Insecticide resistance and its management

The resistance challenge

Arthropod pests can cause direct feeding damage to crops, transmit plant viruses and present contamination issues. Like all living organisms, they have adapted over millions of years to their environment. By colonising crops, however, their pace of evolution has accelerated to contend with the chemical control tactics used against them. This process has resulted in various forms of insecticide resistance developing. This resistance is present in a range of crop pests, including aphids, whiteflies, thrips, beetles and spider mites.

What is resistance?

Resistance can be defined as 'a heritable change in the sensitivity of a pest population that is reflected in the repeated failure of a product to achieve the expected level of control, when used according to the label recommendation for that pest species'. Cross-resistance occurs when resistance to one insecticide confers resistance to another insecticide, even where the pest has not been exposed to the latter product. As pests can reproduce quickly and because their populations are often large, there is always a risk that insecticide resistance may evolve and spread, especially when insecticides are misused.

History of insecticide resistance

Synthetic organic insecticides were introduced in the 1940s (e.g. DDT) and it was not long before the first cases of resistance were detected. By 1947, resistance to DDT was confirmed in houseflies. With every new insecticide introduction (e.g. cyclodienes, organophosphates, carbamates, formamidines, pyrethroids, *Bacillus thuringiensis*, spinosyns, neonicotinoids and diamides), cases of resistance developed in key pest species two to 20 years later. The length of this process is dependent on a range of factors (see below). Interestingly, some species appear to be more likely to evolve resistance than others.

How does resistance happen?

When an insecticide is first introduced, the pest(s) it targets are usually controlled effectively. All living species show diversity that arises from naturally occurring mutations. Resistance occurs by natural selection. Initially, pests carrying resistance genes are rare. When an insecticide is used, pests with resistance genes are more likely to survive and pass on the resistance traits to their offspring.

Through continued application of insecticides with the same mode of action (MoA), selection for resistant individuals continues, while susceptible individuals are eliminated. As a result, the proportion of resistant individuals in the population increases. The resistant forms become increasingly difficult to control at the label rate. This often leads to more frequent applications of the insecticide, which accelerates the development of resistance. This phenomenon has been described as the 'pesticide treadmill'. Eventually, users switch to another pesticide, if one is available. The genetics of the heritable resistance traits and the intensive repeated application of pesticides together are responsible for the rapid build-up of resistance in most pests.

The speed with which resistance develops depends on several factors, including how fast the pests reproduce, population size, the migration and host range of the pest, the availability of nearby susceptible populations, the persistence and specificity of the plant protection product, and the rate, timing, number of applications made and method of treatment. Resistance increases fastest in

situations such as greenhouses; where pests reproduce quickly, there is little or no immigration of susceptible individuals and when pests are subjected to frequent sprays.

What are the mechanisms of insecticide resistance?

There are four main broad groups of resistance mechanism.

1. *Target-site resistance*

In pests carrying this type of resistance, a mutation occurs in the various target proteins that insecticides normally bind to and block or inactivate. The result is that the proteins are no longer sensitive to the insecticidal effect. Several target-site mechanisms are known and may occur in the same species. For example, in the peach–potato aphid (*Myzus persicae*) the following mechanisms are known to be present – in addition to metabolic (esterase) resistance:

Knockdown resistance – '**kdr' and 'super-kdr'**: Pyrethroids act on a protein in part of the aphids' nervous system called a sodium channel. This is responsible for the passage of signals along the nerve. The insecticides hold these channels 'open' so that the nervous system becomes overexcited, leading to the death of the pests. Aphids with kdr or super-kdr (an enhanced form) contain a modified sodium channel protein, insensitive specifically to pyrethroids. Both types of kdr mechanism can be detected in simple insecticide bioassays. They can also be detected by DNA-based tests. Aphids either do or do not have kdr/super-kdr. **Kdr confers moderate levels of resistance and super-kdr confers high levels of resistance**.

