

Review

# A comprehensive review of new pesticides developed between 2015 and 2025

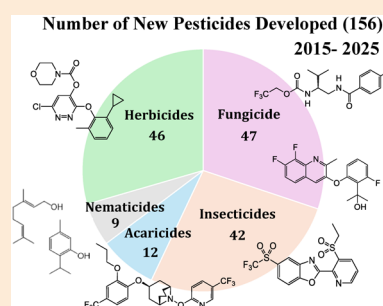
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General trends and strategies for the development of new pesticides are summarized. From 2015 to 2025, 156 chemical pesticides were launched or are under development: 47 fungicides, 54 insecticides/acaricides, 9 nematocides, and 46 herbicides. Most are safe to humans and environmentally friendly. The most developed fungicides are succinate dehydrogenase inhibitors, quinone outside inhibitors, quinone inside inhibitors, and demethylation inhibitors. The general trend of insecticide development is in the progress of four major classes of insecticides: nicotinic insecticides, diamide insecticides, GABA-gated chloride channel allosteric modulators, and insect behavior or growth regulators. Due to the development of resistance to fungicides and insecticides with existing modes of action, many compounds possessing various novel modes of action have been developed. Peptide pesticides and RNAi-based insecticides have been put into practical use. Although no herbicides with novel modes of action appeared for approximately 30 years before 2018, since then eight herbicides with five novel modes of action have emerged, including those for existing herbicides. The development of useful acaricides and nematocides is also progressing.



**Keywords:** new pesticides, novel modes of action, fungicides, insecticides, herbicides, acaricides.

## Introduction

The human use of pesticides began 4,500 years ago when the Sumerians used sulfur compounds to control pests. This was followed by early pest management: before 1000; the use of plant, animal, or mineral derivatives: 1000–1850; the use of inorganic products and industrial byproducts: 1850–1940; the use of synthetic organic compounds: 1940–1970; and the use of lower-risk synthetic organic compounds: 1970 to the present.<sup>1)</sup> After World War II, the organic chemistry-based pesticide industry emerged in Europe and the United States, and various kinds of pesticides have been launched throughout the world. The wave of pesticide science came to Japan, and Japanese-origin pesticides were de-

veloped one after another from the late 20th century to the early 21st century.

Reflecting the current social situation, the pesticides developed and marketed in recent years are not only highly effective but also highly safe for humans, environmentally friendly, and only active on target organisms at low doses. The development of pesticides that pose a lower risk to natural enemies and useful organisms and are compatible with IPM (Integrated Pest Management) has also been an important target.

In our previous review, “Development of novel pesticides in the 21st century,”<sup>2)</sup> we summarized the registration and marketing status, efficacy, action characteristics, and mode of action of 106 chemical pesticides (43 fungicides, 35 insecticides/acaricides, 6 nematocides, 21 herbicides, and 1 safener) that have been developed worldwide from 2007/2008 through the beginning of 2020. In addition, we reported on research into the development of 116 new pesticides, including several compounds that were omitted from the review and compounds with newly assigned ISO common names by October 2020.<sup>3)</sup>

Pesticide development has continued, and many newer pesticides have been developed. In March 2023, a book titled *Trend in Research and Development of Chemical Pesticides, Biopesticides*

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and *Biostimulants* (in Japanese),<sup>4)</sup> overviewing recent pesticide discovery research in the world, was published by the CMC Publishing Co. In the book, which was edited by Umetsu, one of the authors of the current review, 50 Japanese scientists gave an overview of the trends in pesticide discovery research in their area of expertise from around 2015 to the end of 2022. Since significant progress has been made in pesticide discovery research after the book's publication, the contents of the pesticide discovery research, including progress through mid-2024, have been summarized as a series of commentary articles (in Japanese).<sup>5,6)</sup>

This review is an attempt to summarize the overall trends in the research, development, and commercialization of safer and environmentally friendly pesticides from around 2015 until August 2025 based on the information on pesticide discovery research contained in the above book, the commentary articles, and the latest information.

### 1. Strategy for developing new pesticides

The development strategy for creating new pesticides in recent years has been (1) the development of pesticides that are effective at an extremely low dosage, (2) the development of pesticides that are readily degradable and less residual in the environment, (3) the development of selective toxic agrochemicals, and (4) the development of pesticides derived from natural products, as described in the previous review articles.<sup>2)</sup> This trend in pesticide development has become more pronounced during the past decade (2015–2025), and peptide pesticides of natural origins and RNAi (RNA interference)-based pesticides have joined the developmental lineup of new pesticide molecules.

The first strategy resulted in a remarkable decrease in the active ingredient required for the control of pest insects, fungi, mites, nematodes, and weeds and eventually brought about a reduction in the pesticide load on the environment. The second strategy realized a remarkable lowering of pesticide residue levels in crops and the environment. The third strategy of seeking a compound that effectively targets only organisms such as insects, fungi, mites, nematodes, and weeds but is not toxic against non-target organisms such as humans and beneficial organisms was a tool for finding safer and environmentally friendly pesticides.

Some of the pesticides of natural origins—including peptide pesticides and RNAi-based pesticides—are classified as biopesticides.

## 2. Global pesticide sales and pesticide discovery research

### 2.1. Sales by pesticide companies involved in pesticide discovery research worldwide

It is worthwhile seeing the sales figures of domestic and international pesticide companies responsible for developing new pesticides. Figure 1 shows the 2023 sales turnover of major pesticide companies worldwide (AgbioInvestor, 2024). Though the figure includes pesticide companies whose main business is the manufacture and sale of pesticides such as Albaugh and Rainbow,

with \$15,251 M (approximately 2.13 trillion yen, calculated at 140 yen to the dollar) in sales, Syngenta (acquired by ChemChina in 2017) is the top company engaged in pesticide discovery. In second place is Bayer, with \$13,281 M. In third place is BASF, and in fourth place is Corteva Agriscience. Following them are FMC, ADAMA—which is an Israel-based company owned by Chem China—and UPL. Among Japanese companies, Sumitomo Chemical is ranked 8th (\$3,093 M: 433.0 billion yen), followed by Mitsui Chemicals Crop & Life Solutions (hereafter referred to as Mitsui Chemicals CLS) (1,854 million dollars), Kumiai Chemical, Nihon Nohyaku, Nissan Chemical, Ishihara Sanyo Kaisha, Nippon Soda, Hokko Chemical, Agro Kanesho, and OAT Agrio. Despite their relatively small sizes, Japanese pesticide companies are very active in pesticide development.

Recently, many Chinese pesticide companies other than ChemChina (such as Shandong Sino-Agri United Biotechnology, Sinochem, KingAgroot, Jiangsu Yangnong Chemical, *etc.*, see Table 3) have reported on the development of new pesticides; however, these companies' names do not appear in this worldwide sales ranking.

