[*In the following pages, the author has reviewed briefly, how pests became a problem, the limitations of available pesticides and alternative methods of control, the difficulties in discovering new pesticides with newer modes of action and the impact of Government regulatory restrictions on the introduction of pesticides, all of which directly affect plant protection strategies of future and hence food production.*]

PESTICIDES, PEST CONTROL AND THEIR FUTURE

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PESTS AND PESTICIDES

INTENSIFICATION of agriculture brought about the prosperity of many pests. The cultivars had enriched biopolymers but low content of physiologically active substances that deterred insects and thus improved biotic potential of many phytophagous species. Man through agriculture, influenced the constitutents of agro-biocoenoses leading to the rapid development of biotypes, unlike slow natural evolution of biocoenoses through the millenia.

Modern knowledge of plant physiology and biochemistry has contributed to the understanding of the role of secondary metabolites in regulating the vital functions of plant pests. Plant products that are similar to the juvenile harmones and their inhibitors, such as trecapen, alter the humeral regulation of many vital activities of insects and can influence sexual reproduction. Some substances stimulate or inhibit oviposition[1].

In the field of toxicity potentiation, the effects of pesticides are to be investigated in depth. Related interaction in mammals may also include pesticide-drug combinations and influence of pesticides on the immunity reactions. No method is currently known to circumvent the problem of resistance.

THE PESTICIDE INDUSTRY

Pesticide industry emerged between 1918 and 1940. Pesticide use in agriculture was not popular. Labour was cheap, food was abundant at that time. The second world war stimulated pesticide research. The usefulness of DDT, its wide spectrum of activity, its residual action, all appeared miraculous[2].

The publication *Silent Spring*, appeared in 1962. Soon pesticides became more suspect. Rachel Carson's criticism was mostly emotional. The environmentalist became even more vocal.

Now, the chance of finding one commercially useful pesticide is 1 in 10,000 to 15,000. World-wide, annually 200,000 pesticides are being screened. It takes 8–10 years and 20 million dollars before all the data required by the regulatory authorities are provided. After this, the company has only 8–10 years before its patent expires. Due to enormous costs involved in the pesticide research, many companies have merged their agrochemical research interests. The pesticide development programme is multidisciplinary and considerable management skills are required to control and make a success of the programme.

PESTICIDES—THEIR LIMITATIONS

The criteria by which pest control methods are judged are:

Practical utility, efficacy, safety to crop, availability, ease of application, attrition due to development of resistance, safety to man during production, transport, storage, application and effects following application.

Ecological safety: Permanence, mobility after application, biological spectrum and above all the cost and risk benefit to the user.

The views expressed by the author are not necessarily those of the Management.

The defects of pesticides are many. With fungicides, the control is often inadequate or lacking, as in the post harvest fungal rots, bacterial diseases, soilborne root rots, the vascular wilts and virus diseases. Herbicidal control is unsatisfactory with weeds like *Cyperus*, *Cynodon*, *Digitaria*, *Salvinia*, *Eichhornia*, the parastic weeds *Striga*, and *Orobanche*.

With insecticides, there is the problem of resistance to many compounds.

Activity spectrum

An ideal pesticide should kill only the target insect. This is not so in practice. Beneficial insects are also affected by pesticides. Pest resurgence is not necessarily due to the elimination of predators and parasites.

Insecticides that are specific to pests are useful but as they require greater developmental outlay and fixed costs,are not attractive for the industry.

Target resistance

Resistance will occur when the population already contains some individuals (propagules) which are able to survive pesticide fortuitously. Organisms can acquire inheritable resistance in the life-time. Pesticides can increase the mutation rate[3]. Benomyl is mutagenic to *Fusarium* at sublethal doses[4]. The resistance could be due to detoxification of the chemicals by microsomal enzymes, reduced uptake, or to altered site of action, or the insect may avoid, the pesticide by behavioural response[5].

Cross resistance may occur in the same chemical group and also in chemically unrelated pesticides. The molecular basis for cross resistance is not fully understood[6]. The sequential pattern of cross resistance which developed in the house fly will be useful in planning strategies of efficient sequence of use of pesticide on related pests[7,8].

There are over 360 pests which are resistant to pesticides. Resistance has also been reported in beneficial insects that are natural enemies of pests[9]. The problem of resistance is being tackled by developing more effective synergists at present. Resistance to benomyl was found even before its commercial introduction[10–12]. There are a few reports of resistance to herbicides also[13,14].

Human safety

The public can become exposed to pesticides in the form of treated crops. The intake of pesticided residues in/or on tolerances based on toxicological evaluation of acceptable daily intake (ADI). ADI has a large safety margin.