MACE (**M**odified **A**cetyl**C**holin**E**sterase): Organophosphate (OP) and carbamate insecticides affect an enzyme (acetylcholinesterase) that regulates the flow of a chemical messenger across the gap (synapse) between a pest's nerve cells. The disruption kills the pest. In MACE aphids, this disruption process does not occur effectively. Aphids either do or do not have the MACE mechanism. It can be detected by biochemical or DNA-based tests. Peach–potato aphids with this type of resistance are highly resistant to pirimicarb (a carbamate). In the UK, pirimicarb is the only approved insecticide affected by MACE resistance. It is not approved for use on broad acre crops in the UK.

Neonicotinoid resistance (Nic-R++): Low levels of resistance to neonicotinoids were observed in certain peach–potato aphid populations soon after the first neonicotinoid, imidacloprid, was introduced in the early 1990s. The initial resistance was due to a combination of enhanced expression of a gene responsible for the detoxification of neonicotinoids and/or reduced penetration of neonicotinoids through the aphid cuticle. The low levels of resistance meant pests were still controlled effectively at recommended rates in the field. In 2009, the situation changed when a clone of peach–potato aphid (collected from peach in southern France) showed strong resistance to neonicotinoids. Subsequently, highly resistant aphids have been found on other hosts in southern Europe and North Africa and, most recently, in Belgium. Resistance is conferred by a simple point mutation which renders the insecticide target immune to neonicotinoids. To date, no neonicotinoid control failures or resistant forms have been reported in the UK.

2. *Metabolic resistance*

Pests carrying this type of resistance make increased amounts of certain enzymes which break down or wrap up (sequester) insecticide molecules before they reach their target sites (these target sites are primarily in the insect nervous system). In pollen beetles, overproduction of a specific P450 enzyme confers resistance to pyrethroids. In peach–potato aphids, overproduction of two different esterase enzymes confers resistance primarily to organophosphates (OPs), although carbamates and pyrethroids are also affected to a lesser extent. Individual aphids can contain different amounts of esterases and are categorised as being either: S (susceptible), R_1 (moderately resistant), R_2 (highly resistant) or R_3 (extremely resistant). This species also overproduces P450 enzymes with confers low resistance to neonicotinoids.

3. *Penetration resistance*

Pests with this form of resistance possess modifications of the outer cuticle that can delay the rate at which insecticides penetrate into the body cavity. Penetration resistance is frequently present along

with other forms of resistance, and reduced penetration intensifies the effects of those other mechanisms.

4. *Behavioural resistance*

This form of resistance is where pests evolve behavioural adaptations that reduce the likelihood of being exposed to high concentrations of an insecticide. It seems to be rare in crop pests but more frequent in pests of medical or veterinary importance. This mechanism of resistance has been reported for several classes of insecticides, including organochlorines, organophosphates, carbamates and pyrethroids. Pests may simply stop feeding if they come across certain insecticides or leave the area where spraying occurred (for instance, they may move to the underside of a sprayed leaf, move deeper in the crop canopy or fly away from the target area).

How common are the mechanisms of insecticide resistance?

By monitoring resistance mechanisms over time, trends can be identified and linked to patterns of insecticide use or changes in the environment. The most-studied pest is the peach–potato aphid. Results obtained since 1996 are summarised in Figure 1.

Screening bioassays applying diagnostic insecticide doses to peach-potato aphids continue to show strong resistance to pyrethroids. This is backed up by DNA tests showing that peach-potato aphids carrying the north european (*Ne*) form of super-kdr (conferring strong resistance to pyrethroids) continue to be common and widespread in the GB with them being found in 60% of the samples in 2020. Kdr, conferring moderate pyrethroid resistance, was found in just over 20% of the samples tested in 2020. The testing has not shown that peach potato aphids in GB have both mutations concurrently.

Aphids with high esterase levels (conferring variable resistance to a number of insecticide groups, particularly organophosphates) and MACE (conferring strong resistance to pirimicarb) continue to be found in the samples. Therefore, at present, peach–potato aphids with high levels of resistance to pyrethroids and pirimicarb predominate across the UK.

