FEATURE ARTICLE

Sterile insect technique and area wide integrated pest management

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Abstract: The known fact of resistance development towards the insecticides by majority of the insects has developed a consensus of requirement of the alternative approach for the efficient management of the insect pests. An approach of species specific, sustainable and nonpolluting serves to be a better approach. Quite, among the several approaches, Sterile Insect Technique (SIT) turns to be an outstanding option. SIT is defined to be an autocidal approach wherein the target insects are mass reared, exposed to gamma/x-rays followed by the field release. Many scientists studied and experimented with the idea, but it wasn't until E.F. Knipling succeeded in controlling the screwworm fly, Cochlomia homnivorax Curacao and Florida. Following the success, other dipteran insects were prioritised and successfully managed, thus efficient protocol was standardized against the insect of same order. The application of the SIT for the management of lepidopterans tends to be challenging due to its cytogenetic and cytological characters that differs from the dipteran insects. It includes achaismatic mode of female meiosis, holokinetic structure of chromosomes and dichotomous spermatogenesis. The complications concerned led to the upraisal of the Inherited Sterility (IS) where F1 off springs exhibit a higher level of sterility than the parents following the irradiation with sub sterilizing doses of ionizing radiation. The concept proves to be an efficient and provides ample scope for exploiting SIT against the insects of order Lepidoptera. SIT includes the strategies such as local suppression, eradication, containment and prevention of invasive pest establishment for the management. On behalf of its nature of being pest specific and autocidal, this forms to be efficient component for Area-wide Integrated Pest Management Strategy (AW-IPM). Additionally, this technique found to be compatible with other management strategies viz., biological control etc and hence could potentially stand out as a efficient, sustainable approach

Insects predicted to be conquerors over 350 million years ago from Devonian period had set out to be the most evolutionary successful group on the Earth and are successfully present in all ecological niches. Among these, majority serves to provide ecological services in the ecosystems while few of them represent a group that threatens the agricultural production. In view of the management, insecticides are considered to be the most important resort. Unfortunately, the irrational and erratic use of insecticides have aroused in the genesis of resistance to each and every class of insecticides, additionally impacting negatively on the human health, food chain and environment. This has resulted in the failure of the efficient management system. The current scenario demands the needs of environment-friendly, species-specific and sustainable approach such as Sterile Insect Technique (SIT) for the control of insect species and disease vectors. SIT is an autocidal control method which is based on the mass rearing, radiation-based sterilization and release of the same species that is targeted for population control. The principle includes sterilizing the mass reared insects with suitable doses of γ-radiations that induces sterility without impairing the ability of the insects fly and mating ability followed by its release in sufficient numbers in order to achieve sterile-to-wild insect over flooding ratios resulting in the reduction of fertile matings proportion in wild population which in turn reduces the population. This approach serves out to be a component of area-wide integrated pest management (AW-IPM) to suppress contain, prevent

Insect	Place	Year of application/ reference
Dipterans		
Screw worm,Cochliomyia hominivorax	Florida	1957-1958
	South-Western USA	1964-1966
	US-Mexico Border	1974
	Central America	1986
	North Africa	1988
	Caribbean	1999
Melon fly, Bactrocera cucurbitae	Mariana Islands	1963
	Japan	1980
Mediterranean fruit fly Ceratitis capitata	Mexico	1970
	Guatemala (Mexico)	1980
	Chile	1995
	Western Australia	1985
	Japan	1993
	California (Preventive release)	1994
	Florida (Preventive release)	1998
Mexican fruit fly	South California	1964
Anastrepha ludens	Rio Grande valley	1974
West Indian fruit fly Anastrepha obliqua		
Queensland fruit fly Bactrocera tryoni	Western Australia	1990
Onion maggots	Netherlands	1981
Tsetse fly, Glossina sp.	Sub Saharan Africa	1960s
Mosquitoes	El Salvador and India	1960s
Coleoptera		
Field Cockchafer, Melolontha vulgaris F.	Switzerland	1959
		1962
Sweetpotato Weevils, C. formicarius	Kume Island	2013
Lepidoptera		
Codling moth	Okanagan Valley of British Columbia	1994
Pink bollworm	San Joaquin Valley of California (Preventive release)	1967
False codling moth	South Africa	Boersman,2021
Painted apple moth	New Zealand	Suckling et al.,2007
Cactus moth	Mexico	Bello-Rivera et al.,2021
Gypsy moth	Mexico	Simmons et al.,2021
Sugarcane borer	South Africa	Conlong and Rutherford, 2017
Navel orange worm	California	Klassen et al., 2021
European grapevine moth	Chile,	Klassen et al., 2021
Carob moth	North Africa	Klassen et al., 2021