The most important pesticide contaminants of food are organochlorines[15]. DDT is the most widely used insecticide in the world. Considering that populations have been exposed to it for long periods of time and that those in production had exposures 200 times more than that received by the public and that over 3 million tonnes have been produced and used to date, it appears reasonable to conclude that DDT is not hazardous to man. DDT eliminated the threat of malaria which killed over 1000 million people in the world[16]. Most of the present day pesticides are not persistent in the environment. "There is, as yet, no experimental or conclusive evidence that the survival of any species has been threatened by the use of insecticides[15]." Herbicides seem to cause little direct harm to wild life.

Impurities in a product can cause problems like TCDD in 2,4,5-T. There are reports of 80 ppm of dioxin in some cases of manufacture of 2,4,5-T. The acute oral LD_{50} of dioxin is 0.002 mg/kg to guinea pig[17]. Pesticides are not the only poisons contaminating food. Toxicants can be of plant and animal origin also[18]. Mycotoxins like aflatoxin, patulin are potential carcinogens and also some of the chitin moults of grain pests like *Tribolium castaneum* which contain quinones[19]. Benzpyrene formed during burning of fossil fuels is widespread in the environment and is also a carcinogen[20].

Economics

The avoidable losses due to pests, diseases and mites, and grain damage due to storage pests, rodents, birds, etc., are estimated at 5000 crores per annum in India. Currently with Rs. 300 crores being spent on pesticides we are possibly protecting crop loses upto Rs. 1000 crores. With the pesticides, the cost benefit varies from crop to crop. The use of pesticides involves relatively small inputs of energy, probably less than 2% of the total input in agriculture[21].

METHODS OTHER THAN CHEMICAL CONTROL

The future of pesticides depends on the available alternative methods of control. Let us see their merits.

Viruses

The best known insect viruses are in the baculovirus group. They are nuclear polyhedrosis viruses (NPV) and the granulosis viruses (GV). These affect 350 species of insects[22]. The cytoplasmic polyhedrosis viruses (CPV), resemble pathogenic viruses of vertebrates and may pose safety risk.

In plant protection, *Heliothis* NPV is the most important[23,24]. Some of them have been commercialised. These viruses are sensitive to UV light, temperature and pH[25,26]. They are slow to act[27]. Viruses being obligate, their production requires live host. Multiplying them in tissue cultures holds promise. One is not certain that a viral preparation is free from contaminants, which could be allergens.

The European rabbit has developed genetic resistance to myxoma virus which was used in killing it[28]. Some naturally occurring strains of insects may be resistant to viruses. A strain of *Pieris brassicae* L. was a thousand times resistant to granulosis virus than the susceptible strain. Being host specific, viruses are safe to man. There is a remote possibility of a recombination between an insect virus and genes of a vertebrate virus[29].

For developing a virus the initial costs are greater in preliminary bioassay, testing for pathogenicity on non-target organisms and field trials. Absence of patent protection for virus was a disadvantage, but now with advances in biotechnology this aspect will be taken care of. A major difficulty will be in establishing if the virus multiplied has not changed through the passage of time. Serotyping will be useful for this purpose. Multiplying viruses in yeasts or bacteria through genetic engineering may simplify production technology.

Bacteria

Bacillus popilliae Dutky, *B. lentimorbus* Dutky and *B. thuringiensis.* Berliner are in use at present. Some of these are registered as pesticides.

The spores responsible for the biolgoical activity of *B. thuringiensis* contain crystals of an endotoxin, a polypetide causing paralyses and epithelial break down of the gut of lepidoptera, in 10–20 minutes[30]. There is also an exotoxin. This is an adenine nucleotide which is a competitive inhibitor of RNA polymerase. There are over 130 spp. of insects susceptible to *B. thuringiensis.*

These bacteria can be grown by the usual fermentation methods. Field resistance has not been observed, but *in vitro* endotoxin resistance has been demonstrated[31].

Bacteria once introduced into environment may persist and there is the lurking fear about the human safety of bacteria, especially if mutants appear[32].

Fungi

Beauveria bassiana (Balsamo) Vuillemin causes the muscardine disease of silkworms. *Metarhizium anisopliae* (Metchinkoff) Sorokin was used to kill beetle larvae by Russians[33]. There are over 35 genera of fungi which infect insects. Recently, *Hirsutella thomsoni* is being tested as a mycoacaricide in USA[34]. Rishbeth[35] used asexual spores of *Peniophora gigantea* (Fr.) Massee on the freshly cut pine stumps to prevent infection by *Fomes annosus* (Fr.) Cooke in East Anglia. Nematode capturing fungi were studied in detail but they are of little use[36]. Control of skeleton weed *Chondrilla juncea* L. by *Colletotrichum gloeosporioides* is very well known[37]. While there is not much of evidence on resistance, the fungi can cause allergies. The results with fungal control have been variable and hence the future remains doubtful.