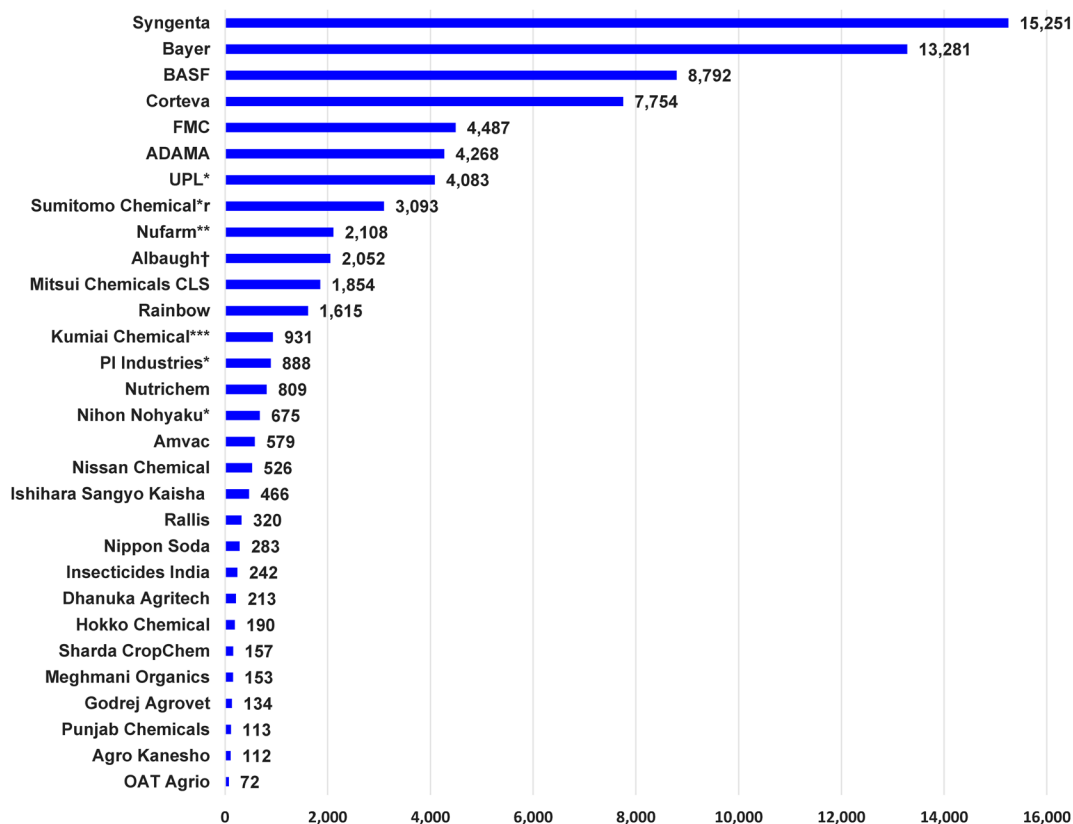
### 2.2. General trends in new pesticide discovery research

Over the past decade (between 2015 and 2025), different kinds of chemical pesticides such as fungicides, insecticides, nematocides, acaricides, and herbicides, as well as biopesticides have been subjected to development. In addition to general chemicals and biopesticides, peptide pesticides (fungicides, insecticides) and RNAi-based pesticides (insecticides, acaricides) have emerged over the past decade. The first RNAi-based pesticide was developed in the United States and registered as a biopesticide.

A total of 156 pesticides—excluding general biopesticides—have been launched or are under development during the past decade; most are safe to humans and environmentally friendly. These include 47 fungicides (including one with nematocidal activity), 54 insecticides/acaricides (39 insecticides, 4 insecticides and acaricides, 11 acaricides), 9 nematocides (one with fungicidal activity), and 46 herbicides. Though pesticide discovery studies based on genomic information or by the structure–activity relationship and chemical biology have been actively conducted over the past decade, almost no products have been developed for practical use.

## 3. Trends in the number of pesticides developed by country (region) and company

The development of new pesticides has traditionally been dominated by Western-based multinational companies, such as Bayer and Syngenta (which is now under the umbrella of ChemChina but is considered a Western company because the headquarters of its pesticide business is in Basel, Switzerland), as well as Japanese companies. However, in recent years, Chinese companies have been gaining prominence. Generally, the creation of new pesticides begins with basic research into new candidate compounds, followed by the acquisition (assignment) of



\*Fiscal year Apr -Mar / \*\* Fiscal year Oct -Sep / \*\*\* Fiscal year Nov-Oct / † AgbioInvestor estimate / r 2022 restated. (Based on AgbioInvestor data), \*Punjab Chemicals and Crop Protection, <sup>b</sup>Nippon Kayaku is excluded from the chart because most of its sales are not related to pesticides.

Fig. 1. Global agrochemical company sales in 2023 (\$m.).

an ISO common name (generic name) for compounds deemed promising, full-scale development activities, registration, and marketing. However, there have been many cases in which Chinese manufacturers have obtained new ISO common names for compounds that were already registered and marketed in China, making the assessing of developmental status difficult. In addition, the development of these compounds is mainly limited to China and its neighboring countries or countries with close ties to China, and there is no sign of expansion into Japan, Europe, or the USA.

Furthermore, there is a problem with mutual recognition of OECD-GLP data and Chinese domestic GLP data. Currently, there is no mutual recognition between OECD-GLP and Chinese GLP data, and OECD-GLP data cannot be used for pesticide registration in China. Therefore, even if pesticide companies in Japan and other OECD countries (EU countries, the UK, Switzerland, the USA, Australia, etc.) have safety data that meet the OECD guidelines, they generally cannot obtain pesticide registration in China unless they conduct Chinese GLP testing. This makes it difficult to develop and register new OECD country of origin pesticides in China. On the other hand, it is not easy for Chinese companies to obtain registration in OECD countries such as the EU, the USA, and Japan.

Table 1 shows the number of pesticides (fungicides, insecticides/miticides, nematocides, herbicides) developed in Japan and other Asia-Oceania regions since 2015. Sumitomo Chemical ranks first with 7, but after the acquisition of Meiji Seika Pharma, which developed 4 pesticides, Mitsui Chemicals Agro (currently Mitsui Chemicals CLS) comes in at the top with 10. Each company has its own area of expertise; for example, Sumitomo Chemical excels in fungicides, Nihon Nohyaku in fungicides/insecticides, and Kumiai Chemical in herbicides. Ishihara Sangyo Kaisha has developed a variety of pesticides in a balanced manner. The total number of pesticides developed by Japanese companies is 42, accounting for 26.9% of the total number of pesticides developed in the world. As of May 2021, Japan's share was about 40%, but this has fallen due to the rise of Chinese companies. In addition, two South Korean companies have developed one pesticide each, and Australian and Indian companies have contributed one pesticide each to the development.

Table 2 shows the number of pesticides developed by European and US multinational companies and other companies based in Europe, the USA, and Israel. The total number of pesticides developed by multinational companies was 51 (32.7%), and like Japan, their share is declining due to the rise of China. A total of 11 compounds have been launched or are under development by

**Table 1.** Number of pesticides developed by pesticide companies based in Japan and other Asia–Oceania regions (2015–2025)

| Company name                        | Fungicide | Insecticide     | Acaricide | Nematicide | Herbicide | Total (Ratio: %) |
|-------------------------------------|-----------|-----------------|-----------|------------|-----------|------------------|
| Japanese companies                  |           |                 |           |            |           |                  |
| Sumitomo Chemical                   | 5         | 1               | 0         | 0          | 1         | 7                |
| Kumiai Chemical                     | 1         | 0               | 1         | 0          | 2         | 4                |
| Nihon Nohyaku                       | 1         | 2               | 1         | 0          | 0         | 4                |
| Nissan Chemical                     | 1         | 1               | 0         | 0          | 2         | 4                |
| Ishihara Sangyo Kaisha              | 1         | 2               | 0         | 0          | 2         | 5                |
| Mitsui Chemicals Agro <sup>a)</sup> | 3         | 2               | 0         | 0          | 1         | 6                |
| Meiji Seika Pharma <sup>b)</sup>    | 1         | 3               | 0         | 0          | 0         | 4                |
| Nippon Soda                         | 2         | 0               | 1         | 0          | 0         | 3                |
| OAT Agrio                           | 0         | 0               | 1         | 0          | 0         | 1                |
| Nippon Kayaku                       | 0         | 1 <sup>c)</sup> | 1         | 0          | 0         | 1                |
| Kyoyu Agri                          | 0         | 0               | 0         | 0          | 1         | 1                |
| ZEN-NOH                             | 0         | 1               | 0         | 0          | 0         | 1                |
| Kureha Corporation                  | 1         | 0               | 0         | 0          | 0         | 1                |
| Japan total                         | 16        | 12              | 5         | 0          | 9         | 42 26.9%         |
| Other regional companies            |           |                 |           |            |           |                  |
| FarmHannong (South Korea)           | 0         | 0               | 0         | 0          | 1         | 1                |
| Moghu Research Center (South Korea) | 0         | 0               | 0         | 0          | 1         | 1                |
| PI Industries (India)               | 0         | 1               | 0         | 0          | 0         | 1                |
| Innovate Ag (Australia)             | 0         | 1               | 0         | 0          | 0         | 1                |
| Total                               | 16        | 14              | 5         | 0          | 11        | 46 29.5%         |

<sup>a)</sup> Currently Mitsui Chemicals Crop & Life Solutions (Mitsui Chemicals CLS). <sup>b)</sup> The crop protection business was transferred to Mitsui Chemicals Agro in January 2022. <sup>c)</sup> Figure includes the product jointly developed with Meiji Seika Pharma, but is excluded from the total insecticide figures.

