Anabrolepis bifasciata* was recommended against scale insect in view of its abundance [84]. Several parasitoids and predators were recorded from mealybugs [56, 57, 82, 85] and whiteflies *A. barodensis* and *N. bergii* [57, 86, 87].

1961–70

Borers

A number of natural enemies were reported on shoot borer [88, 89], top borer [90, 91], internode borer [92, 93],

stalk borer *Chilo auricilius* (Lepidoptera: Crambidae) [94, 95] and *A. steniellus* [96].

Trichogramma chilonis performed better when reared at alternating temperatures than at constant temperatures [97]. Considerable variation in adaptability to high temperature and low humidity was observed in samples of the parasitoid collected from selected locations in the country, namely Delhi, Ambajipet, Ludhiana, Lucknow and Cuddalore. Breeding of cultures from the first three places through 30 generations at progressively increasing temperature and decreasing humidity indicated the possibility of producing improved strains tolerant to high temperature (35°C) and low humidity (10%) [98].

A laboratory rearing technique for the indigenous tachinid parasitoid *Sturmiopsis inferens* was described [99]. A number of exotic tachinid and hymenopteran parasitoids were evaluated against sugarcane pests [100–103]. Among the new world species tried, Antiguan, Jamaican and Dominican strains of *Lixophaga diatraeae* caused 50–86%, 64–80% and 60–85% parasitization, respectively, of top borer in the laboratory. However, in the wild, it did not parasitise top borer because of the presence of operculum blocking the larval tunnel [104]. When 563 and 443 gravid females were released in Uttar Pradesh and Karnataka States, respectively, only three puparia could be recovered from stalk borer in Uttar Pradesh [105]. Parasitization rates by a Trinidad strain of *Paratheresia claripalpis* were 20.0, 11.0 and 0.0% on top borer, internode borer and shoot borer, respectively. The Mexican strain did not parasitise internode borer but caused 17.9% parasitization in top borer [101].

Laboratory rearing techniques for *C. flavipes* [106] and *I. javensis* [15, 107] were described. It was suggested that when larvae of alternative hosts were used for breeding *I. javensis*, they had to be parasitised by *B. hebetor* or *Bracon brevicornis* before the parasitoid eggs were transferred to them as the females failed to lay eggs on alternative hosts [108]. Inoculative releases of *I. javensis* made against top borer in two different places of Tamil Nadu, namely Pugalur in 1958 [107, 109–111] and Thanjavur during 1961–63 [15], enhanced parasitism rates and arrested borer proliferation with considerable dispersal of the parasitoid. During the same period, the parasitoid was also introduced into Mandya district of Karnataka where it established and successfully suppressed the pest [112]. The introduction of the parasitoid became an outstanding success in this part of the country because of the following factors: continuous availability of the host in overlapping generations throughout the year under tropical conditions; short life cycle of the parasitoid, which enabled it to complete nearly three generations during one generation of the host; efficient distribution of eggs in the host tunnels; and high searching ability of the parasitoid even under low levels of pest infestation. Since its introduction, top borer continues to be reduced to a minor problem in the area, warranting no suppressive measures.

A bacterium *Aerobacter* sp., fungi *Aspergillus parasiticus* and *Beauveria bassiana* [113], and the EPN *Neotylenchus* sp. and *Hexameris* sp. [114, 115] were reported to infect larvae of top borer. *Bacillus thuringiensis* formulations, viz. Bakthane and Thuricide were effective against Gurdaspur borer in laboratory and pot culture experiments [116]. Spray application of 0.4% Thuricide at weekly intervals during July–October reduced infestation of the borer from 11.3 to 4.8–5.8% in Punjab [117]. The white grub *Holotrichia* sp. was susceptible to *B. thuringiensis* [118]. In studies on the EPN *Steinernema carpocapsae*, more than 100 000 juveniles could be produced from a single full grown larva of top borer [119].

Sucking pests

Of the three parasitoids of pyrilla, namely *Ooencyrtus pyrillae*, *Ooencyrtus papilionis* and *T. pyrillae* that appeared by July–August, the first two disappeared by November while *T. pyrillae* continued to be active for another month [120]. Increase in populations of *Epiricania* sp. and *Tetrastichus* sp. in proportion to that of the host was not adequate to control pyrilla in outbreak years in Uttar Pradesh [121]. *Epiricania melanoleuca* remained unaffected by the ultra low volume sprays of malathion applied by aircraft in 1968; on sprayed canes the cocoons of the parasitoid increased by 19.2–25.0% as compared with 11.0% on untreated canes, probably due to early pupation [122]. Hymenopteran parasitoids and predatory coccinellids were found to be important in regulating the populations of scale insect [123].

Epizootics of the fungus *M. anisopliae* in populations of pyrilla led to 60–75% adult mortality and 71–75% nymphal mortality during September–October [124]. In a pilot experiment conducted in Annamalai Nagar, Tamil Nadu, 100% mortality of pyrilla was observed with *M. anisopliae* [125]. *Hirsutella* sp. was found to infect nymphs and adults of pyrilla [126]. The whitefly *A. barodensis* was effectively checked by the fungus *Aschersonia placenta* during the monsoon months [127].

1971–1980

Borers

Natural enemy records on shoot borer [128–132], top borer [133, 134], stalk borer [133, 135] and root borer [136] continued during the decade. Natural parasitism of shoot borer by *T. chilonis* varied widely (2–95%) within and between regions [130]. A new method for continuous maintenance of *C. cephalonica* culture was described [137]. Five species of *Trichogramma* were imported, released and recovered from sugarcane borers [136, 138].

Despite the debate on the success or failure of early experiments, studies carried out during this decade indicated the usefulness of inundative releases of *Trichogramma*, which revived interest in the parasitoid [128, 139]. In Tamil Nadu, weekly releases of 50 000 adults of *T. chilonis*

per ha (from 4 to 11th month age of the crop) were found to reduce damage by internode borer, on both cane basis and joint basis [140], resulting in higher yield and sugar recovery [141]. Adequate control of internode borer could be obtained even with 12 releases, each comprising 12 500 parasitoids/ha. However, in view of probable loss of parasitoids in the field, a higher dosage of 250 000/ha in 10 equal batches was recommended [142]. *Trichogramma* colonization in an area of 1200 ha at Madurantakam Cooperative Sugar Mills, Padalam, Tamil Nadu, during 1976–77 increased sugar recovery by 0.18 units contributing to an additional 69.7 kg sugar per ha – an increase that could account for an additional production of 145.8 tonnes for the entire released area [143]. The impact of inundative releases of *T. chilonis* for the suppression of internode borer was found to vary with the type of insecticide sprayed prior to parasitoid release [144]; various workers studied the influence of insecticides on *T. chilonis* [144–146].

In studies on other borers, periodical releases of *T. chilonis* in contiguous areas of cane fields throughout the year gave effective control of shoot borer in Andhra Pradesh [147]. The parasitoid was also found effective against Gurdaspur borer when 125 000 adults per ha were released against each brood [148].

The tachinid *St. inferens* parasitised shoot borer at Coimbatore throughout the year [149]. In Haryana, however, it was less active from April to July due to high temperature when shoot borer was active [150]. During 1977–82, the parasitoid was released and found established in Chengalpattu district of Tamil Nadu, where shoot borer was a serious problem and the parasitoid had not been recorded earlier; it was also released in Thanjavur district of Tamil Nadu [151]. Amongst the exotic tachinids evaluated, *Diatraeophaga striatalis* from Indonesia parasitised shoot borer and internode borer in the laboratory [152]; in field trials against internode borer, the parasitoid showed initial establishment [153]. *Sturmiopsis parasitica* from Ghana showed differential parasitization rates on sorghum borer, pink borer, internode borer, shoot borer [154] and stalk borer [155].

In studies on other parasitoids, a rearing technique was described for *C. flavipes* [156]. In the modified cage method devised for *I. javensis* rearing, Avasthy and Tiwari [157] placed top borer larvae in straw piping pieces closed at one end and exposed them to the parasitoid. This method resulted in 70–80% parasitization.

Sucking pests

Several natural enemies were recorded on pyrilla [133] and scale insect [158–160]. In Uttar Pradesh, conservation of *E. melanoleuca* and *T. pyrrillae* led to low incidence of pyrilla in eastern parts of the state [161], while field releases of *E. melanoleuca* proved effective against pyrilla in different studies. The parasitoid was also established in states like West Bengal and Karnataka [162]. Some exotic predatory coccinellids were tried unsuccessfully against scale insect [163].