Rickettsiae, Protozoa and Nematodes

Rickettsiae have several disadvantages. They are associated with diseases of man, like typhus and trench fever. *Ricketsiella melolonthae* which infects cockchafer beetles can infect mammals lethally. Protozoa pose difficulties as living hosts are required for culturing them. They are debilitating parasites and there is no disruption of any vital function by them and hence slow in action.

Nematodes of mermethidae group are promising in mosquitoes. But, most trials indicated unsatisfactory control[38].

Control by insects

Many insect pests are controlled by parasites, predators or both. The first attempt to control weeds by insects was made in India in 1863[39]. The best known example is the control of *Opuntia inermis* De Candolle in Austrialia by *Cactoblastis cactorum* Berg. *Trichogramma* is a well known egg parasite for controlling several insect spp. including *Heliothis* and *Pectinophora* of cotton. According to De Bach[40,41] nearly 120 spp. falling into 9 major orders are controlled by insects, 42 completely, 48 substantially and 30 indifferently. Over 30 weeds have been controlled totally or partially by biological means.

For successful biological control the released insects should have (a) good searching ability, (b) high degree of host specificity, (c) high reproductive capacity with reference to the prey, and (d) adaptability over a wide range of conditions.

Genetic Control

Artificial sterialization of insects, and releasing them into wild population is the autocidal method. Insecticides generally tend to be efficient when the populations are large while the sterile insect method becomes progressively more efficient. The difficulty is in mass rearing of insects[49]. The sterilization should not reduce the competitiveness of the insect in copulation. Insects are sterilized with gamma radiation. Chemical sterilants are good but they are alkylating agents and possibly mutagenic[42]. The other methods are dominant lethal mutation by genetic contrivance using translocation heterozygotes, triploids, sterile hybrids or cytoplasmic incompatability. The scope is vast but genetic manipulation should be viewed with some caution.

Breeding for resistance and cultural control

Resistant plants may become susceptible soon and instances are many.

In cultural control, methods are simple timing operations, crop rotation, plant sanitation destruction of pest hosts, trap crops, water management and other good farm practices.

Physical Methods of Control

Some mineral oils asphyxiate insects, inert dusts like tricalcium phosphate are abrasive, there are others like drione acting on cuticle or absorb water from the insect and kill them by desiccation.

Irradiation of stored grains from a cobalt or cesium source has been used by Sehgal[43] reported that the irradiated wheat might cause polyploidy in humans.

Sonic energy for grain pests and ultra high frequency electromagnetic fields and microwave radiations to kill weeds are most unlikely to replace the chemical methods.

IMPROVED USAGE OF PESTICIDES

With conventional methods most of the pesticides applied on plants are wasted. The insecticide actually taken by the insects varies from 0.03% to 6% of the total pesticide applied[44,45]. Additives may play an important part in future formulations and it is necessary to define the partition coefficients for penetrating the lipid barrier of plants, for herbicides. There is an urgent need for improved spreaders, stickers, wetting agents, dispersants, defoamers and anticaking agents. Controlled release, or microencapsulation of pesticides by interfacial polymerization or other techniques will be developed for toxic chemicals. Improved methods of spraying like electrodyne and electrostatic spraying are being tested. The controlled droplet application recognized the concept of optimum droplet sizes and the lowest effective diluent rate for a given crop/pest situation. A new development is herbigation in which herbicide is distributed through irrigation water.

It is very unfortunate that there is a world-wide lack of harmonization of safety testing requirements. Some of the countries have enforced these requirements without sufficient scientific manpower or facilities to police the legislation. It is earnestly felt that FAO/WHO will ultimately harmonize the safety testing requirements.

NEW DEVELOPMENTS IN PLANT PROTECTION CHEMICALS

Introduction of the chemotherapeutant benomyl in 1967 revolutionized the fungicidal control of plant diseases. But, systemics being largely single site action chemicals, there have been many cases of resistance.

Systemics are not active against phycomycetes. There are exceptions like metalaxyl, pyroxychlor, and prothiocarb. Many are apoplastic in plants, while some are symplastic.

Recently a group of several fungicides has been discovered which inhibit ergosterol biosynthesis. They are triarimol, fenarimol, triforine, triadimefon, biloxazol, clotrimazol, imazolil, nuarimol, phenapronil, fluotrimazol, fenpropemorph, prochloraz, and diclobutrazol[46-49].

Phytoalexins, are antifungal compounds elicited by plants through infection by pathogens. Over 100 different phytoalexins have been characterised. Some of the isoflavonoid group of phytoalexins are kievitone, maackiain, medicarpin, phaseolin, sativan and vestitol. A fragment of β glucan from the cell wall of soybean pathogen could elicit the production of glyceolloin, a soybean phytoalexin[50,51]. The molecules require defined stereoisomers for activity rendering commercial scale production difficult, expensive and hence unattractive to the industry.