Table 1. Success of SIT in curacao and in other places

the introduction and eradicate the populations of insect pests and disease vectors (Vreysen et al., 2021). This technique is termed out to be species-specific, nonpolluting and resistance-free.

History of SIT

The concept of impairment of the fertility in insect's dates back to 1916 when Runner observed that cigarette beetle, *Lasioderma serricorne* (F.) exposed to large doses of X-rays resulted in the incapability of reproduction. Further, in 1927 H. J. Muller showed that ionizing radiations induced larger number of dominant lethal mutations in *Drosophila* which was expressed through reduction in hatching of eggs laid by treated females. Later, in due search of chemicals that induce sterility, Charlotte Auerbach discovered that Mustard gas was mutagenic in *Drosophila* and affected fertility (Auerbach et al., 1947). With this, much research was done over 125 pest species of public health and agricultural importance. The negative impacts due to these alkylating agents against higher animals, including humans and bioaccumulation in natural food chain led to the discontinued the application of chemosterilants. Besides, the means of achieving sterilization in the insects, the idea of releasing sterile insects into wild population and control them was independently conceived in 1930s and 1940s by A. S. Serebrovskii at Moscow State University, F. L. Vanderplank at a tsetse field research station in rural Tanganyika (now Tanzania), and E. F. Knipling of the United States Department of Agriculture (USDA).

Serebrovskii moved ahead with an idea of translocation of segments between two chromosomes resulted in the formation of gametes with lethal genetic duplications and deficiencies in heterozygotes due to an abnormal association of four chromosomes during meiosis which was considered to be partial sterility. In this line, he started the work on translocations in *Musca domestica* L. and *Calandra granaria* L., practically but presumably was impossible to continue due to catastrophic conditions during World War II and death of Serebrovskii in 1948.

In the 1930s and 1940s, Vanderplank and his colleagues attempted to control the insect pests based on the sterility in the hybrids from the crossing over of species. Complete and partial sterility was achieved in males and females of hybrids that resulted from crossings of *Glossina morsitans* and *G. swynnertoni.* The field release of *G. morsitans* pupae in an area with *G. swynnertoni* virtually eliminated the less numerous *G. swynnertoni* population. Besides, the arid climate supported the non-establishment of the *G.morsitans* to establish permanently. The lack of publicity of this remarkable trial for longer periods resulted in the failure of further trials and its establishment.

Fig.1 Edward F. Knipling

Further, the successful debut of development and practical applicability of the SIT occurred in the 1950s in the USA under E. P. Knipling's leadership (Fig. 1). The basis of mass rearing of insects and sexually sterilizing the insects with radiation-induced dominant lethal mutations, proposed by H. J. Muller helped him to transfer the concept into reality. Through these ideas, Knipling and his colleagues achieved success in sterilization of the screwworm flies by radiation without damaging their mating ability or diminishing their longevity. The first decisive test that confirmed the feasibility of SIT was implemented in 1954 on the island of Curacao, close to Venezuela. It is culminated to be the most successful AW-IPM Programme integrating the SIT till date. Following the success of SIT in curacao, this approach was applied in various places (Table 1).

Dose levels for sterilization in insect orders

Selection of the dose for the irradiation acts to be critical factor in SIT. Doses ought to be chosen by minimizing somatic damage (allowing normal insect behavior), normal mating performance, flight ability, longevity, fertility, and fecundity levels. As an effort of wide number of studies, radiation doses to achieve sterility in insects belonging to various taxonomic orders are predicted. The mean dose for sterilization ranges from 130 to 400 Gy in Lepidoptera, 30 to 280 Gy in Acari, 40 to 200 Gy in Coleoptera, 10 to 180 Gy in Hemiptera, 20 to 160 Gy in Diptera, 20 to 150 Gy in Araneae, 5 to 140 Gy in Dictyoptera, 100 Gy