Others

The milky disease bacterium *Paenibacillus popilliae* (= *Bacillus popilliae*) was found highly pathogenic to *Holotrichia serrata* (Coleoptera: Scarabaeidae) [164]. The predators recorded on white grubs include the carabid beetle *Anthia sexguttata* and the toad *Bufo melanostictus* [165]. Several natural enemies of termites were also recorded [166].

1981–1990

Borers

The natural enemies of Gurdaspur borer occurring in Punjab were listed [167]. *Cotesia ruficrus* was a new larval parasitoid found parasitizing *C. auricilius* along with *C. flavipes* [168]. Some fungal and bacterial pathogens were reported to infect sugarcane pests [169, 170].

Natural parasitism of internode borer eggs at Coimbatore was 0.0–16.1% due to *Trichogramma* spp. and 0.0–34.7% due to *Telenomus* spp., while mean maximum temperature had a significant influence on *Telenomus* spp. [171]. A Taiwan strain of *T. chilonis* parasitised 60.6% of stalk borer eggs in the laboratory and reduced the percentage of infested canes significantly when released in the field [172].

The influence of temperature on the tachinid *St. inferens* was examined [173]. The parasitoid hibernated during winter in the larvae of its host *C. auricilius* under north Indian conditions [174, 175]. A hyperparasitoid *Nesolynx thymus* was recorded on *St. inferens* by Varma [176], who cautioned against its accidental introduction into new areas along with the parasitoid. When shoot borer larvae were inoculated with a lethal dose of granulosis virus (GV) and maggots of *St. inferens* on the same day, the virus killed 74.8% of the host larvae but the parasitoid developed only in 5.5% of them indicating the superiority of the virus [177]. The tachinid *P. claripalpis* from Trinidad failed to establish in the field when released against shoot borer, stalk borer and sorghum borer in both subtropical and tropical parts of the country [178–180].

Natural parasitism by *C. flavipes* ranged between 2.0 and 2.5% in *A. steniellus* [181]. In field trials against *C. auricilius*, the cocoons of the exotic parasitoid *Allorhogas pyralophagus* could be recovered from release plots [182]. This parasitoid was also recovered at two out of three release sites in field trials against *A. steniellus* and *C. infuscatellus* [183].

Sucking pests

In Punjab, *T. pyrrillae* parasitised up to 80% of pyrilla eggs and *E. melanoleuca* up to 85% of nymphs and adults [184]. *Epiricania melanoleuca* produced the greatest number of viable eggs when a sex ratio of 1:1 was maintained [185]. Release of 4000–5000 cocoons and 4–5 lakh eggs/ha provided good control of pyrilla [186]. Successful establishment of *E. melanoleuca* on pyrilla had been reported from Karnataka [187], Gujarat [188, 189], Uttar Pradesh [190] and Orissa [191]. Conservation of *E. melanoleuca* and its augmentation through mass releases in Haryana, Uttar Pradesh,

Gujarat and Maharashtra were beneficial [18]. *Metarhizium anisopliae* readily infected overwintering populations of pyrilla and infected individuals were capable of spreading the infection and inducing an epizootic. The fungus was compatible with the naturally occurring fungi *Hirsutella citriformis* and *Entomophthora* sp. as well as the parasitoid *E. melanoleuca* [192].

Several natural enemies of scale insect [193–195] and mealybugs [196] were recorded. The crazy ant *Anoplolepis longipes* was reported as a natural enemy of mealybugs [197].

Three new parasitoids [198] and four coccinellid predators [199] were reported on *M. glomerata*. The developmental period of *Adelencyrtus mayurai* was reduced when the parasitoids were exposed to artificial fluorescent light for 9 h [195]. The parasitoid appeared in the field in late July and its population fluctuated more or less synchronously with that of its host [200]. The effect of several insecticides on scale insect mortality and *A. mayurai* activity was studied under field conditions [201]. Trash burning adversely affected the natural enemy complex of scale insect [202].

Each grub and adult of *Pharoscyrnus horni* consumed 24.2 and 43.2 individuals of *M. glomerata* in a day; one individual was capable of destroying 1890 scale insects during its life span [203]. The exotic predator *Chilocorus cacti* could be multiplied in the laboratory easily; it was effective in controlling the scale when released in the field [204]. Based on the biology and behaviour, *Sticholotis madagassa* seemed to be promising for the control of *M. glomerata* followed by *P. horni*, *Chilocorus nigritus* and *C. cacti* [205], and *S. madagassa* could be reared successfully on the scale infesting *Erianthus munja* in the laboratory [206]. However, when *P. horni*, *C. nigritus* and *S. madagassa* adults were released at 800/ac, fewer individuals of *S. madagassa* than those of *P. horni* or *C. nigrita* were recovered [207].

Others

The natural enemies of a few species of termites were studied [169]. The crazy ant *A. longipes* was recorded as a predator of termites [197]. The common crow *Corvus splendens*, mynah *Acridotheres tristis* and sparrow *Passer domesticus* were observed to feed on the grubs, pupae and adults of *H. serrata* when they were exposed at the time of ploughing [208]. Basic studies of pathogenicity and effect of rearing environment on the fungus *Beauveria brongniartii* as a potential biocontrol agent of the white grub *H. serrata* were conducted [209–211]. Preliminary evaluations of *P. popilliae* and various EPF and EPNs were carried out against the white grub *H. serrata* [212].

1991–2000

Borers

A new technique for release of *T. chilonis* was developed by placing gelatin capsules containing parasitised *C. cephalonica*

eggs, and the adults were released by opening the capsules in the field [213]. Releases of the parasitoid reduced shoot borer incidence whereas *Trichogrammatoidea eldanae* releases were ineffective, and *A. pyralophagus* was as effective as *T. chilonis* [214]. *Trichogramma chilonis* dispersed to a distance of 10 m in field studies. Nine releases at the rate of 50 000/ha per release at 10 day intervals reduced shoot borer incidence by 57.2% and similar dosages reduced stalk borer incidence as well. The efficacy of the parasitoid was also demonstrated in large-scale trials. The parasitoid released in combination with *C. flavipes* reduced stalk borer incidence to a greater extent than when they were used alone [215]. Its releases marginally reduced root borer incidence [216]. *Trichogramma japonicum* releases reduced top borer incidence [215]. Parasitism of internode borer eggs by *T. beneficiens* to the tune of 32.3–73.5% was observed in tropical India [217].

Parasitism levels of *C. flavipes* were the highest on stemborer of sorghum, followed by internode borer and shoot borer of sugarcane in southern India during 1990–94; no other parasitoid was recorded from these borers [218]. Mean parasitism of *C. tumidicostalis* in Assam State was 6.65 and 6.07% in 1991 and 1992, respectively. Parasitoid activity was generally low at the end of June but increased from August onwards peaking in September (19–21%) [219].

Laboratory parasitization rates of an Indian population of *C. flavipes* in a group-rearing method were positively related to the percentage of males and negatively related to the larval number and number of larvae per female parasitoid [220]. The parasitoid was not affected by some plant products [221]. In augmentative field trials, the parasitoid reduced the progress of internode borer infestation inconsistently [222]. However, in northern India, the native strain of the parasitoid was more effective than an Indonesian strain against different borers [223]. The parasitoid showed positive response to aqueous extracts of host frass [224] and volatiles from frass and infested plant [225], which suggested that the efficacy of this parasitoid could probably be enhanced by the use of kairomones [218]. *Isotima javensis* releases against top borer indicated the importance of time of release [214].

The tachinid *St. inferens* caused 11.2–17.2% parasitism of shoot borer and weather parameters seemed to have little influence on the parasitoid at Coimbatore during a 5-year study period [226]. This parasitoid could easily be multiplied in the laboratory on diet-reared pink borer *St. inferens* larvae [227]. Fifteen gravid *S. inferens* females released to one acre at fortnightly intervals caused 12.5–25.0% parasitism of *C. auricilius* during July–August and 26.5–43.5% during September–November. Parasitism decreased marginally during December–January but increased from the second fortnight of January [228].