**Table 2.** Number of pesticides developed by pesticide companies based in Europe, the USA and Israel (2015–2025)

| Company name                                       | Fungicide | Insecticide | Acaricide | Nematicide      | Herbicide <sup>a)</sup> | Total (Ratio: %) |
|----------------------------------------------------|-----------|-------------|-----------|-----------------|-------------------------|------------------|
| European and US-based multinational companies      |           |             |           |                 |                         |                  |
| Syngenta                                           | 4         | 4           | 0         | 1               | 3                       | 12               |
| Bayer                                              | 3         | 4           | 1         | 3 <sup>b)</sup> | 3                       | 13               |
| BASF                                               | 3         | 2           | 0         | 0               | 3                       | 8                |
| Corteva Agriscience                                | 5         | 4           | 0         | 1               | 3                       | 13               |
| FMC                                                | 1         | 1           | 0         | 0               | 3                       | 5                |
| Subtotal                                           | 16        | 15          | 1         | 3               | 15                      | 51 32.7%         |
| Other companies in Europe, the USA and Israel      |           |             |           |                 |                         |                  |
| Greenlight Biosciences (the USA)                   | 0         | 1           | 1         | 0               | 0                       | 2                |
| Vestaron (the USA)                                 | 0         | 1           | 0         | 0               | 0                       | 1                |
| Ecospray (the UK)                                  | 0         | 0           | 0         | 1               | 0                       | 1                |
| CEV S. A. (Portugal)                               | 1         | 0           | 0         | 0               | 0                       | 1                |
| Eden Research (the UK) /Eastman Chemical (the USA) | 0         | 0           | 0         | 1               | 0                       | 1                |
| Silvateam S. p. A. (Italy)                         | 1         | 0           | 0         | 0               | 0                       | 1                |
| ADAMA (Israel)                                     | 1         | 0           | 0         | 1               | 0                       | 2                |
| Plant HealthCare (the USA) <sup>c)</sup>           | 1         | 0           | 0         | 0               | 0                       | 1                |
| Invio Science (the USA)                            | 1         | 0           | 0         | 0               | 0                       | 1                |
| Pennwalt Corporation                               | 0         | 0           | 0         | 0               | 1                       | 1                |
| Eli Lilly                                          | 0         | 1           | 0         | 0               | 0                       | 1                |
| Total                                              | 21        | 18          | 2         | 6               | 16                      | 64 41.0%         |

<sup>a)</sup> Includes plant growth regulator. <sup>b)</sup> Figure includes the product jointly developed with ADAMA, but is excluded from the total nematicide figures. <sup>c)</sup> Became a wholly owned subsidiary of PI Industries Ltd. of India.

**Table 3.** Number of pesticides developed by Chinese companies and university (2015–2025)

| Names of companies, universities and research institutes               | Fungicide | Insecticide | Acaricide | Nematicide | Herbicide | Total (Ratio: %) |
|------------------------------------------------------------------------|-----------|-------------|-----------|------------|-----------|------------------|
| Shandong Sino-Agri United Biotechnology <sup>a)</sup>                  | 3         | 0           | 0         | 1          | 0         | 4                |
| Shandong Kangqiao Biotechnology                                        | 0         | 0           | 1         | 0          | 0         | 1                |
| Shandong Shenbon Greenland Chemical                                    | 1         | 0           | 0         | 0          | 0         | 1                |
| Shandong Jingbo Agrochemicals Technology                               | 1         | 0           | 0         | 0          | 0         | 1                |
| Sinochem                                                               | 0         | 1           | 1         | 0          | 0         | 2                |
| Hailir Pesticides and Chemicals Group (Hailir)                         | 0         | 1           | 0         | 0          | 0         | 1                |
| Zhejiang Udragon Pesticides and Chemicals <sup>b)</sup>                | 0         | 2           | 1         | 0          | 0         | 3                |
| CAC Nantong Chemical                                                   | 0         | 1           | 0         | 0          | 0         | 1                |
| KingAgroot                                                             | 2         | 2           | 0         | 0          | 12        | 16               |
| Central China Normal University/Shandong Cynda Chemical <sup>c)</sup>  | 1         | 0           | 0         | 0          | 2         | 3                |
| Jiangsu Shaanxi Sunger Road Bio-Science                                | 0         | 0           | 1         | 0          | 0         | 1                |
| Jiangsu Flag Chemical Industry                                         | 1         | 0           | 0         | 0          | 0         | 1                |
| Jiangsu Agrochem Laboratory                                            | 0         | 0           | 0         | 0          | 1         | 1                |
| Jiangsu Yangnong Chemical <sup>d)</sup>                                | 1         | 2           | 1         | 0          | 0         | 4                |
| Hebei Chemical International                                           | 0         | 1           | 0         | 0          | 0         | 1                |
| Shandong Binnog Technology                                             | 0         | 0           | 0         | 0          | 1         | 1                |
| Shenyang Sinochem Pesticide Chemical R&D/Jiangshan Stock <sup>e)</sup> | 0         | 0           | 0         | 0          | 1         | 1                |
| Shandong Dehao Chemical                                                | 0         | 0           | 0         | 0          | 1         | 1                |
| Shandong Xianda                                                        | 0         | 0           | 0         | 0          | 1         | 1                |
| Ningxia HugeRise Chemical                                              | 0         | 0           | 0         | 1          | 0         | 1                |
| China total                                                            | 10        | 10          | 5         | 2          | 19        | 46 29.5%         |

<sup>a)</sup> Shandong Sino-Agri United Biotechnology includes its subsidiary Shandong United Pesticide Industry. <sup>b)</sup> Zhejiang Udragon Pesticides and Chemicals includes its subsidiary Zhejiang Udragon Bioscience. <sup>c)</sup> Shandong Cynda Chemical is involved in the development of two herbicides, but not a fungicide. <sup>d)</sup> Includes subsidiary: Shenyang Sinochem Agrochemicals R&D Co., Ltd. <sup>e)</sup> Nantong Jiangshan Agrochemical and Chemicals Co., Ltd. (commonly known as Jiangshan Stock).

other European and US companies. Two compounds were developed by an Israel-based company.

Table 3 shows the number of pesticides developed by Chinese companies and universities, totaling 46, accounting for 29.5%. Many Chinese pesticide companies have become involved in the creation of new pesticides. KingAgroot, which has demonstrated its strength in the creation of herbicides (12 herbicides from 2015–2025), has recently begun to develop fungicides and insecticides.

#### 4. New pesticides developed over the past decade

##### 4.1. Fungicides

###### 4.1.1. General trends in development

The general trend in fungicide development is, first, progress in research and development of the three major classes of fungicides: (1) SDHIs (succinate dehydrogenase inhibitors) that act on complex II of the mitochondrial respiratory chain electron transport system or agents that are considered to be SDHI based on their chemical structure, (2) mitochondrial respiratory chain electron transport system III inhibitors (QoIs: quinone outside inhibitors, and QiIs: quinone inside inhibitors), and (3) DMIs (demethylation inhibitors) that act by inhibiting sterol biosynthesis in the cell membrane.