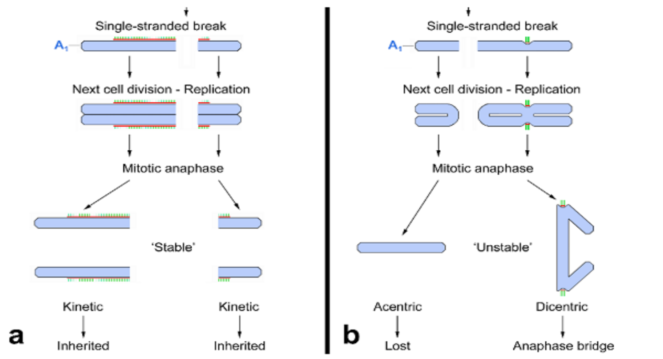

Fig. 2: Comparison of structure of holokinetic and monocentric mitotic chromosomes and consequences of chromosome breakage

in Thysanoptera, and 4 Gy in Orthoptera. Acrididae (Orthoptera) and Blaberidae (Dictyoptera) were the most radiosensitive (<5 Gy) (Bakri et al., 2005).

SIT in Dipterans and Lepidopterans

Research activities towards different insect orders displayed differences in radio sensitivity. Many have considered that SIT is less effective for Lepidopterans in comparison to the other insect orders (much exploited Dipterans) given their high resistance to ionizing radiation requiring higher doses of γ-rays or X-rays to induce complete sterility. These higher doses result in genetic damage and various physiological defects which reduce the ability of sterile moths to compete with wild ones. The genetic studies on this aspect revealed specific cytogenetic and cytological features of Lepidoptera about SIT. The main differentiating features of Lepidoptera are (i) female heterogamety, which is associated with the achiasmatic mode of female meiosis, (ii) the holokinetic structure of chromosomes, which significantly contributes to the radio resistance, and (iii) dichotomous spermatogenesis (apyrene and eupyrene), which is closely related to the competitiveness of males. Hence, the designing of SIT for Lepidopterans should be done with the consideration of these points.

Genetics of SIT differentiating Dipterans and Lepidopterans

The main feature of SIT is Dominant Lethal Mutations (DLMs) in the sex chromosomes upon irradiation. The primary event leading to DLMs is a break in the chromosome induced by radiation. In the series of events of fusion and division, the broken chromosome undergoes normal replication during early prophase, but during metaphase the broken ends can fuse leading to the formation of a dicentric chromosome and an acentric fragment. The acentric fragment is frequently lost, while the dicentric fragment forms a bridge at anaphase leading to another chromosomal break. This whole process then repeats itself, leading to the accumulation of serious imbalances in the genetic information of

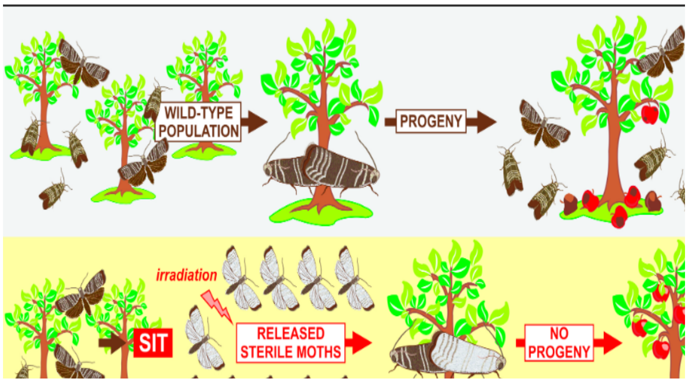

Fig. 3. Illustration of SIT

the daughter cells. The accumulation of this genetic damage finally leads to the death of the zygote (Fig. 2). While in Lepidopterans, it doesn't follow classical breakage fusion bridge cycle which is a characteristic of dominant lethal. The kinetochore plates are large and cover a significant portion of the chromosome length, ensuring that more radiation-induced breaks will not lead to the loss of chromosome fragments in comparision to monocentric chromosomes (Fig. 2). The holokinetic chromosomes possess special character wherein the fragments could persist for a number of mitotic cell divisions and even transmit through germ cells to the next generation. The plates also reduce the risk of lethality due to formation of dicentric chromosomes, acentric fragments and other unstable aberrations.