Sugarcane ecosystem harboured predatory groups such as spiders [229, 230] and ground beetles [231], which were active throughout the year, probably feeding on the ground-dwelling stages of sugarcane pests. In three

states of southern peninsular India, 57 species of spiders belonging to 13 families of Araneae were observed in sugarcane; two species, viz. *Hippasa greenalliae* and *Cyrtophora cicatrosa* were the most abundant [229]. Seven new species of predatory spiders recorded in sugarcane in Assam were amenable to multiplication in the laboratory on some insect pests [232]. Individual *H. greenalliae* enclosed in caged plants inoculated with neonate larvae of *C. infuscatellus* reduced deadheart formation by about 50% [230]. A technique was developed to evaluate the predatory role of spiders [233]. Cultural practices like manual weeding, earthing-up and detashing significantly reduced spider abundance, while furrow irrigation was more detrimental than drip irrigation to spiders, and postharvest trash-burning drastically reduced spider abundance [234]. Among the coccinellids, *Cheilomenes sexmaculata* was widely distributed and fed on the nymphs and adults of aphids [235]. Pulses grown as intercrops with sugarcane did not enhance spider and coccinellid abundance significantly [236].

In the laboratory, early instars of internode borer were more susceptible than late instars to GV [237]. Viral infection significantly reduced shoot borer larval weight, which was more pronounced in III, IV and V instars, and a positive correlation was observed between larval weight and virus recovery [238]. Shoot borer GV was safe to albino rats [239] and very specific to the borer [240]. A wettable powder formulation of GV remained viable up to 12 months of storage [241]. Restriction enzyme analysis of shoot borer and internode borer GVs with the endonucleases Eco RI, Bam HI, Xho I and Sal I produced readily distinguishable DNA profiles with very few co-migrating fragments. The approximate size of the genome was calculated to be 112 kbp for both GVs. The relative hybridization between the two DNAs was in the range of 30–40% [242]. High volume spray of the crude preparation of shoot borer GV was as effective as purified preparation in reducing borer infestation [243]. In other studies, GV at 10^9 or 10^8 IBs/ml also decreased shoot borer infestation significantly [244]. A granulovirus was found to infect sugarcane top borer for the first time with infection levels of 1.6–14.4%, and the virus caused up to 55.2% mortality of final instar larvae in 4–8 days in the laboratory [245].

Five formulations of *B. thuringiensis* differed in their toxicity to shoot borer and internode borer larvae in laboratory and pot culture experiments [246]. *Beauveria bassiana* caused more than 65% mortality of second and third instar larvae of shoot borer at 10^6 spores/ml [247]. *Beauveria bassiana* and *M. anisopliae* were isolated from root borer and in laboratory bioassays, a root borer isolate of *B. bassiana* caused 100% mortality in the borer at 10^7 spores/ml with a shorter incubation period than that shown by a shoot borer isolate [248, 249]. However, in a preliminary field trial, the fungus did not reduce root borer incidence [216]. *Hirsutella nodulosa* was recorded for the first time from India on *C. sacchariphagus indicus* [250], and the fungus was active throughout the year except during summer (April–June) unlike GV, which was prevalent throughout the year [251].

Sucking pests

Epiricania melanoleuca showed peak activity during October–December and overwintered as eggs or pupae [252]. In Gujarat, egg masses of the parasitoid were first observed in early August with a peak in mid-October [253]. The cocoons were hyperparasitised by *Echthrodryinus* (= *Ooencyrtus*) sp. with attack rates of 0.83% in April and 27.94% in October [254].

Amitus minervae and *Encarsia ochai* were observed parasitizing the whitefly *A. barodensis*, with the former showing as high as 80% natural parasitism in Tamil Nadu and very high multiplication rate in the laboratory [255]. *Fusarium coccophilum* was recorded infecting *A. barodensis* [256]. Biology and laboratory multiplication of the scale parasitoid *Botryoideclava bhartiya* were studied [257].

Others

A new EPN *Heterorhabditis indicus* was isolated from the white grub *H. serrata* [258]. The nematodes *Steinernema carpocapse*, *Steinernema glaseri* and *H. indicus* could be multiplied on *C. sacchariphagus indicus* larvae [259]. Mass production potential of the *H. indicus* – *Photorhabditis luminescens* (symbiotic bacterium) complex was worked out with success [260]. Susceptibility of nine lepidopteran insects to *S. glaseri*, *Steinernema feltiae* and *H. indicus* infection was examined [261]; of these three species of EPN, *S. glaseri* and *H. indicus* showed promise in white grub control [262].

From 2001 until present

Borers

Differences in growth rates of wild and laboratory-reared subtropical strains of *T. chilonis* were observed in laboratory studies [263]. The percentage of emerged and deformed adults, sex ratio, fecundity and mobility of *T. chilonis* were severely affected after 3 weeks of storage at low temperature [264]. Insecticide tolerance of a Ludhiana (Punjab) strain of *T. chilonis* was greater than that of a temperature-tolerant strain of the parasitoid [265]. Recurrent selection for heat and insecticide tolerance was attempted [266] and a temperature-tolerant strain of the parasitoid performed on par with the native strain against shoot borer [267]. The searching range of a heat-tolerant strain of *T. chilonis* was superior to that of the native strain, irrespective of the change in the monthly temperature, and the mean parasitism rate in each month was also higher for the former [268].

Whole body extracts of male and female moths of stalk borer were analysed by gas liquid chromatography; male body extract elicited the least response from *T. chilonis* compared with other hosts [269]. Kairomonal effect of hexane washings of shoot borer and internode borer adults on the parasitoid in pot culture suggested that the parasitoid retained its inherent genetic response to the native host volatiles [270]. Y-tube olfactometer studies with

hexane washings of internode borer eggs, scales and adult body indicated that *T. chilonis* was able to recognize and respond to the native host cues despite being reared on the factitious host *C. cephalonica* [271]. Laboratory studies indicated that plant volatiles in intercrop/multicrop systems probably act as both attractants and arrestants to the polyphagous *T. chilonis* [272].

Studies on dispersal pattern of *T. chilonis* in sugarcane led to the inference that at least 13 release points are required per acre of target area for ensuring uniform dispersal [273, 274]. The fate of released trichocards, i.e. cards with glued eggs of *C. cephalonica* parasitised by *T. chilonis*, in sugarcane regarding ant predation was examined and inferences were drawn on the appropriate time of release [275]. Field observations in subtropical India indicated that the gregarious *T. chilonis* and solitary *Telenomus dignus* coexist on internode borer in September [276].

Doubts were expressed on the efficacy of *T. chilonis* in the control of internode borer, based on analysis of empirical data of host and parasitoid biology [277], even as combined use of *T. chilonis* with 5% tomato extracts or soybean intercrop was found to be superior to the parasitoid release alone [278]. The impact of release frequency of *T. chilonis* against internode borer was examined in field trials [279]. Fortnightly releases of *T. chilonis* at 5 cc parasitised host eggs/ha (100 000 parasitoids/ha) continued until 1 month before harvest reduced internode borer incidence and intensity when the releases were commenced in the 5th or 7th month but releases after 9th month were ineffective [280]. Weekly releases of the parasitoid at 2.5, 5.0 and 12.5 cc/ha reduced internode borer incidence and intensity resulting in higher yields with 5 cc/ha producing better benefit-to-cost ratio than 12.5 cc/ha [281]. Compatibility studies of sex pheromones and *T. chilonis* for the management of internode borer indicated the superiority of the parasitoid [282].

Group dynamics of *C. flavipes* adults were examined in the laboratory [283] and comparative advantages of group-rearing and individual-exposure methods for *C. flavipes* were demonstrated [284]. Subtropical Indian populations of *C. flavipes* exhibited variation in biological parameters such as development time, progeny per female, adult emergence and progeny sex ratio but not tolerance to low temperature, while different populations, including one from Indonesia, showed reproductive compatibility [285]. *Cotesia flavipes* released at 2000 females/ha/month split into four doses of 500 each from July to October was effective against *C. auricilius* [286]. Sequential releases of *T. chilonis* and *C. flavipes* in different combinations reduced incidence of shoot borer, internode borer and top borer in the subtropics [287]. Similar sequential release of *T. chilonis*, *C. flavipes* and *T. howardi* reduced internode borer incidence to a greater degree than individual release of the three parasitoids [288]. Top borer was able to withstand extreme summer variations better than the parasitoid *T. howardi*, in terms of adult mortality, under field conditions [289]. The suitability of three hosts for the multiplication of *T. howardi*

was examined using parasitoid output and sex ratio as parameters [290].

In a 5-year study at Coimbatore, *St. inferens* was active on shoot borer throughout the study period with an overall 0.0–23.3% fortnightly incidence. Augmentative releases of 25–95 gravid females/ha of the parasitoid enhanced parasitism rates and reduced borer incidence in some trials but produced variable effects in some other trials [291].