Although the number of SDHIs on the market or in development (nine, since 2015; one additional SDHI is listed as a ne-

maticide) is now comparable to those of DMIs and QoIs, post-SDHI fungicides or the SDHIs that are effective against SDHI-resistant strains are now desired due to successive reports on fungal pathogen resistance to existing SDHIs. Regarding mitochondrial respiratory chain electron transport system III inhibitors, five QoIs acting on the outer membrane of complex III and three QiIs acting on the inner membrane have been developed since 2015. Meanwhile, DMIs continue to play an important role in controlling plant diseases due to their broad spectrum, high therapeutic effect, and relatively slow development of resistance; although limited, four new DMIs have been in development since 2015.

The second trend is the development of fungicides with various novel modes of action other than the three major class fungicides, while other trends include the development of peptide fungicides, natural product-derived fungicides, and novel resistance inducers. Fungicides with novel modes of action include oxysterol-binding protein inhibitors, dihydroorotate dehydrogenase (DHODH) inhibitors, tubulin dynamics modulators, and histone deacetylase (HDAC) inhibitors. In some of the new fungicides that have recently been given ISO common names, the mode of action remains unknown.

###### 4.1.2. Fungicides of three major classes recently launched or under development

###### 4.1.2.1. SDHI fungicides

**Table 4.** SDHI fungicides launched or under development since 2015

| Common name      | Company name                                     | Registration year in Japan | Remarks                                                                                                                                                   |
|------------------|--------------------------------------------------|----------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|
| Isofetamid       | Ishihara Sangyo Kaisha                           | 2017                       | A broad-spectrum fungicide, especially effective against Ascomycota ( <i>Botrytis</i> , <i>Sclerotinia Monilinia</i> etc.) at low dose rates              |
| Pyraziflumid     | Nihon Nohyaku                                    | 2018                       | Excellent activity against Ascomycete and basidiomycete fungi and good activity against many diseases in the field.                                       |
| Fluindapyr       | FMC                                              | 2017*                      | Broad-spectrum against a wide range of diseases in row and specialty crops, as well as turf. Registered in the USA, South Korea, Brazil etc.              |
| Inpyrfluxam      | Sumitomo Chemical                                | 2019                       | Robust activity against Asian soybean rust, apple scab and other important phytopathogenic fungi on various crops.                                        |
| Pyrapropoyne     | Nissan Chemical                                  | 2017*                      | Effective against powdery mildew, sclerotinia, and gray mold                                                                                              |
| Isoflucypram     | Bayer                                            | 2017*                      | Outstanding fungicidal efficacy against all major leaf disease in cereal at a low use rate of 75 g a.i./ha. Registered in New Zealand and the UK          |
| Isopyrazam       | Syngenta                                         | 2017                       | For foliar application to control rust and net blotch of wheat                                                                                            |
| Pydiflumetofen   | Syngenta                                         | 2020                       | Effects against a wide range of crop pests including <i>Alternaria</i> , gray mold, leaf spot, septoria, powdery mildew, <i>Fusarium</i> head blight etc. |
| Flubeneteram     | Central China Normal University                  | 2020*                      | Dongguan Hec Tech R&D Co. (China) is developing                                                                                                           |
| Fenopyramid      | Shandong United Pesticide Industry <sup>a)</sup> | 2024*                      | Considered to be SDHI based on chemical structure                                                                                                         |
| Cyclobutrifluram | Syngenta                                         |                            | Listed in the “Nematicides” section                                                                                                                       |

\*Year of ISO common name given. <sup>a)</sup> A wholly owned subsidiary of Shandong Sino-Agri United Biotechnology Co., Ltd.

Table 4 shows information on ten SDHI fungicides (plus an SDHI that was listed in the nematocide section) that have been launched or are under development since 2015.<sup>4,5)</sup> Their chemical structures are shown in Fig. 2.

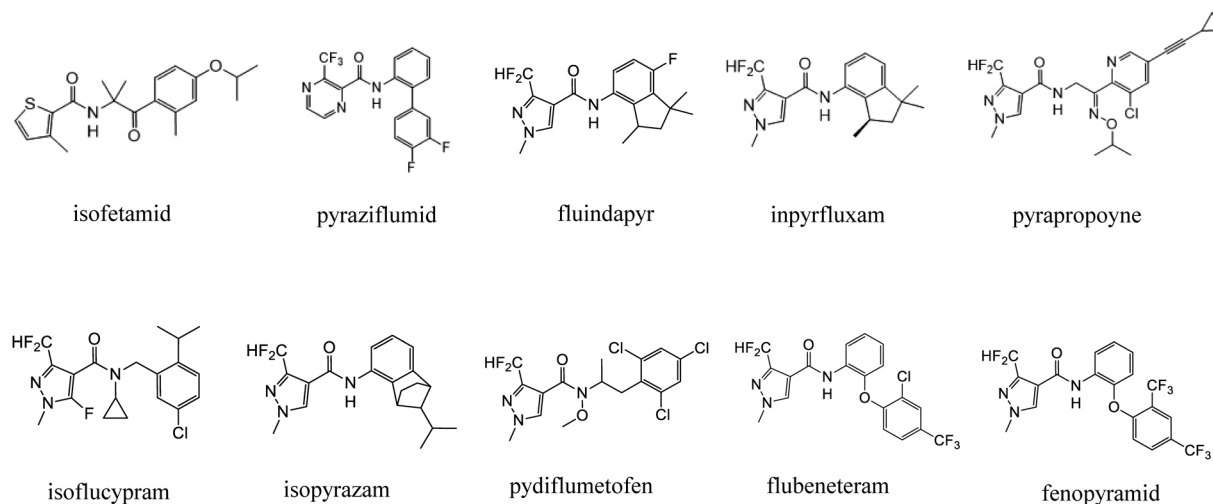
**Isofetamid** (Kenja<sup>®</sup>, Zenby<sup>®</sup>, etc., Ishihara Sangyo Kaisha) is the first SDHI fungicide launched in the market since 2000 that does not contain any halogen atoms.<sup>7)</sup> This unique feature clearly differentiates isofetamid from all new SDHI fungicides. Isofetamid has a broad fungicidal spectrum against Ascomycota and Deuteromycota and is effective against existing SDHI-resistant pathogens.<sup>7)</sup>

**Pyraziflumid** (Parade<sup>®</sup>, Decide<sup>®</sup>, Nihon Nohyaku) is a versatile fungicide applicable to a wide range of crops such as rice,

horticulture products, and turf and has a favorable safety profile for the IPM program.<sup>8)</sup> It has a pyrazine carboxamide skeleton.

**Fluindapyr** (Kalida<sup>™</sup>, Adastrio<sup>®</sup>, FMC) provides broad-spectrum activity against a wide range of diseases. Kalida<sup>™</sup> fungicide, a combination of fluindapyr and flutriafol, fits extremely well in turfgrass disease management programs.<sup>9)</sup> Adastrio<sup>®</sup> fungicide (mixture of fluindapyr, flutriafol, and azoxystrobin) provides effective and reliable control against tar spot, Southern rust, gray leaf spot, Northern corn leaf blight, etc.<sup>10)</sup> The products containing fluindapyr were commercialized in many countries such as Argentina, Brazil, South Korea, and the USA.

**Inpyrfluxam** (Indiflin<sup>™</sup>, Kaname<sup>®</sup>, Millionair<sup>®</sup>, Sumitomo Chemical) exhibits high efficacy against major plant diseases in

**Fig. 2.** Chemical structures of SDHI fungicides.

the European region, such as brown rust on wheat, net blotch on barley, and black scurf on potatoes.<sup>11)</sup> It provides a new solution for soybean farmers struggling to control Asian soybean rust, since its efficacy against Asian soybean rust is stable. It might be effective against SDHI-resistant strains.<sup>12)</sup>

**Pyrapropoyne** (Nissan Chemical) is the pyrazolecarboxamide SDHI fungicide. No data is available regarding the development status of this compound.