Inherited Sterility in Lepidopterans

The term 'inherited sterility' (IS) or 'F_1 sterility' refers to the phenomenon where F_1 off springs exhibit a higher level of sterility than the parents that are irradiated with sub sterilizing doses of ionizing radiation. Additionally, radiation-induced deleterious effects can be inherited for several generations. IS was first reported in the silkworm, *Bombyx mori* L., and then confirmed in the wax moth, *Galleria mellonella* (L.) but due to the lack of publication, the concept was completely forgotten. Much later, the phenomenon of IS was rediscovered in the codling moth, *Cyadia pomonella* (Proverbs, 1962). The radio sensitivity nature of the females than males make IS very appropriate for pest control programs, because lower doses of radiation increase the quality and competitiveness of the released insects. The studies by Marec et al., 1999 reported the translocations as the main chromosomal mechanism of IS. The study also suggested modified Synaptonemal Complexes in the achiasmatic meiosis of females and the ability to invert the order of the main meiotic events in males. Both the modified SCs and the so-called inverted meiosis facilitate proper chromosome segregation and hence rescue the fertility of heterozygotes for chromosomal aberrations, as recently demonstrated in wood white butterflies of the genus *Leptidea* (Lukhtanov et al., 2018).

SIT as Area Wide Integrated Pest Management Strategy (AW-IPM)

AW-IPM is defined as the Integrated Pest Management applied within a delimited geographical area against an entire pest population with a minimum size large enough or protected by a buffer zone so that natural dispersal of the population occurs only within this area. Suppressing highly mobile pests on an area-wide basis is usually more benign environmentally, more effective, and more profitable, than on a farm-by-farm basis because of economies of scale. Area wide programmes to be effective, can take an advantage of power and selectivity of specialized methods for the management of the insect pests unlike farm-by-farm basis. The SIT turns out to be pest specific autocidal method and hence can form the component of AW-IPM and also AW-IPM serves to critical approach for SIT to be effective. The SIT requires the mass rearing of the large numbers of the target pest species followed by exposing them to ionizing radiation to induce sexual sterility and releasing them on area wide basis at appropriate proportions for the pest suppression. The major pest management strategic options include suppression, eradication of well-established pest populations, containment (exclusion) and prevention of invasive pest establishment. SIT being pest-specific play a role in implementing all of these area-wide strategies (Fig. 3).

Local Suppression of pest populations

Since 1981, a trial on local suppression of the Onion maggot fly, *Delia antiqua* (Meigen) has been carried out on an area of ca.10000 ha in Netherland through SIT. But indeed the free riders (growers in the release area who benefit but do not pay) has weakened the programme leading to only 40 % of extension in onion producing area. Additionally, as the onion fields receiving sterile flies do not form a contiguous block the success of the programme is hindered (Everaarts, 2016).

SIT and Total population suppression

The SIT could be applied for population suppression than the eradication. AW-IPM programmes using the SIT for suppression were established against the Mediterranean fruit fly in some fruit-producing areas of Israel, Jordan, and the Territories under the Jurisdiction of the Palestinian Authority. These programmes benefitted in terms of net returns than the SIT with eradication as the eradication programme would have payback period of 4 years. Codling moth in Canada was successfully reduced with the SIT suppression programme and it also reduced the number of insecticidal sprays. Similar success was achieved in South Africa (Bloem et al., 2001; Boersma 2021; Nelson et al., 2021).

Eradication of well established populations

Eradication of the pest refers to the sustainable removal of every individual of the pest species in an area surrounded by natural or man-made barriers sufficiently effective to prevent reinvasion. An AW-IPM containing SIT was successfully implemented to eradicate New World screwworm in its native range in the southern USA, Mexico, and Central America. Similarly, using the programme ,pink bollworm in southern USA and northern Mexico, Mediterranean fruit fly in areas of Argentina, Chile, USA, and Mexico and the melon fly *Zeugodacus cucurbitae* (Coquillett) in the Okinawa archipelago of Japan was eradicated using the SIT as area wide programme (Staten and Walters, 2021; Kuba et al. 1996; Enkerlin,2021). Successful eradication of tsetse population from the Island of Unguja, Zanzibar, Niayes area of Senegal (Vreysen et al., 2000; Vreysen et al., 2021).