On shoot borer, GV was the most predominant natural enemy occurring throughout the year followed by *St. inferens*, whereas *C. flavipes* was least active, and natural enemy activity was not significantly related to weather factors [292]. GV alone acted in a density-dependent manner showing significant correlation with shoot borer incidence in one of the two study years [293]. While the application of GV and *B. thuringiensis* reduced shoot borer incidence most, *B. bassiana* reduced it least [294]. Augmentative application of GV at 10^5 and 10^9 IBs/ml, either alone or with endosulfan [295], reduced shoot borer infestation significantly. *Metarhizium anisopliae* var. *anisopliae* [296] and *B. bassiana* [297] were recorded on internode borer and their pathogenicity to the host was established. In what appears to be the first report of endophytic colonization of *B. bassiana* in sugarcane, five of several isolates, screened by conventional stem culture technique and polymerase chain reaction (PCR)-based approach using specific sequence characterized amplified region (SCAR) primers, were found to be endophytic in sugarcane, and some of the isolates were highly pathogenic to internode borer larvae [298].

EPNs developed and reproduced in GV infected shoot borer and internode borer larvae [299]. Three of the 29 EPN isolates (Heterorhabditidae and Steinernematidae) tested for infectivity at 18 and 27°C in the laboratory caused 100% mortality of *C. infuscatellus* [300]. Five species of *Steinernema* and *Heterorhabditis* displayed variable penetration and pathogenicity in late instar larvae of internode borer [301].

Sucking pests

The woolly aphid *C. lanigera*, a pest of sugarcane in north-east India, invaded tropical India during 2002–03 beginning with Maharashtra and Karnataka and later extending to Tamil Nadu and Andhra Pradesh [302–305]. The predator *Dipha aphidivora* (Lepidoptera: Pyralidae) emerged as a potential candidate in the initial surveys conducted in Maharashtra [306], and the brown lacewing *Micromus igorotus* (Neuroptera: Hemerobiidae) was later reported from Karnataka [307].

Biology and feeding potential of different predators [302], including *D. aphidivora* [308], were studied. *Dipha aphidivora* was mass-multiplied in shadenet with variable output [302, 309] and in galvanized iron trays in the laboratory by providing woolly aphid infested leaf bits [310]. Only late instars of the predator showed survival on frozen woolly aphid suggesting the possibility of using frozen aphid as transit food for the predator [311]. *Micromus igorotus* was also bred in the laboratory [312].

In field studies, predators responded positively to fluctuations in woolly aphid populations in Assam [313] and Karnataka [314]. Significant positive correlation, with a clear density-dependent cause and effect association, between the aphid and *D. aphidivora* populations was observed in Uttar Pradesh. While relative humidity (RH) and rainfall showed significant positive correlation, maximum and minimum temperatures displayed significant negative correlation with the aphid population [315]. The aphid was most active during May–October whereas the predators *M. igorotus* and *D. aphidivora* were active during June–November, and a minor predator *Eupeodes confracter* (Diptera: Syrphidae) was present during August–December. The aphid and predators showed variable relationships with weather parameters [316]. In a 3-year study of seasonal dynamics at Coimbatore, the aphid was active throughout the year with peaks during October–January. *Dipha aphidivora* was more predominant than *M. igorotus*, and the aphid intensity and predator abundance showed a gradual decline over the study period [317].

Release of 500–1000 *Micromus* or *Dipha* per acre in early stages effectively suppressed woolly aphid [318]. Field releases of *D. aphidivora* [319] at a dosage equivalent of more than 5000 cocoons/ha enhanced predator numbers and decimated aphid populations but did not prevent the spread of the aphid in the field [320] nor the subsequent yield loss [321]. In a comparative study of biological methods of control, inoculative releases of 1000 larvae/pupae of *D. aphidivora* gave the highest suppression [322]. In augmentative trials, *M. igorotus* failed to establish in the release areas at Coimbatore, whereas *D. aphidivora* releases enhanced its own numbers and reduced aphid intensity [317]. *Micromus igorotus* was evaluated in further field studies in Karnataka [323].

The parasitoid *E. flavoscutellum* showed signs of establishment in southern India about a year after it was introduced from Assam, multiplied in insectaries and released in the aphid-invaded areas [16]. Thereafter, the parasitoid usually appeared along with the first appearance of the aphid [324] and, despite temporal and spatial variation in the level of activity [325], restricted the spatial and temporal spread of the pest thereby preventing economic loss to the crop [17, 321]. Based on these observations, a protocol for the detection, conservation and distribution of the parasitoid for effective control of the aphid has been outlined [326]. The parasitoid continues to trail the aphid causing significant levels of parasitism whenever the aphid sporadically occurs in the crop system [327].

The fungus *Acremonium zeylanicum* was reported as a first record on woolly aphid in Sankeshwar, Karnataka [328]. Several entomopathogenic fungi evaluated against the aphid in the field either produced variable results [329] or failed to suppress the aphid population despite showing concentration-dependent mortality in the laboratory [330]. In another field trial, *M. anisopliae* and *B. bassiana* were next best to augmentative releases of *D. aphidivora* [322].

Conservation and augmentative mass releases of *E. melanoleuca* against pyrilla produced beneficial results in Haryana, Uttar Pradesh, Gujarat and Maharashtra [331]. In further field studies of parasitoid stage and dosage, 7000–10 000 cocoons or 1.0 million eggs/ha of *E. melanoleuca* provided the highest level of parasitism with no significant difference between eggs and cocoons, and the deployment of *E. melanoleuca* for pyrilla management cost a fifth of that of chemical control [332].

The levels of infection due to *H. citrifomis* in pyrilla adults infesting sugarcane germplasm, foreign hybrids and clones were assessed at Kannur, Kerala State [333]. Bioecology of the scale insect predator *Sticholotis cribellata* was studied [334]. *Camponotus compressus* was found to interfere with the activity of the predatory coccinellid *Cryptolaemus montrouzieri* against pink mealybug *Saccharicoccus sacchari* (Hemiptera: Pseudococcidae) by physically removing larvae of the predator [335].

Others

Beauveria brongniartii was mass-cultured on molasses-based media and formulated with press-mud as the carrier. This paved the way for the establishment of a laboratory in a sugar factory in Tamil Nadu, which mass-cultures and supplies the fungus to its registered growers [336]. Subsequent laboratory studies further economized the mass culture method by removing expensive components from the molasses media [337]. The viability and virulence of selected *B. brongniartii* formulations with various carrier materials were evaluated against *H. serrata* [338]. Supplements such as calcium chloride, chitin, lactic acid and polyethylene glycol 6000 used with molasses-based liquid media selectively enhanced spore production of three EPF [339, 340]. Compatibility of pesticides with three species of EPF was examined and strategies for the integration of the two tools were suggested [341]. An improved bioassay method for evaluating EPF of sugarcane pests by maintaining treated larvae under starvation was standardized, and the method was further evaluated in studies of EPF virulence in subcultures [342].

In a series of laboratory and pot-culture experiments for 4 years, *B. brongniartii* was effective against different instars of *H. serrata*, while in field studies the fungus at 10^{14} – 10^{16} spores/ha caused significant infection in the grubs [343]. When applied at a single moderate dosage of 2.5×10^{12} /ha, *B. brongniartii* survived in the soil for more than 5 years as evidenced from mortality of field-collected grubs due to the fungus, albeit with year-to-year variation in the levels of infection [344]. In studies with *M. anisopliae*, application of the fungus at 1×10^{13} spores/ha was next best to chlorpyrifos in reducing grub numbers and enhancing crop yield and returns [345]. In further studies, *M. anisopliae* at a lower dosage of 4×10^9 conidia/ha [346], higher dosage of 1×10^{13} conidia/ha [347], and as formulations at 3×10^{12} conidia/ha [348] reduced grub populations and increased yield significantly.

In studies on the identification of *B. thuringiensis* (*Bt*) isolates from selected *H. serrata* endemic soils of sugarcane ecosystem in Tamil Nadu, PCR screening with *cry8* gene universal primers revealed the presence of *cry8* positive isolates of *Bt*. In further studies, the first scarabaeid specific *Bt* gene from India was obtained from an isolate of the bacterium cultured from a white grub endemic soil sample and named as *cry8Sa1* [349, 350].

Biocontrol potential of two species each of *Heterorhabditis* and *Steinernema* against pupae and adults of the white grub *H. serrata* was investigated [351]. In further laboratory tests, a combination of EPNs and EPF produced higher levels of mortality than individual treatments [352]. PCR screening of native *Bt* strains obtained from soils of Tamil Nadu revealed the presence of a nematode-active *cry6* gene, and a sequence from one isolate showed homology to nematode active *cry6A* gene [353].