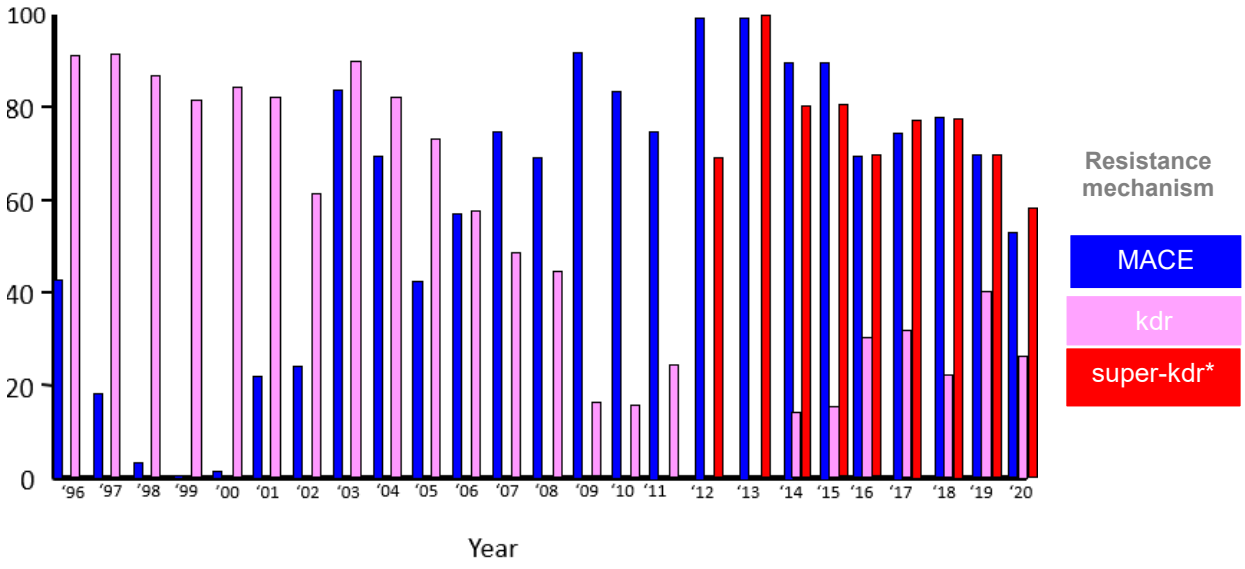

Figure 1: Percentage of UK field samples of peach–potato aphid with MACE, kdr or super-kdr aphids. *Super-kdr testing commenced in 2012. (Data courtesy of the 'Monitoring for resistance in UK pests' project).

Peach–potato aphids that carry strong neonicotinoid resistance (conferred by a combination of a metabolic mechanism and a target site mechanism) are now common in some peach growing regions of southern mainland Europe and have spread to Greece, North Africa and Belgium and are now found on other crops, such as sugar beet. There is no evidence of strong resistance to neonicotinoids in aphid populations in the UK. The situation is being monitored carefully in this country and guidelines will be updated if the resistance status changes.

The maximum number of applications of any neonicotinoid-containing product is a statutory restriction introduced by CRD, in collaboration with IRAG, as a pro-active resistance management measure. Such restrictions take account of exposure of peach–potato aphids to neonicotinoid sprays when they are not the intended target of the spray.

How can insecticide resistance be managed?

- **The first, and most effective, approach to manage resistance is to minimise insecticide use by following appropriate threshold guidance and using integrated pest management (IPM) programmes, including chemical and non-chemical (e.g. resistant crop varieties) means of control.**

- Correct identification of pests is essential to inform the management strategy. Identification resources can be accessed from the AHDB website.

- Pests should be monitored during the period in which the crop is vulnerable and during the early stages of infestation (including within chitting sheds, for potatoes). Monitoring tools can be used to assist monitoring efforts. These include the aphid monitoring tools published at rothamsted.ac.uk/insect-survey and aphmon.fera.co.uk

- Pests should be monitored as long as conditions remain conducive. Aphids in the autumn, for example, will fly if temperatures are above 15°C. They will, however, continue to move within crops at relatively low temperatures. It is hard to be precise about the level of frost needed to deliver a knock-out blow but three to five consecutive days with grass minima dropping below -6°C should cause high aphid mortality.

- Natural fluctuations in pest numbers should be taken into account when making treatment decisions. For example, aphid populations usually 'crash' in July and August and it may be possible to delay spraying.