Herbicides and growth regulators

Some of the growth regulators are being used for terminating the crop to prevent the build up of pests. May be auxins, gibberillins, cytokinins, abscissic acid, ethylene will be used in crops and there is a great need for antitranspirants for crops in dry land farming and drought-prone areas. There could also be investigation into areas for herbicide protectants and antidotes for application in field.

There are instances where plants release into the rhizosphere chemicals (allelopaths) which affect the growth of associated plants. Known allelopaths are simple compounds. Probably greater search is needed for allelopaths that can be copied or modified to be useful as herbicides.

Insecticides

The major insecticide groups are organochlorines, organophosphates, carbamates and recently introduced synthetic pyrethroids. Carbamates and organophosphates mimic synaptic transmitter acetylcholine and inhibit acetylcholine esterase. Resistance resulting from a modified AChE in mites and insects has been reported[52]. The fundamental studies on structure activity relationships has led to the synthesis of permethrin, cypermethrin, deltamethrin, fenvalerate, cyfluthrin, vivithrin and cyhalothrin and many others. These are very active chemicals[53,54].

The synthetic pyrethroids, interfere with axonal transmission. Rojakovick and March[55] have shown that chinomethionate, an acaricide/fungicide is a potent inhibitor of phosphodiesterase which degrades cyclic AMP. This is an area of activity worth exploring further.

NEWER MODES OF ACTION

Juvenile Harmones

The harmone maintains the insect in a juvenile state but when its secretion stops the insect matures[56]. An insect subjected to this harmone at the wrong time in its life cycle will be affected lethally and hence the time of application is important. These may find useful application in public health and animal health. Some plants are known to contain chemicals which are antijuvenile harmone in activity and they are antiallatrotrophic chemicals[57]. These chemicals can induce precoicious metamorphosis (precocenes).

Ecdysis harmones

Ecdysone largely controls moulting in insects. These are steroids and as the endocrine system of humans is partly based on steroids safety testing becomes important. Amongst these chemicals, diflubenzuron has been commercialized. This chemical interferes with moulting. The larvae are unable to split the exuviae and come out[58]. UDP-N-acetyl glucosamine the immediate precursor of chitin accumulates in the presence of diflubenzuron. Insecticides resistant to house flies have shown cross resistance to diflubenzuron *in vitro*[59].

Attractants and repellants

Methyl eugenol, protein hydrolysate and farnesol in apple wax are all attractants[60,61]. There are many insect pheromones; some stimulate aggregation, trail following, dispersion, sexual behaviour, oviposition, alarm and specialized behaviour in social colonies[62]. The pheromones are mixtures and cross mating is possibly prevented by the nature of these mixtures. Pheromones used on crops at a few grams per hectare are known to disrupt the mating for weeks due to habituation[63]. They may also possibly attract predators. The scope for repellants in agriculture is not attractive. They may be useful in public health and animal husbandry.

Chemosterilants

As most of the chemosterilants are alkylating agents, they are mutagenic and hence unsafe and possibly cannot replace irradiation for autocidal control. They can be used with a lure to attract insects and sterilise them. By "Booby trapping" the females, the copulating males are contaminated. Insect growth regulators have been shown to sterilize females and more rarely males[64]. Proverbs reported resistance to chemosterilants also[65].

INTEGRATED PEST MANAGEMENT

There has been great accent on the integrated pest management recently to curtail the additive load of pesticides in the environment. What is the optimum strategy in any particular situation is debatable. We require an integrated knowledge of a vast amount of information on population dynamics of the pest, its natural predators and parasites, of ecology, epidemiology of disease, economics of cropping systems, which are most variable, and the complex interrelationships of all the edaphic and biotic factors in the environment. This would necessitate newer advanced approach involving introduction of systems analysis and construction of mathematical models and the computerizing data which will reduce to a large measure the empiricism which is plaguing the development of integrated pest control[66].

THE OUTLOOK

Due to population and economic pressures it is likely that the following trends in agriculture will emerge with greater accent on pesticide usage.

(i) Intensification of agriculture on existing land and opening up of non-traditional areas.

(ii) The inputs dependent on non-renewable source of energy will increase in cost considerably.

(iii) In developed countries there will be a marked shift from animal to crop production programmes.

(iv) In developing countries with newer cultivars, there will be more of monoculture. There will be greater accent on cash crops, with emphasis on grain protection in storage.

It is estimated the use of plant protection chemicals will increase by atleast five fold by the turn of the century[44]. The future of pesticides is bright.

ACKNOWLEDGEMENTS

The author is thankful to Dr. C. A. Varghese, President of Rallis India Limited for permission to publish this article.

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