An apparently new *Bracon* sp. (Hymenoptera: Braconidae), two *Pediobius* spp. (Hymenoptera: Eulophidae) and one *Eurytoma* sp. (Hymenoptera: Eurytomidae) were recovered from the leaf miner *Asamangulia cuspidata* (Coleoptera: Chrysomelidae: Cassidinae: Hispini), which was observed in sugarcane as a first record at Coimbatore. While *Bracon* sp. contributed 70% to the overall parasitism rate of 39.3%, the remaining parasitoids accounted for 30% with likely hyperparasitism among them [354].

Retrospective overview

Research progress

A 100 years of biological control research in sugarcane passed through the sequential phases that are characteristic of biological control programmes for any other pest or crop. Surveys and seasonal occurrence studies of parasitoids and predators carried out in the early decades laid the foundation for further work on their utilization in biological control as a component of pest management. Seasonal fluctuations and parasitism levels, examined for major natural enemies such as *T. chilonis* [57], *C. flavipes* [49], *I. javensis* [59] and *E. melanoleuca* [355] in the first half of the 20th century, continue to be part of the investigations even in the subsequent decades for various natural enemies [134, 171, 184, 194, 218, 291]. These studies led to the understanding of new associations, region-specific dynamics, role of density-independent weather factors [218, 226, 292, 356], relative role of natural enemies in host regulation [293] and occurrence of hyperparasitoids [151]. Entomopathogens received greater attention in the second half of this century [357] when seasonal fluctuations of viruses and fungi had been examined [124, 251, 292, 358]. Some such studies elicited interesting information on density-dependent natural control and the predominance of pathogens such as GV in the natural enemy spectrum [293].

Early observations of failure of candidate bioagents to provide expected levels of control led to speculations and investigations of underlying causes, and possible solutions for enhanced success. For example, superparasitization leading to the loss of vitality, reduced longevity and fecundity, preponderance of males and malformation in individuals [359–361] had been related to the failure of *Trichogramma* spp. [362]. Attraction of *C. flavipes* adults to cues of non-target hosts [224, 225] suggested not only the reason for its failure against internode borer [222] but also the possibility of enhancing the parasitoid efficiency through semiochemicals. The competitive interaction between *St. inferens* and GV attacking shoot borer indicated the superiority of the latter [177] and explained the negative interaction observed between them in field populations [293]. The vulnerability of larvae of the predatory coccinellid *C. montrouzieri* to eviction from plant surface by the aggressive black ant *C. compressus* [335] indicated the possibility of its failure to control pink mealybug in some situations. On the contrary, elucidation of the maggot distribution behaviour of *St. inferens* adults [363], and dispersal and host searching ability of *I. javensis* [151] led to the understanding of the observed levels of efficacy of the parasitoids. Group dynamics of *C. flavipes* adults in the laboratory provided clues to the parasitoid's behaviour in the field soon after eclosion and the possible advantages for mating and host finding [283].

Attempts made to conserve and enhance the activity of egg parasitoids of pyrilla by holding the egg masses in cages with wire mesh to facilitate their selective exit were well documented [47, 78, 161]. Conservation of natural enemies occurs as a natural process in the relatively stable sugarcane crop ecosystem where pesticide consumption is far lower than in other crops [364, 365]. Nevertheless, relative safety of conventional and non-conventional insecticides to *T. chilonis* [145, 366], *St. inferens* [367], *A. mayurai* [368], *C. flavipes* [221], predatory spiders [229], *D. aphidivora* [369] and EPF [341] was examined to promote their selective application. Early and sustained activity of *A. barodensis* parasitoids in unsprayed plots rather than in aerially sprayed plots, despite lack of difference in pest population status [370], emphasized the role of conservation of natural enemies in a stable crop system. Deleterious effects of earthing-up, detrashing, post-harvest trash-burning and furrow irrigation on scale insect natural enemies [202] and predatory spiders [234] suggested the need to selectively avoid these practices. Although pulse intercrops failed to increase predator numbers [236], higher spider numbers in a weedy crop [234] indicated the possibility of enhancement of natural enemy abundance through habitat manipulation [371]. Implementation of such conservation and enhancement practices may, however, be governed more by agronomic and economic than entomological considerations.

Besides conservation and enhancement, other traditional approaches such as introduction and colonization, and mass multiplication and field augmentation had been followed

in biological control of sugarcane pests. Field colonization or augmentation included inoculative, supplementary and inundative release strategies against various pests. The introduction from Uttar Pradesh and successful colonization at Pugalur [110, 111] and Thanjavur district, Tamil Nadu [15], and Mandya district, Karnataka [112], of the top borer parasitoid *I. javensis* was an outstanding example that demonstrated how inoculative releases of a parasitoid could effectively reduce pest abundance in the introduced area. Recolonization of the parasitoid against top borer increased the levels of parasitism [6]. In a similar manner, the introduction from Assam and establishment in tropical India of the woolly aphid parasitoid *E. flavoscutellum* [16] led to natural regulation of the invasive pest preventing crop losses [17]. These two case studies exemplified introduction and colonization, the underlying principle of classical biological control of exotic pests, in a restricted sense for the control of pests introduced into new areas within the country. On the other hand, the colonization and establishment of *St. inferens* in Chingleput and Thanjavur districts of Tamil Nadu [151] with sustained positive results in the later years, despite the mixed results obtained with the parasitoid against different borers in subtropical India in field release studies [6], illustrated the success of inoculative release approach within a geographical area. The success story of *E. melanoleuca* for pyrilla control in subtropical India was based on a combination of inoculative, inundative and supplementary release strategies: introduction into new areas led to the parasitoid's establishment [18, 372], inundative releases of cocoons and eggs at high dosages gave good control of the pest [373], and mass multiplication in the laboratory and field release of the parasitoid upon detecting the pest in surveys [374] represented a sort of supplementary release strategy.

Realising the importance of two-tier mass culture programs of host insects and candidate biological control agents ever since the pioneering studies of *T. chilonis* multiplication on *C. cephalonica* [14], attempts were made to improve production technology of *C. cephalonica* [137, 375]. Subsequently, artificial diet-based techniques were developed for several lepidopteran hosts such as *C. partellus* [376], *C. sacchariphagus indicus* [377], *Se. inferens* [378] and *C. infuscatellus* [379, 380] to serve as natural or factitious hosts for parasitoids and entomopathogens. In addition, such techniques were developed for a number of homopteran host insects [151], including pyrilla [381].

Mass culture methods were developed for an array of natural enemies covering the entire geographical range of the country. *Trichogramma chilonis*, the most ubiquitous and one of the most intensively mass-multiplied parasitoids in the country, went through different stages of improvement [137, 382] while going commercial [383]. Parasitoids with a similar nation-wide distribution, such as *St. inferens* [384], *C. flavipes* [106, 156, 284], *I. javensis* [15, 107, 108, 157], *A. mayurai* [195] and the largely subtropical parasitoid *E. melanoleuca* [374] were mass-multiplied by different

methods. Some exotic braconid [385] and tachinid [386] parasitoids and strains [220] were also mass-multiplied using methods similar to those standardized for indigenous natural enemies. Successful development of efficient mass multiplication methods for potential predators such as *D. aphidivora* [302, 309, 310] and *M. igorotus* [312] in a short span of time to combat the invasive woolly aphid pointed out the concerted efforts that went in to such endeavour.

Entomopathogenic viruses and some bacteria went through significant developments in the late 90s leading to their mass production. After carrying out preliminary studies of pathogenicity, host range, mode of transmission and safety to beneficial organisms on shoot borer and internode borer GVs [387], shoot borer GV was even formulated as a wettable powder and its storage stability established [241]. The standardization of an artificial diet for *C. infuscatellus* [379, 380] precluded the need for expensive research to develop cell lines of the borer for GV multiplication. Following preliminary studies on *B. brongniartii* against white grubs [209–211], mass culture and formulation techniques were developed for the fungus using sugar industry by-products [336–338]. Subsequently, the mass culture methods were further improved by supplementing the culture media with additives [339, 340].