**Isoflucypram** (Iblon<sup>®</sup>, Bayer) very efficiently controls all relevant leaf diseases in cereals. It was registered in New Zealand and the UK. The two unique structural moieties, the *N*-cyclopropyl substituent and the C1 linker between carboxamide and phenyl, supported the introduction of a discrete subclass for isoflucypram in the FRAC complex II inhibitory family, *i.e.*, *N*-cyclopropyl-*N*-benzyl-carboxamides.<sup>13)</sup>

**Pydiflumetofen** (Adepidyn<sup>®</sup> active, Miravis<sup>®</sup>, Syngenta) is a new broad-spectrum foliar fungicide and the first example of a new group of *N*-methoxy-(phenethyl)-pyrazole-carboxamides within the class of SDHIs. As the very first SDHI fungicide, it delivers outstanding performance against *Fusarium* head blight.<sup>14)</sup> Pydiflumetofen is currently being used on more than 100 crops in more than 50 countries.<sup>15)</sup>

**Flubeneteram** discovered by Central China Normal University is under development by Dongguan Hec Tech R & D Co. Since it induces wheat's defenses against *Puccinia striiformis* f. sp. *tritici*, which causes stripe rust, flubeneteram could be an effective fungicide for managing stripe rust.<sup>16)</sup>

#### 4.1.2.2. Inhibitors of mitochondrial electron transport chain complex III

As shown in Table 5, since 2015, eight compounds have been launched or are under development as inhibitors of the mitochondrial electron transport chain complex III.<sup>4,5)</sup> Their chemical structures are shown in Fig. 3. Five of these compounds are

QoI fungicides (Fig. 3a), and three are QiI fungicides (Fig. 3b).

**Picoxystrobin** (Onmira<sup>™</sup> active, Acanto<sup>®</sup>, Vessarya<sup>®</sup>, Dupont, currently Corteva Agriscience; Major Flowable, Nihon Nohyaku), which was discovered by Syngenta and transferred to DuPont in 2006, is a strobilurin fungicide (QoI inhibitor) effective against a wide range of diseases. DuPont registered it in the USA in 2012. In Japan, Nihon Nohyaku marketed it in 2016.<sup>17)</sup>

**Mandestrobin** (Sclea<sup>®</sup> flowable, Intuity<sup>®</sup>, Sumitomo Chemical), a strobilurin fungicide, was discovered by Shionogi & Co., Ltd., and commercially developed by Sumitomo Chemical. It is effective against sclerotinia rot, fruit tree scab, *etc.*, and has a low risk of phytotoxicity. It was launched in 2016 in Japan.<sup>18,19)</sup> Mandestrobin has been commercialized as Intuity<sup>®</sup> in many countries such as the USA, New Zealand, Australia, and Canada.

**Metyltetraprole** (Pavecto<sup>®</sup>, Sumitomo Chemical), despite being a QoI, exhibits equivalent efficacy against both susceptible and QoI-resistant strains because of its unique chemical structure.<sup>20)</sup> It is the first member of a new generation of QoIs—the tetrazolinone fungicides.<sup>21)</sup> Therefore, metyltetraprole can manage various diseases in important crops such as wheat, barley, soybean, cotton, and sugar beet. It also has favorable characteristics such as long-lasting activity and rainfastness. The product, called Muketsu DX (mixed with mancozeb), was released in 2020 in Japan, and its development is underway in Europe and South America.

**Bifemetstrobin** (Sumitomo Chemical) is a new strobilurin fungicide, whose ISO common name was given in 2024. It can control plant diseases caused by plant pathogenic microorganisms such as fungi (Ascomycota, Basidiomycota, Blastocladiomycota, *etc.*), Oomycetes, Phytomyxea, and bacteria.<sup>22)</sup>

**Metcyclofenstrobin** (Syngenta) is another new strobilurin fungicide, whose ISO common name was given in 2025. It is a methoxyacrylate-based compound engineered for broad-

**Table 5.** Recently launched or under development QoI and QiI fungicides

| Common name           | Company name                                              | Registration year in Japan | Remarks                                                                                                                                                                                            |
|-----------------------|-----------------------------------------------------------|----------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>QoI Inhibitors</b> |                                                           |                            |                                                                                                                                                                                                    |
| Picoxystrobin         | Syngenta→ DuPont <sup>a)</sup><br>Nihon Nohyaku in Japan  | 2016                       | A general-purpose strobilurin fungicide, effective against a wide variety of diseases in vegetables and field crops, including downy mildew, sclerotinia rot, and gray mold.                       |
| Mandestrobin          | Shionogi→<br>Sumitomo Chemical                            | 2016                       | Effective against sclerotinia fungi, and has a high control value against black spot of pear, brown spot of peach, and Phomopsis rot                                                               |
| Metyltetraprole       | Sumitomo Chemical                                         | 2020                       | Having a tetrazolinone structure in the molecule, and is effective against pathogens that are resistant to existing fungicides. It can control a wide range of diseases, including wheat leaf spot |
| Bifemetstrobin        | Sumitomo Chemical                                         | 2024*                      | Strobilurin fungicide recently given ISO common names.                                                                                                                                             |
| Metcyclofenstrobin    | Syngenta                                                  | 2025*                      | Strobilurin fungicide recently given ISO common names, chemical structure being similar to bifemetstrobin.                                                                                         |
| <b>QiI inhibitors</b> |                                                           |                            |                                                                                                                                                                                                    |
| Fenpicoxamid          | Meiji Seika Pharma <sup>a)</sup> →<br>Corteva Agriscience | 2016*                      | Effective against ascomycetes such as wheat leaf blight and basidiomycetes fungi such as wheat rust.                                                                                               |
| Florpyicoxamid        | Corteva Agriscience                                       | 2017*                      | Neopicolinamide fungicide with the same mode of action as fenpicoxamid                                                                                                                             |
| Metarypicoxamid       | Dow <sup>b)</sup>                                         | 2021*                      | A novel broad-spectrum, protective picolinamide fungicide                                                                                                                                          |

\*Year of ISO common name given, <sup>a)</sup> Currently Mitsui Chemicals CLS, <sup>b)</sup> Currently Corteva Agriscience.

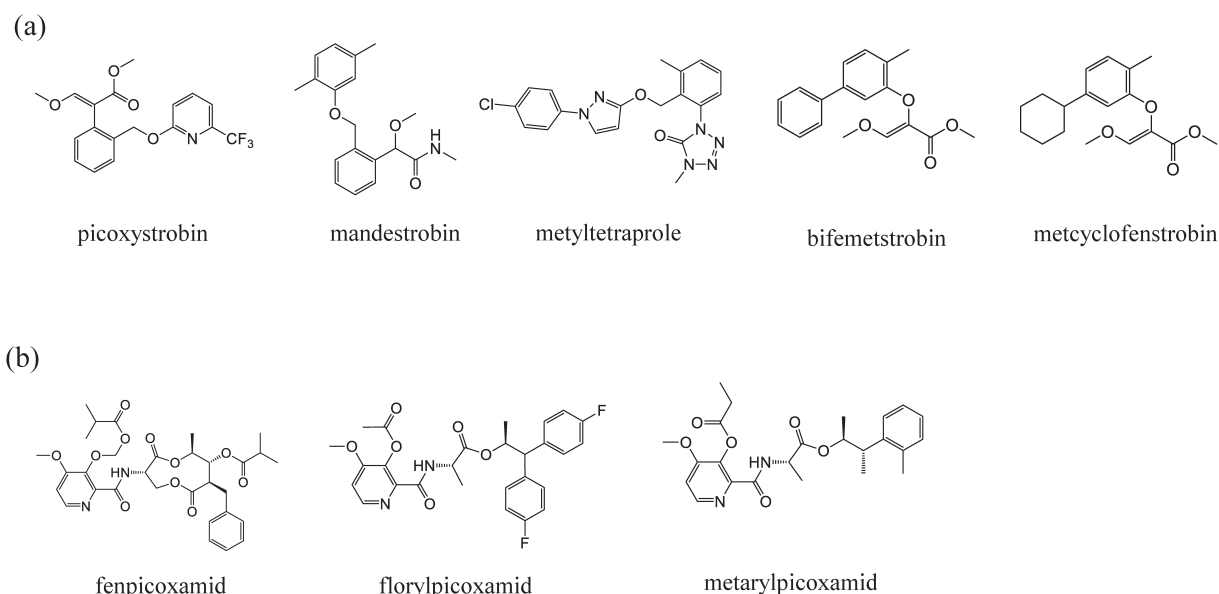


Fig. 3. (a) Chemical structures of five QoI fungicides. (b) Chemical structures of three Qil fungicides.