SIT and Containment and prevention of invasive pest populations

For containment strategy, examples include barrier development for sterile New World screwworm flies is maintained to contain the screwworm at the Panama-Columbia border (Vargas-Terán et al., 2021) and sterile Mediterranean fruit flies is maintained to exclude this pest from Mexico (Enkerlin et al., 2017). Sterile pink boll worms were released in California's San Joaquin Valley to prevent the pest from establishing on cotton. Similarly, preventive releases of the male-only strain of the Mediterranean fruit fly over the Los Angeles Basin in California and major metropolitan areas in Florida was carried out (Hendrichs et al., 2021)

Misconceptions and Constraints of SIT

SIT though applicable against wide variety of invertebrate pests, it is practically exploited against few major pests. This may be due to persistence of some common misconceptions but mainly due to some constraints. Some of the common misconceptions include: (1) released insects retain residual radiation (2) females must be monogamous (3) released males must be fully sterile (4) eradication is the only goal (5) the SIT is too sophisticated for developing countries and (6) the SIT is not a component of an area-wide integrated pest management (AW- IPM) strategy. The two most evident constraints include reduced competitiveness of releasing sterile males and the perceived high expenses of the SIT. The high up-front costs and limited private investments serves to be serious constraints. Apart from that, insufficiently trained, funded or committed managers and limited support hinders the success of SIT application. Further, SIT compels the strategic research in ecology, genetics, population dynamics and insect behavior. Studies on the increasing the competitiveness of released sterile males remains the major research objective.

Future developments of SIT

Applicability of the SIT technology in the AW-IPM program is increasing and will continue to increase due to burgeoning negative impacts of the chemical pesticides' usage and public's concern towards the cleaner environment and residue free food. In this view,efforts for the improvement of overall effectiveness and efficiency of the technique and research for the expansion of the technique for the new key pest species are necessary. The story line of development and application of the technology against many insect species aroused few concerns that needs to be addressed *viz.,* artificial rearing systems or obligate diapauses *etc*. Increased globalization has and will inevitably lead to a further rise in the invasion of non-native or invasive insect pests into new areas and increased survivability due a changing climate. These situations and identified technical bottlenecks in the mass rearing, sterilizing and releasing of the sterile insects provides the avenue for newer opportunities to integrate the SIT into the process of creating pest free or low prevalence areas under a systems approach. Modern biotechnological approaches such as transgenesis and gene editing and paratransgenesis will contribute in improving SIT efficiency in terms of strain marking, genetic sexing, molecular sterilization and disease refractoriness. Exposing male insects to hormonal, nutritional, microbiological, and semiochemical supplements appears to hold great potential for enhancing sterile male performance. Furthermore, there will be significant improvement of mother colony management to reduce the effects of colonization and to slow down mass-rearing effects on key behavioral parameters that often result in rapid colony deterioration. Progress pertaining to the cost-effectiveness of all components of SIT implementation, from cage design to facility design, and from programme planning to evaluation will be made. The concept of sterile insects for pest suppression rather than the eradication, particularly in commercially important commodities will favour the involvement of the private sector and hence accelerate these improvements. *i.e*. Considering the benefits of sterile insects, their expertise with managing live creatures, and their knowledge of the biological control industry, commercial producers of beneficial insects will likely be the natural investors. As the program for the pest control is logistically complex, management plays to be a critical factor for determining the success and failure of any area wide approach. Hence, spite of the many successes achieved and to be expected, in many least-developed countries the SIT may be a technology that is "ahead of its time".

Conclusion

The public's concern towards the residue free produce, less aggressive pest control methods emphasize the need of target specific, biologically based and sustainable suppression methods. Additionally, Globalization has resulted in more incursions and outbreaks of invasive pests. In current scenario, SIT turns out to be a potential management tool for the need. This approach functions as a component of AW-IPM. Several insects have been successfully targeted and suppressed or eradicated by the application of SIT. This technology is quite successful on Dipteran insects while less effective on the Lepidopterans due to the special cytological and cytogenetic characters. IS plays an eminent role in case of Lepidopternas than SIT. Few studies regarding the IS has proved its potentiality in management of the Lepidopterans. Finally, this approach turns out to be excellent tool for the insect management in the future days.

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