In the area of field validation of biocontrol agents, *T. chilonis*, the parasitoid with the longest history, has always been used under the inundative strategy. Field trials with the parasitoid span over eight decades, beginning in the 1930s and still continuing today. Aspects such as dosages, frequency and release techniques were explored and standardized against various borer pests in both subtropical and tropical India and the research results summarized in various reviews [6, 151, 388]. The causes proposed for its apparent ineffectiveness [70, 277] are often conjectural and not based on experimental evidence. Despite the conflicting perspectives and published evidence on its success or failure, the parasitoid continues to be subjected to intensive evaluation, often bordering on redundancy, to resolve issues and revalidate field efficacy. Regarding larval parasitoids, inundative releases of the larval parasitoid *C. flavipes* against different subtropical [214] and tropical borers [222] produced contrasting results, possibly due to the involvement of tri-trophic factors [218, 224, 225]. Augmentative releases of *St. inferens* enhanced parasitism rates in the subtropical *C. auricilius* [228] but produced variable parasitism rates and borer incidence in different trials against the tropical *C. infuscatellus* [291], probably due to differences in target host, parasitoid dosage and strains, and climatic conditions. In augmentative trials against the invasive woolly aphid [318, 319], selective establishment of predators [317] indicated the possible role of differential habitat suitability and the need to exercise caution in the choice of the predator for different geographical regions.

Among the pathogens used under the augmentative strategy, field applications of shoot borer GV, particularly as high volume spray [243] facilitated by the young crop, reduced borer incidence and increased cane yield and

quality [358, 389]. Although field predominance of the virus [293] seemed to justify the extensive field investigations, widespread use of the virus was apparently limited by lack of mass multiplication technique for the host and consequently the obligate virus. Artificial diet developed for shoot borer [379, 380] should expedite the process of mass multiplication of GV on a diet-based host culture system. Despite the positive field efficacy results obtained against some subtropical borers in very early studies [117, 390], commercial formulations of *B. thuringiensis* failed to gain acceptance possibly due to the internal feeding habits of the borers, dosage and volume of sprays required and canopy constraints in the grand growth phase. Similarly, the high pathogenicity [164] and field virulence [391] in white grub failed to promote *B. popilliae* as a biological control agent apparently due to its poor amenability to *in vitro* multiplication. *Beauveria brongniartii* emerged as a promising biocontrol agent [336, 343], with long-term persistence in treated fields [344], against *H. serrata* in an endemic area. Soil habitat of the grub stage, synchrony of its life-cycle with humid months and amenability of the facultative fungus to laboratory mass multiplication are some factors that apparently accelerated its promotion, notwithstanding the low natural activity of the fungus in the white grub endemic area [344]. However, the year-to-year variation in field virulence of the fungus [344] indicated the possible role of microbial ecology, besides crop management practices that are often difficult to monitor. Rhizosphere competence of fungi in relation to host plant and inter-specific interaction [392], and species interactions with opportunistic fungi [393] observed in subsequent laboratory and glasshouse studies, need careful extrapolation to field situation. On the other hand, EPF received far less attention as candidates for the control of borers and sucking pests, as exemplified by their field evaluation against shoot borer with encouraging results [294] and woolly aphid with variable results [329]. Besides the hostile canopy limiting field delivery in the later stages of crop growth, factors such as specific climatic requirements of the EPF, on both spatial and temporal scales, may have deterred extensive studies of their field evaluation.

Biological control research in sugarcane has often stepped into the unconventional field of improvement of natural enemies and exploration of semiochemicals or infochemicals, in tune with the trends in the rest of the biocontrol world. Recurrent selection studies were conducted with *T. chilonis* to induce high temperature and low humidity tolerance [97]. Similarly, selective breeding of cultures from different parts of the country, showing variable adaptability to high temperature, indicated the possibility of producing improved strains tolerant to high temperature or low humidity [98]. Recent studies also indicated the possibility of enhancing adaptability to temperature and humidity, besides insecticide tolerance [215]. Hybridization of the female-dominated Indian and male-biased Indonesian populations of *C. flavipes* in the laboratory produced fertile offspring that progressively veered towards male-biased ratio over a couple of generations, ultimately decimating the

culture (J. Srikanth and S. Easwaramoorthy, unpublished data). In preliminary studies on genetic improvement of GVs of shoot borer and internode borer, six geographical isolates of the viruses compared for DNA homology and comparative biological activity did not show significant differences [394]. Biochemical comparison of nucleocapsids and granulin of the two GVs with enzyme-linked immunosorbent assay (ELISA) and sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) techniques showed no differences, except for polypeptide composition [395]. In behavioural studies, volatiles from sugarcane plant damaged by host larvae and larval frass elicited positive response in *C. flavipes* [224, 225]. Preliminary identification of attractant compounds in shoot borer frass [396] should lead to further studies on these semiochemicals to enhance parasitoid attraction.

Organizational evolution

Biological control research in sugarcane during the early 1920s was mainly pursued in a few locations, particularly in Mysore and Bihar States. Work gained momentum during the 1960s with the involvement of both national and international organizations. The Indian Station of Commonwealth Institute of Biological Control played a role in sugarcane biological control by importing and screening natural enemies of sugarcane pests during the 1960s. These included several species and strains of *Trichogramma*, tachinid parasitoids and predatory coccinellids [397, 398], which were evaluated in both subtropical and tropical India [6, 151, 386].

In 1977, the ICAR-Sugarcane Breeding Institute (SBI), Coimbatore, along with other Institutes of the Indian Council of Agricultural Research (ICAR) and State Agricultural Universities, became part of the AICRP on Biological Control of Crop Pests and Weeds. The AICRP was shifted to the Biological Control Centre (BCC) under the National Centre for Integrated Pest Management in 1988. The BCC was elevated to an independent Project Directorate of Biological Control (PDBC) during 1993 and further upgraded to the National Bureau of Agriculturally Important Insects (NBAII) during the XI Plan, which was subsequently re-named as National Bureau of Agricultural Insect Resources (NBAIR). The AICRP centres, including the SBI (Coimbatore), ICAR-Indian Institute of Sugarcane Research (Lucknow), Punjab Agricultural University (Ludhiana) and Tamil Nadu Agricultural University (Coimbatore), had been conducting research in diverse areas of sugarcane biological control for over three decades to generate technologies for subtropical and tropical pest problems. Over the years, the NBAIR imported parasitoids/strains such as *A. pyralophagus* and *C. flavipes*, which were evaluated against subtropical and tropical pests. The AICRP on Sugarcane was initiated in 1971 with ICAR Institutes, including SBI, and State Agricultural Universities (SAU) as participating centres and

development of region-specific strategies for integrated pest management as its entomology mandate. The project included in its gamut of activities some biological control aspects such as identification of potential natural enemies and their evaluation in sugarcane pest control. Besides participation in the AICRPs, ICAR Institutes and SAUs are engaged in biocontrol research either in sponsored or internally funded projects. For example, SBI investigated entomophilic nematodes against white grubs under a European Economic Commission funded project, Tamil Nadu Agricultural University, Coimbatore, undertook work on shoot borer GV in a scheme sponsored by the Department of Biotechnology, Government of India and Haryana Agricultural University, Hisar, had contributed significantly towards the biological control of pyrilla using egg and nymphal parasitoids.

Besides research, promotion of biological control too has received support from both central and state government organizations. The Directorate of Plant Protection, Quarantine and Storage, Faridabad, has set up Central Integrated Pest Management Centers (CIPMC) in different parts of the country to implement a pilot project for the establishment of parasitoids and predators for biological control of insect pests. Also, the State Departments of Agriculture have their share in propagating biological control. For instance, the Department of Agriculture, Karnataka, has been maintaining a *Trichogramma* breeding laboratory at Mandya since about 1935 and supplying parasitoids to cultivators. The Department has also recommended the integration of parasitoid releases with cultural practices like light earthing-up for shoot borer control [388]. Research establishments associated with cooperative and public sector sugar mills such as the Main Biocontrol Research Laboratory (MBRL) of the Tamil Nadu Cooperative Sugar Federation, Chengalpattu, and Vasantdada Sugar Institute (VSI), Pune, Maharashtra, engage in the validation, and eventually promotion, of biocontrol technologies.