spectrum fungal control. It shows strong efficacy against a wide range of plant diseases, such as *Alternaria solani*, *Colletotrichum lagenarium*, and *Erysiphe graminis f. sp. tritici*.<sup>23)</sup>

As Qil fungicides, three compounds are under development.

**Fenpicoxamid** (Inatreq<sup>TM</sup> active, Meiji Seika Pharma, currently Mitsui Chemicals CLS; Dow, currently Corteva Agriscience) is a member of a new picolinamide class of fungicides derived from the antifungal natural product UK-2A.<sup>24)</sup> It is a propesticide, since it is converted to UK-2A in crops and fungi. Fenpicoxamid offers outstanding biological performance, since it shows no cross-resistance to existing cereal fungicides. It was registered in the UK as Univoq<sup>TM</sup> in 2021 and was already approved for use in cereals in countries such as France, Belgium, and Luxembourg, with the registration process continuing across Europe and in other key cereal-growing areas.<sup>25)</sup>

**Florylpicoxamid** (Adavelt<sup>TM</sup> active, Zectigo<sup>TM</sup> PRM, Corteva Agriscience) is the second member of the Qil class of picolinamide fungicides, joining fenpicoxamid. Florylpicoxamid was discovered using UK-2A as an inspirational starting point. The molecule was created using structure–activity relationship studies focused on improving the control of wheat leaf blotch caused

by *Zymoseptoria tritici*.<sup>26)</sup> Florylpicoxamid was launched commercially with registrations in the three countries—Australia, Canada, and South Korea—in 2023<sup>27)</sup> and in the USA in 2025.<sup>28)</sup>

**Metarylpicoxamid** (Haviza<sup>TM</sup> active, Corteva Agriscience) is the third generation of the novel picolinamide fungicide discovered, following fenpicoxamid (Inatreq<sup>TM</sup>) and florylpicoxamid (Adavelt<sup>TM</sup> active). Metarylpicoxamid is effective against Asian soybean rust and other fungal diseases,<sup>29)</sup> and it is expected to be launched in Brazil, Argentina, Paraguay, and Bolivia by 2027. Actually, metarylpicoxamid was registered in Argentina in 2023 under the commercial name Vicroya Ora.<sup>30)</sup>

#### 4.1.2.3. DMI fungicides

As shown in Table 6, four DMIs have been launched or are under development since 2015. Their chemical structures are shown in Fig. 4.

**Mefentrifluconazole** (Revysol<sup>®</sup> active, Belanty<sup>®</sup> Flowable, Revystar<sup>®</sup> EX (mixture), BASF) is the first isopropanol-azole discovered and developed by BASF. Its registration was approved in the EU in 2019. It is highly effective against key fungal diseases in both row and specialty crops, including cereals, corn, soybeans, rice, grapevines, fruits, vegetables, and turf.<sup>31,32)</sup>

Table 6. Recently launched or under development DMI fungicides

| Common name         | Company name                               | Registration year in Japan | Remarks                                                                                                                                                 |
|---------------------|--------------------------------------------|----------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------|
| Mefentrifluconazole | BASF                                       | 2023                       | Highly effective against various diseases, especially in fruit trees                                                                                    |
| Ipfentrifluconazole | BASF                                       | 2016*                      | Effective against wheat leaf blight, apple scab, and various powdery mildews                                                                            |
| Fluoxytioconazole   | Corteva Agriscience/Viamet Pharmaceuticals | 2021*                      | Effective against wheat leaf spot                                                                                                                       |
| Prothioconazole     | Bayer                                      | 2021                       | Effective against a wide range of diseases, including Fusarium head blight, the most important disease of wheat, as well as red rust and powdery mildew |

\*Year of ISO common name given.

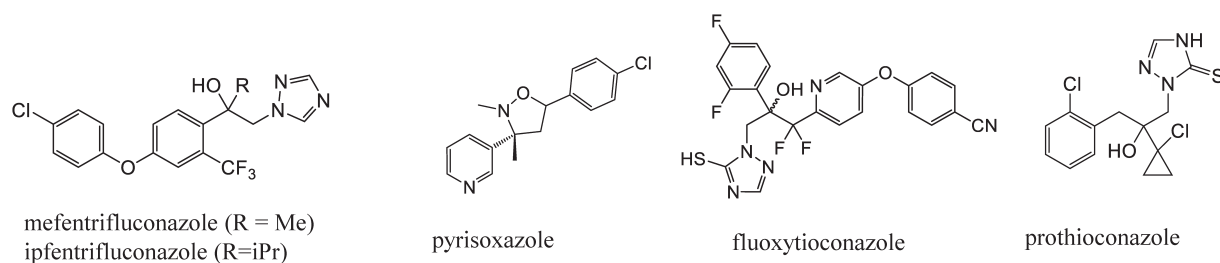


Fig. 4. Chemical structures of DMI fungicides.

**Ipfentrifluconazole** (BASF) is a broad-spectrum and protective conazole fungicide. No information is available on its developmental status.

**Fluoxytioconazole** (Corteva Agriscience) is a novel conazole fungicide demonstrating broad-spectrum activity. No information is available on its developmental status.

**Prothioconazole** (Bayer) obtained its ISO common name in 2002 and was already on the market in Europe in 2004. In Japan, it was registered in 2021 as Proline<sup>®</sup> flowable. It is characterized by a broad fungicidal spectrum, excellent systemic and penetrating properties, and high effectiveness against Fusarium head blight, a major disease of wheat.<sup>33)</sup>

It became clear that **pyrisoxazole** (by SYRICI), which obtained its ISO common name in 2012 and was previously reported as a new DMI fungicide developed after 2010,<sup>2)</sup> was already registered and approved for use in China since 2002.<sup>34)</sup> Therefore, pyrisoxazole is excluded from the list of new fungicides.

#### 4.1.3. Trends of new fungicides other than the three major classes of fungicides

##### 4.1.3.1. Various fungicides with novel modes of action

As shown in Table 7, ten fungicides with novel modes of action other than SDHI, QoI, QiI, and DMI fungicides have been subjected to development since 2015, and their chemical structures are shown in Fig. 5.