- Where treatment thresholds are available (see the AHDB *Encyclopaedia of pests and natural enemies in field crops*: ahdb.org.uk/pests), they should be followed to minimise the number of applications and resistance risk in target and non-target species.

- Numbers of natural enemies, such as hoverfly larvae, parasitoid wasps and ladybirds, should be monitored in crops. Although it is risky to rely on natural enemies completely, the application of a selective insecticide should allow them to continue feeding on aphids. Non-selective insecticides, such as pyrethroids, affect a broad range of insect species and will harm natural enemies, affecting the control they provide.

- If an insecticide treatment is deemed necessary, products should be applied at their **full** label rate. Applying insecticides below label rates can lead to a subsequent increase in resistance problems.

- If more than one insecticide application is required, MoAs should be alternated in the spray programme, if available.

- Any tank mixes should take account of the impact to IPM programmes and resistance management strategies.

- No species of pests should be managed in isolation. For example, insecticides used on other aphid species or other pests, such as caterpillars, may impact on peach–potato aphids in the crop, thereby selecting for resistance in both the target pest and peach–potato aphid. Peach–potato aphids, as well as potato aphids, are able to colonise a wide range of crops, including potato, sugar beet, brassicas, lettuce and weeds, as well as various protected crops, including ornamentals. As populations can move from one crop to another, product choice should, ideally, reflect insecticide usage in nearby crops.

Mode of action (MoA)

Information on MoAs is regularly updated by the IRAC (Insecticide Resistance Action Committee):

irac-online.org/modes-of-action

- Careful attention should be paid to insecticide labels. Modern labels often contain general information on resistance management. Labels also detail how many times a product or mode of action (MoA) can be used per crop during a growing season. These restrictions are based on consideration of resistance risks and are intended to sustain the effectiveness of insecticides and prevent resistance occurring.

- If in doubt, advice should be sought from the insecticide manufacturer/retailer or from a BASIS-qualified adviser.

- Treatment efficacy should be monitored at a suitable time after application.

- Be aware that poor control can sometimes be due to poor spray coverage or other factors, and not resistance. For example, many insecticides work through direct contact with the target – including pyrethroids. The performance of such insecticides can be impaired when used on dense canopies or where the pest target is on the underside of the plant leaves.

- **If an insecticide has been applied correctly at the full recommended label rate and it has failed to control the target pest as expected, do not make repeat applications of any insecticide from the same MoA – an alternative should be used. Any potential new resistance concerns should be reported to a BASIS-qualified adviser.**

- Any new suspected cases of resistance should be reported to Dr Steve Foster to arrange for resistance tests to be conducted – stephen.foster@rothamsted.ac.uk. **Please make contact before sending samples.**

- Consideration of resistance risk is a key part of the pesticides approvals process, with companies and the Chemicals Regulation Division (Health and Safety Executive) working closely to ensure appropriate management strategies are in place. IRAG-UK and various resistance research projects also play important roles in informing this process and communicating findings to growers.

Acknowledgements

The 'Background', 'Development' and 'Penetration resistance' and 'Behavioural resistance' sections have been adapted from IRAC (Insecticide Resistance Action Committee) – irac-online.org/about/resistance

Further information

Specific information on a range of crops is available from ahdb.org.uk/irag

- Insecticide resistance status in UK oilseed rape crops
- Insecticide resistance status in UK cereal rape crops
- Insecticide resistance status in UK brassica crops
- Insecticide resistance status in UK potato crops

Efficacy guidelines are available from hse.gov.uk/pesticides/topics/resources.html:

- Efficacy guideline 601 – Resistance warnings on labels of insecticide and acaricide products: hse.gov.uk/pesticides/resources/G/g601.pdf

- Efficacy guideline 606 – Resistance risk analysis and use of resistance management strategies: hse.gov.uk/pesticides/resources/G/g606.pdf

EPPO Standard PP 1/213 Resistance risk analysis: https://pp1.eppo.int/standards/general

Annual reports from the industry-funded insecticide resistance testing project are available from AHDB 21510015 Managing and monitoring insecticide resistance in UK pests