Participation of industry

Biological control in sugarcane enjoys the active involvement and patronage of sugar industry, without which the success story of biological control in sugarcane would be incomplete. Realizing the significance and advances made in this field, several cooperative and private sugar factories in different states, including Tamil Nadu [399], established biological control laboratories to multiply natural enemies of pests specific to the region. *Trichogramma chilonis* heads the list of natural enemies with a nationwide distribution and most laboratories set up for its production. Several cooperative sugar factories in Tamil Nadu initiated laboratories to multiply *T. chilonis* with financial aid from the state government. Private mills, such as EID Parry (India) Ltd and Rajshree Sugars and Chemicals Ltd, are producing and distributing the parasitoid through a rural entrepreneur model

[400–402]. Amongst the region-specific natural enemies, *E. melanoleuca* was targeted in the subtropical region, and based on the advice of the Entomologist (Sugarcane), Haryana Agricultural University, Uchani (Karnal), laboratories were set up by both cooperative and private mills, with financial support from the development funds of the mills [374]. The Simbhouli Sugar Mills, Ghaziabad, Uttar Pradesh, multiplied parasitoids like *St. inferens* and *C. flavipes* to combat stalk borer. Convinced by the results obtained with *B. brongniartii* against white grub in field trials conducted by SBI in growers' farms, M/s Bannari Amman Sugars Ltd., Sathyamangalam, Tamil Nadu, set up a biological control laboratory where the fungus is mass-cultured on cost-effective molasses-based media, formulated using press-mud as carrier and supplied to its registered growers [344].

Bio-factories

Biocontrol Research Laboratories (BCRL) of Pest Control (India) Pvt. Ltd., Bangalore [388], pioneered commercial production of biocontrol agents, including *Trichogramma*, in the country almost five decades after *T. chilonis* was first used against shoot borer [14]. A resource inventory compiled in 1997 lists about 100 sources and suppliers, including BCRL, of bio-products in the country against several candidate biocontrol agents [403]. The inventory features both public funded organizations that provide small cultures for research purpose and private or commercial insectaries that supply or sell large quantities to meet growers' needs. The product range includes parasitoids (39), predators (22), bacterial formulations (12), viral insecticides (6), entomopathogenic fungi (7), EPNs (2) and fungal antagonists (10), besides weed killers, bio-nematicides, pheromones and neem-based pesticides, with intended use against an array of target crops and pests. A few of these biocontrol agents, including the indomitable *Trichogramma* spp., were enlisted against sugarcane pests. Although no updated version of the publication is currently available, some entries may have disappeared from the list over the next two decades due to cessation of need-based research in government organizations and suspension of production in commercial centres.

There has been considerable proliferation of commercial bio-factories that produce a wide range of products and cater to a variety of crops and purposes in the recent past. Several commercial insectaries have been established in the sugarcane tracts of the country. A few representative examples in Tamil Nadu include those set up by enterprising agriculturists and post-graduates to mainly cater to sugarcane requirements. While the laboratories established in major cities, such as BCRL at Bangalore and Green Tech Agro Products Pvt Ltd at Coimbatore, produce a wide range of biocontrol agents, besides *Trichogramma*, some others, like the Bio-control Laboratory of Sri Durga Agro Services at Coimbatore, specialize in *Trichogramma*.

However, *T. chilonis* remains the most commercially exploited natural enemy for sugarcane pest control.

Although only eight manufacturers from India enrolled in the International Biocontrol Manufacturers Association (IBMA) [404], a conservative estimate based on a random internet search projects the number of such manufacturers at over 500 but comprehensive or updated database is currently not available. Among the commercial biopesticides that these bio-factories manufacture in the country [405], only a few products have direct relevance to sugarcane and its pests. Often, sugar mills establish bio-factories on their R & D platform to mass produce biocontrol agents against regional pests. They tend to supply to their registered growers alone for some time but close the units after they serve their purpose or due to shift in policies; commercial insectaries operating in sugarcane crop zones or elsewhere and supplying biocontrol agents such as *T. chilonis* in liaison with the industry stop production due to lack of demand.

Adoption levels

Research centres such as the MBRL and VSI, and bio-factories established by both cooperative and private sugar mills mass multiply and supply biocontrol agents to their registered growers. However, comprehensive published information on adoption levels of biological control is not available due to several possible reasons. These include, for example, spatial and temporal discontinuity of pests and the consequent diversion of R & D emphasis and efforts from biological control to other areas of research, independent practice of biocontrol by public and private sector sugar industry within each state, and absence of concerted efforts or mechanism to implement and document biological control in growers' farms at the regional or national level. Nevertheless, reports presented by R & D personnel of sugar industry and personal communication with them in meetings, as well as other published sources, provide indirect estimates of the levels of adoption of biocontrol for a given pest in a given region.

Trichogramma chilonis against shoot borer and internode borer, GV against shoot borer, and *B. brongniartii* and *M. anisopliae* against *Holotrichia* spp., which all represent the resident or endemic category, are the most extensively used biocontrol agents in sugarcane. A pilot survey on the adoption scenario of *Trichogramma* in sugar factories in Tamil Nadu ($n = 20$) and Andhra Pradesh ($n = 7$) indicated that the parasitoid was used in 100 and 71% of the factories against internode borer, but 0 and 100% of the factories against shoot borer in these two states, respectively [406]. In Tamil Nadu, the parasitoid is produced and distributed by rural entrepreneur centres set up by EID Parry (India) Ltd and Rajshree Sugars and Chemicals Ltd, which have a registered cane area of about 20 000 and 35 500 ha, respectively [400–402]. When the entire crop area under the aegis of sugar industry in Tamil Nadu is considered,

T. chilonis is deployed in about 54 000 ha (25.9% of the total cultivated area) against internode borer and 5700 ha (2.7%) against shoot borer, *Tetrastichus* sp. in 8600 ha (4.1%) against internode borer, GV in 11 000 ha (5.3%) against shoot borer, and *B. brongniartii* or *M. anisopliae* in 3350 ha (1.6%) against white grub [401, 402]. When the invasive woolly aphid was on the marauding trail in tropical India during 2002–06, augmentative releases of predators, including *D. aphidivora* and *M. igorotus*, made by VSI reached peak area of coverage (92 302 ha) during 2003–04. As the intensity of the aphid and area affected declined over the years – primarily due to the effective use of biological control – deployment of predators contributed to a high 77.87% (2005–06) overall control of the aphid in terms of area [319].

Prospective priorities

Although applied biological control holds much promise in the sugarcane industry, the prospects depend on prioritization, refinement and generation of practicable technologies to be delivered to the end-users, i.e. sugarcane growers through sugar industry and private entrepreneurs.

Research endeavours

Notwithstanding the vast array of natural enemies recorded on sugarcane pests [151], identification of potential natural enemies should be a continuous process. The spectrum of natural enemies of a given pest in any geographical area often contains many occasional associations but the more constant associations tend to maintain equilibrium status with clearcut relative abundance. Identification of consistent or dominant natural enemies helps in determining the candidate biocontrol agent for introduction and colonization, if the target pest turns out to be invasive in a different region, and augmentative control of resident pests in the native area. Successful examples of introduction and colonization, such as parasitoids of top borer, pyrilla and woolly aphid discussed in the previous sections, obviously contrast with the mass-produced and inundatively released *T. chilonis*, despite its doubtful association with many of its hosts. While searching new associations, some unexplored groups of parasitoids, such as egg parasitoids other than *T. chilonis* and pupal parasitoids of borers, should be given greater emphasis. Identification of the natural enemy spectrum of the leaf miner *A. cuspidata* in surveys carried out at Coimbatore, where the pest was observed recently as a first record, reiterated the importance of such surveys. Analysis of the past history of the pest and its natural enemies in their subtropical home provided the background information needed for a planned utilization of the natural enemies in the place of introduction, was the pest to reach serious densities [354].

Augmentative release approach is often limited by lack of mass multiplication techniques either for the biocontrol agent or host insect. For example, production of shoot borer GV was constrained by the lack of mass culture method for the host. The standardization of artificial diet for the borer [379, 380] should, however, facilitate production of the obligate GV in a diet-based larva-virus rearing system. Besides, such diet-based mass production of shoot borer would also facilitate the multiplication of *St. inferens*, currently being multiplied on alternative hosts. Similarly, development of an artificial diet for top borer would enable mass multiplication of its effective parasitoid *I. javensis*. *In vitro* culture methods, attempted for the predator *D. aphidivora* [407], need to be extended to predatory coccinellids as was done in other systems [408]. Parasitoids such as *St. inferens* are good candidates for *in vitro* multiplication since such attempts have been successful in the case of other dipteran parasitoids [409]. The progress made with low-cost mass multiplication of EPF such as *B. brongniartii* [336–338] should lead to the development of simpler formulations.