**Picarbutrazox** (Pythilock<sup>®</sup>, Nae Fine<sup>®</sup>, Pisi Rock<sup>®</sup>, Nippon Soda) was registered in June 2017 in Japan.<sup>35)</sup> It belongs to the tetrazolyl oxime class, controlling oomycete diseases such as downy mildew and late blight. The mode of action of this compound is unknown, but it seems to be new, as shown in Table 7.<sup>35,36)</sup>

**Tolprocarb** (Sanblas<sup>®</sup>, Mitsui Chemicals Agro, currently Mitsui Chemicals CLS) is a rice blast fungicide registered in 2015 in Japan. Since tolprocarb has a dual mode of action, *i.e.*, the inhibition of hepatic polyketide synthase and the induction of systemic acquired resistance, it can efficiently control not only rice blast but also bacterial diseases.<sup>37)</sup>

Table 7. Various fungicides with novel modes of action

| Common name     | Company name                            | Registration year in Japan | Remarks: mode of action                                                                                                                                                                                                     |
|-----------------|-----------------------------------------|----------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Picarbutrazox   | Nippon Soda                             | 2017                       | Causes swelling and hyperbranching of mycelia and inhibits zoospore formation, suggesting the new mode of action (FRAC: mode of action is unknown)                                                                          |
| Tolprocarb      | Mitsui Chemicals Agro <sup>a)</sup>     | 2015                       | Inhibition of polyketide synthase in the melanin biosynthesis pathway (FRAC Code 16.3)                                                                                                                                      |
| Oxathiapiprolin | DuPont <sup>b)</sup>                    | 2016                       | Oxysterol binding protein inhibitor (OSBPI) (FRAC Code 49)                                                                                                                                                                  |
| Fluoxapiprolin  | Bayer                                   | 2018*                      | Oxysterol binding protein inhibitor (OSBPI) (FRAC Code 49)                                                                                                                                                                  |
| Dichlobentiazox | Kumiai Chemical                         | 2020                       | Induction of systemic acquired resistance in plants. Dichlobentiazox acts both upstream and downstream of salicylic acid biosynthesis (FRAC Code P08)                                                                       |
| Ipfluenoquin    | Nippon Soda                             | 2020                       | Inhibition of dihydroorotate dehydrogenase (DHODH), a key enzyme in the biosynthesis of pyrimidine-based nucleotides (FRAC Code 52)                                                                                         |
| Quinofumelin    | Mitsui Chemicals Agro <sup>a)</sup>     | 2025                       | Target site is dihydroorotate dehydrogenase (DHODH) (FRAC Code 52)                                                                                                                                                          |
| Pyridachlometyl | Sumitomo Chemical                       | 2023                       | Exhibits fungicidal activity by binding to the tubulin of filamentous fungi, and its target site is different from that of existing tubulin polymerization inhibitors such as benomyl and thiophanate methyl (FRAC Code 53) |
| Flufenoxadiazam | BASF                                    | 2021*                      | Histone deacetylase (HDAC) inhibitor                                                                                                                                                                                        |
| Fluopimomide    | Shandong Sino-Agri United Biotechnology | 2017*                      | Reported to be a SDHI, but FRAC classified fluopimomide as code 43 in the same group as fluopicolide                                                                                                                        |

\*Year of ISO common name given. <sup>a)</sup> Currently Mitsui Chemicals CLS, <sup>b)</sup> Currently Corteva Agriscience.

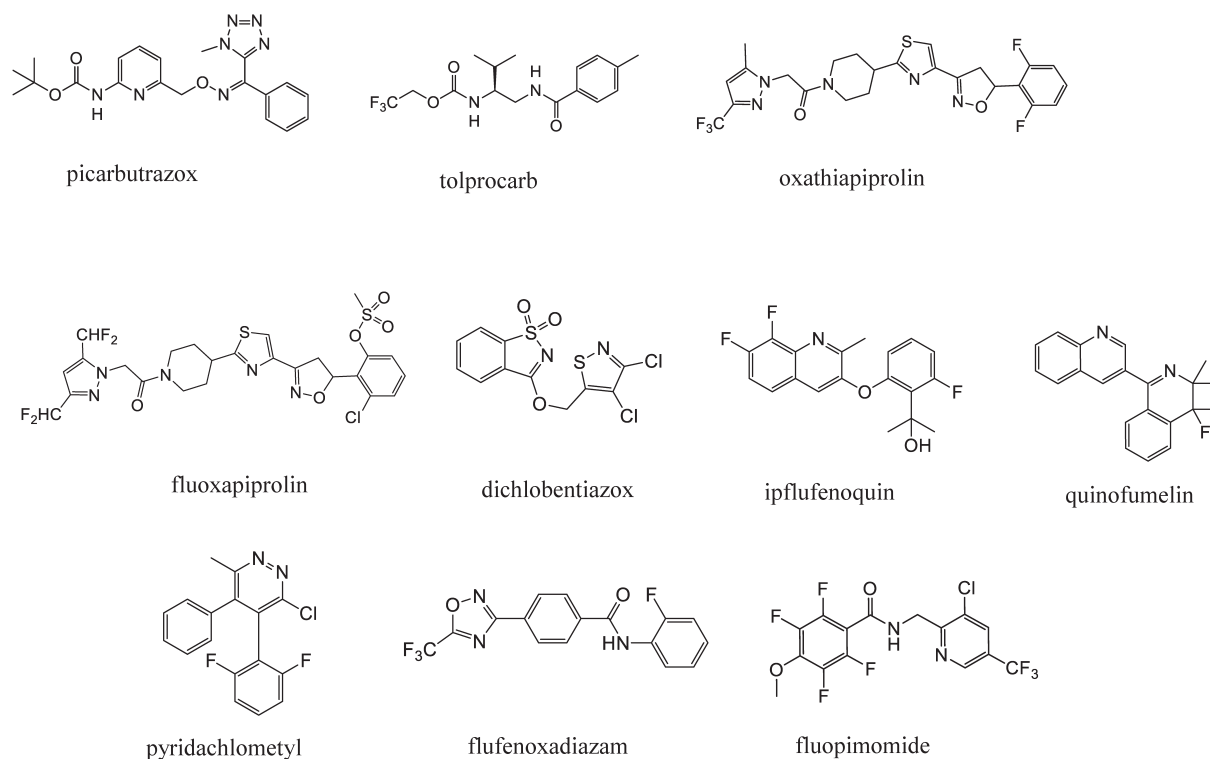


Fig. 5. Chemical structures of various fungicides with novel modes of action.

**Oxathiapiprolin** (Zorvec<sup>TM</sup> active, Orondis<sup>TM</sup>, Segovis<sup>®</sup>, Corteva Agriscience/Syngenta), which targets oxysterol-binding proteins (OSBPs),<sup>38,39</sup> is a piperidinyl thiazole isoxazoline fungicide that can be used to control oomycete diseases and was registered in Japan in 2016.<sup>38</sup> It was registered in the USA as Orondis<sup>TM</sup> in 2015. Corteva Agriscience and Syngenta have a supply and data access agreement in the USA and Canada. Oxathiapiprolin is effective for controlling Downy mildew (grape), late blight (potato, tomato), and various rots (vegetables).<sup>39</sup>

**Fluoxapiprolin** (Xivana<sup>®</sup> Prime, Bayer), which targets oxysterol-binding proteins (OSBPs), is a new fungicide from the piperidinyl thiazole isoxazoline chemical class and is active against a wide range of oomycete fungi, especially downy mildew on grapes.<sup>40</sup> It is already marketed in Australia and New Zealand.