One of the common concerns with mass production of natural enemies on factitious hosts for countless generations is the selection of inferior populations with poor vigor and searching ability. A classic case is *T. chilonis* mass-produced on *C. cephalonica* in laboratories, so much so that there probably is a 'Corcyra strain' of the parasitoid throughout the country though crop-specific strains are often discussed. Some recent studies revealed that the parasitoid retained its ability to recognize and respond to native host volatiles [270, 271], and such apprehensions are not serious. Concerns regarding field efficacy of *T. chilonis* against internode borer [277] were addressed in recent work with proper dosage and timing of releases as remedies [280, 281]. Nevertheless, such consequences could be avoided with routine practices, such as initiating laboratory cultures from field populations and not from the *Corcyra* strain of the nearest insectary, invigorating cultures with crop and pest-specific field populations periodically, inducing the parasitoid to search the factitious or natural host in simulated field environment, and exposing the parasitoid to natural host cyclically for one or two generations. Nonetheless, the dependence on a single candidate agent such as *T. chilonis* from the egg parasitoid guild is likely to give partial and unpredictable control far below the anticipated levels [22], particularly due to the lack of information on the regularity of association with its hosts in the field. Potential egg parasitoids such as *Telenomus* sp. that show higher levels of association [171, 217, J. Srikanth *et al.*, unpublished data] need to be explored.

The principle of associative learning, wherein adults of a parasitoid multiplied on a non-target host from within its host range are exposed to the target host or its cues in the laboratory before field release to allow them to learn the host cues [410], may work for oligophagous parasitoids like *C. flavipes* but not *T. chilonis*, which is multiplied on an unnatural host. Production of heat-tolerant strains of

parasitoids such as *T. chilonis* [97, 98, 266] and *St. inferens* for use against borers during summer needs attention. Insecticide-tolerant strains of *T. chilonis* [215] or other parasitoids are less important in sugarcane under the current minimal pesticide usage [364, 365] situation. They may, however, become more relevant in an altered pest management system with greater emphasis on higher pesticide usage driven by changes in crop production patterns and the consequent pest scenario that includes invasive pests. Parasitoid adaptability can be enhanced by shifting populations from climatically harsher habitats, where natural enemies display greater plasticity and exploitative tendencies, to milder habitats where they tend to be less adaptable but in equilibrium with the host [12].

Besides laboratory manipulation of natural enemies, deployment of infochemicals (semiochemicals) in the field may hold the key to enhancing their effectiveness in a crop wherein inundative releases of natural enemies alone often do not lead to spectacular crashes in the normally stable pest populations. This has greater relevance to parasitoids like *C. flavipes* which show preference to hosts in crops other than sugarcane [218] and *St. inferens* with its preference to *Se. inferens*. The use of infochemicals from either the preferred host plant and host insect or its frass may increase the retention time and enhance parasitoid efficiency. The preliminary work carried out on the identification of these chemicals and their behavioural bioassay in the laboratory [396] should be taken forward to field trials. Establishing the possibility of some sex pheromones mimicking allelochemicals for parasitoids would enhance their value as semiochemicals. Application of sugars or amino acids as nutrient supplements may be less important as a strategy to enhance the activity of general predators of minor homopteran pests. Habitat manipulation or diversification through intercropping, though observed to reduce pest populations [411] despite little effect on predator populations [236], may not always be feasible agronomically.

Long-term research has demonstrated the prospects of entomopathogens like GV and *B. brongniartii* against shoot borer and white grub, respectively. Fungi such as *B. bassiana* or *M. anisopliae* hold promise against below-ground pests such as root borer *P. depressella* for two reasons: (i) the ease of delivery in the form of formulations containing coarse carrier material such as those developed for *B. brongniartii* [338], and (ii) the inaccessibility of subterranean larvae to parasitoids, despite the natural occurrence of a large array of them [412]. Formulations can be improved further by using inert materials that can enhance storage stability and field efficacy, without being affected by or affecting soil properties. On the other hand, very few attempts have been made to utilize EPF against aerial borer pests due to logistics related to field application. EPF need to be explored against these borers especially in view of the amenability of wide row-spaced crop to spray application, which could be facilitated further by the development of powder formulations. Development of nanoparticle-based fungal formulations with greater

affinity to plant surface or tissue may improve their efficacy further, particularly against tissue borers. EPF as endophytes, attempted against pests such as banana weevil [413], could be a possibility against borers in sugarcane with the identification of endophytic strains of *B. bassiana* in a recent study [298]. The switchover to micro-irrigation systems in sugarcane cultivation opens up the possibility of delivering suitable formulations of EPF through irrigation water to target soil-dwelling white grub or termites and tissue borers through endophytic activity. Microbial ecology [392, 393] deserves attention as it helps to elucidate the observed variation in the field performance of EPF [344] and enables formulation of strategies to enhance field efficacy.

Identification of geographical or host-based isolates with greater virulence should be an integral part of the entomopathogen research programme. While molecular techniques can be utilized to identify genetic variability, the tools themselves would be rendered less meaningful unless such variability is related to virulence of the isolates. Sugarcane soils appear to be a rich repository of a wide variety of *Bt* strains with diversity of the *cry* toxin gene, as the recent identification of a toxin gene specific to scarabaeids [349] indicated. Intensive and extensive work on this potential group might yield not only isolates suitable for the development of simple formulations for direct application in the field but also toxin genes with activity against a wide range of soil and aerial pests to be exploited through transgenics approach in sugarcane and other crops. While the techniques standardized for the evolution and evaluation of sugarcane transgenics against shoot borer and top borer [414, 415] would be handy in realizing this goal, the outcome itself might raise questions and necessitate further research on the possible impact of transgenics on the sugarcane natural enemy complex [416].

Entomophilic nematodes that have shown promise against white grubs in laboratory studies need field evaluation either in isolation or in conjunction with EPF such as *B. brongniartii* or *M. anisopliae*. Studies on the symbiotic bacteria such as *Xenorhabdus* and *Photorhabdus*, and identification of their toxin genes, could lead to wider applications in many crops, besides sugarcane. Due to their amenability to recombinant technology, EPF and other entomopathogens can be genetically manipulated to produce newer biological insecticides. Such manipulations can be aimed at improving virulence and tolerance to environmental adversities.

Technology transfer

The success of biological control largely depends on the availability of mass-produced biocontrol agents to the end-user. This can be ensured by the establishment of adequate number of insectaries in sugarcane tracts. Research laboratories that generate the mass-culture and field evaluation technologies may provide the technical expertise

needed for their transfer as well as the subsequent quality maintenance. Besides facilitating knowledge dissemination, i.e. transfer of the latest biocontrol technologies to growers, sugar industry can play a more active role by either mass producing biocontrol agents in R & D laboratories or encouraging entrepreneurial growers to establish production and service centers as is already being practiced by a couple of factories. Such concerted efforts by sugar industry would ensure an uninterrupted supply chain of biocontrol agents to their registered growers despite the possibility of the industry itself emerging as a competitor to commercial insectaries, some of which appeared to have wound up production of *Trichogramma* in the recent past. Nonetheless, when integrated with other suitable pest management tools and practiced under a mandatory mode in all the registered farms of any factory, biological control will become an important component of areawide pest management concept and approach [417] in sugarcane.

Conclusion

The semi-perennial sugarcane habitat promotes natural biological control and provides a conducive environment for applied biological control. The first and foremost strategy in biological control of sugarcane pests should be the sustenance of the natural biological control component through avoidance of system disruption. Sporadic pest outbreaks that occur in the crop, apparently due to localized disturbances whose causes are often difficult to decipher, are sometimes associated with a decline in the activity of the major natural enemy. Often, unusually profuse proliferation of the predominant natural enemy occurs concomitantly with the pest flare-up as was observed in a pyrilla outbreak. Judicious use of emergency insecticide applications coupled with supplementary releases of the major natural enemy in the first case, and avoidance of insecticides together with re-distribution of the proliferating predominant natural enemy in the second case, usually restore balance by the beginning of the next season, as experience in some such cases indicates. The general R & D strategies should include identification, introduction, colonization and establishment of the major natural enemy, especially in the event of an inadvertent introduction or invasion within the country or from another country. Mass multiplication and augmentative field delivery of promising candidate agents against endemic pests in either prophylactic or curative mode will be effective when adopted in an area-wide approach in the spatially and temporally contiguous crop habitat. Factors such as relative abundance and efficiency, occurrence of superior geographical or host-related strains and amenability to multiplication for large-scale delivery should decide the choice of the natural enemy from among the major groups, namely parasitoids, predators and pathogens. Deploying the pesticide umbrella to combat proliferating endemic pests, such as borers and

white grub, would transform sugarcane pest management from the natural/applied biological control mode to insecticide mode, and sugarcane from an insurance crop to a catastrophic crop.

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