**Dichlobentiazox** (Disarta<sup>TM</sup> active, Boon<sup>®</sup>, Kumiai Chemical), a novel type of resistance inducer, controls rice blast (*Pyricularia oryzae*), brown spot, bacterial leaf blight, and bacterial grain rot on rice. It was developed in collaboration with JA ZEN-NOH and registered in Japan in 2020.<sup>41</sup> Boon<sup>®</sup> granules are highly effective in controlling rice blast disease and can be used not only for seedling box treatment but also for direct treatment in rice paddies. In addition, mixtures with various insecticides and fungicides have been developed for paddy rice nursery box application.<sup>42</sup>

**Ipflufenquin** (Kinoprol<sup>®</sup> active, Migiwa<sup>®</sup>20F, AXIOS<sup>TM</sup> 20 SC), an inhibitor of dihydroorotate dehydrogenase (DHODH), is highly effective against black spot, powdery mildew, ripe rot, and gray mold on various fruit trees.<sup>43</sup> It was first registered in

Japan as Migiwa<sup>®</sup> 20F in 2020, followed by South Korea, Australia,<sup>44</sup> and the USA.<sup>45</sup> Development is also underway in Europe and Brazil.<sup>44</sup>

**Quinofumelin** (Aptirel<sup>®</sup> active, A'ina<sup>®</sup>, Mitsui Chemicals CLS), an inhibitor of dihydroorotate dehydrogenase (DHODH), exhibits fungicidal activity against a variety of fungi, including rice blast, gray mold, and apple scab.<sup>46</sup> It has curative effects against rice blast and is not cross-resistant to existing fungicides. Interestingly, quinofumelin inhibits DHODH, which is the fourth-step enzyme of the *de novo* pyrimidine biosynthesis pathway.<sup>47,48</sup> Mitsui Chemicals CLS received the registration of quinofumelin in Japan in 2025.<sup>49</sup>

**Pyridachlometyl** (Fuseki flowable, Sumitomo Chemical) exhibits broad-spectrum antifungal activity, showing high efficacy against sugar beet leaf spot, soybean purple stain, and powdery mildew that affects various vegetable crops in field trials. Owing to a binding site that is distinct from that of existing tubulin polymerization inhibitors, pyridachlometyl shows no cross-resistance to carbendazim and other fungicides (e.g., DMI, QoI, and SDHI).<sup>50</sup> The first commercial product, "Fuseki flowable," received initial registration in Japan in 2023.<sup>51</sup>

**Flufenoxadiazam** (Adapzo<sup>®</sup> active, BASF), which possesses a novel mode of action, *i.e.*, histone deacetylase (HDAC) inhibition, shows unprecedented levels of Asian soybean rust (ASR) control.<sup>52</sup> BASF expects market introductions of flufenoxadiazam-based formulations starting in 2029.

**Fluopimomide** (Shandong Sino-Agri United Biotechnology, China) is a benzamide fungicide targeting cucumber and grape

**Table 8.** Development status of peptide fungicides

| Active ingredient name | Company name                              | Registration year in Japan | Remarks                                                                                                                                                                        |
|------------------------|-------------------------------------------|----------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| BLAD                   | CEV S. A. (Portugal)                      | 2025                       | A 20 kDa polypeptide which is an extract from the <i>Lupinus</i> species of the legume family as its active ingredient. Possess multiple mode of action                        |
| PHC279                 | Plant Health Care <sup>a)</sup> (the USA) | 2021 (in Brazil)           | Harpin-derived peptide that amplifies a plant's natural defense against a range of diseases, increasing plant health and yield. Launched in Brazil in 2021 and the USA in 2023 |
| MaSAMP                 | Invio Sciences (the USA)                  |                            | Antimicrobial peptides from Australian finger lime. Effective to control Citrus Huanglongbing (HLB). Development status is unknown                                             |

<sup>a)</sup> Plant Health Care became a wholly owned subsidiary of PI Industries Ltd. of India.

downy mildew, *phytophthora capsici*, litchi downy blight, potato late blight, rice sheath blight, and cotton rhizoctonia solani.<sup>53)</sup> Although the Pesticide Properties Data Base (PPDB)<sup>54)</sup> states that fluopimomide's mode of action is SDH inhibition, FRAC classified it as code 43 (target site: the delocalization of spectrin-like proteins) in the same group as fluopicolide.

#### 4.1.3.2. Peptide fungicides

The development of pesticides using peptides is gaining momentum. The background for this is the need to search for pesticides with new targets of action due to concerns about the development of resistance to existing pesticides, as well as the strong social demand for pesticides with low environmental impact.<sup>55)</sup> Currently, three peptide fungicides are in development, as shown in Table 8; their chemical structures are shown in Fig. 6.

**BLAD** (ProBLAD<sup>®</sup> Verde, CEV S. A.) is a polypeptide (bio-fungicide) extracted from the *Lupinus* species of the legume family and is effective against more than 20 fungal and bacterial pathogens, including powdery mildew, *Botrytis*, and brown rot.<sup>55–57)</sup> The polypeptide was discovered by researchers of Lisbon University, Portugal, in 1991, and CEV S. A., established after that, was in charge of all R&D activities.<sup>56)</sup> BLAD was registered in the USA, Canada, and China in 2015<sup>58)</sup> and in 2025 in Japan. BLAD is exempt from MRL requirements and could

be applied pre-harvest to maximize crop marketability.<sup>57)</sup> Since BLAD has multiple modes of action (FRAC: BM 01), it creates an effective fungicide while also making it difficult for fungus to develop resistance.<sup>55,58)</sup>

**PHC279** (Saori<sup>®</sup>, Obron<sup>®</sup>, Plant Health Care) is a novel harpin-derived peptide that amplifies a plant's natural defenses against a range of diseases, increasing plant health and yield.<sup>59)</sup> It was launched in Brazil in 2021 as Saori<sup>®</sup> and the USA (defined as biofungicide) in 2023 as Obron<sup>®</sup>. It controls a wide range of fungal and bacterial plant pathogens, particularly in fruits, nuts, vegetables, and row crops.<sup>60,61)</sup> Saori<sup>®</sup> (granular formulation) is the first and only seed treatment fungicide recommended for foliar disease control, and is effective against Asian soybean rust and other soybean diseases. Obron<sup>®</sup> initially focused on corn diseases such as tar spot and common rust as well as powdery and downy mildew. Wilbur-Ellis<sup>®</sup> Agribusiness is starting sales of Obron<sup>®</sup>.

**MaSAMP** (Invio Sciences) is a novel class of stable antimicrobial peptides from the Australian finger lime and other Citrus Huanglongbing-tolerant citrus close relatives.<sup>62)</sup> MaSAMP (stable antimicrobial peptide) effectively controls Citrus Huanglongbing (HLB), the most destructive citrus disease. It has dual functions of inhibiting the bacterium (*Candidatus Liberibacter*

RRQRNPYHFSSQRFQTLTKNRNGKIRVLERFDQRTNRLNLQNYRIVEFQSKPNTLILP  
KHSADADYVLVLNGRATITIVNPDRRQAYNLEYGDALRIPAGSTSYILNPDDNQKLRVV  
KLAIPINNPGYFYDFYPSSTKDDQSYFSGFSRNTLEATFNTRYEEIQRILGNED

BLAD amino acid sequence (single letter code)

MCCNRGKNVSIENLHQGFTHIFESTFESTEGVAEYVSHPSHVEYANLFLANLEKVLVIDY  
KPTTVRV

MaSAMP (precursor amino acid sequence)

Note: single-letter code for amino acids

Glycine (G), Alanine (A), Serine (S), Threonine (T), Cysteine (C), Valine (V), Leucine (L), Isoleucine (I), Methionine (M), Proline (P), Phenylalanine (F), Tyrosine (Y), Tryptophan (W), Aspartic Acid (D), Glutamic Acid (E), Asparagine (N), Glutamine (Q), Histidine (H), Lysine (K), and Arginine (R)

**Fig. 6.** Structures of peptide fungicides.

asiaticus) responsible for HLB and activating host immunity to prevent new infections. The development status of MaSAMP is unknown.

#### 4.1.3.3. Other fungicides with novel or unknown modes of action

As shown in Table 9, 12 new fungicides with novel or unknown modes of action have been subjected to development, and their chemical structures are shown in Fig. 7.

**Flumetylsulforim** (Gilboa™, ADAMA), with an imino-tosylpyrimidinone chemistry, provides valuable protection against key diseases in cereals and oilseed rape, including Septoria and Sclerotinia. It has been classified as having a novel mode of action, with the target site in cereals being nucleic acid metabolism, a biochemical pathway that has never before been utilized by cereal fungicides (FRAC Group 32).<sup>63)</sup>

Flumetylsulforim was submitted for registration in 2023 and is expected to receive approval in the UK in 2027 and in the EU in 2029.

**Seboctylamine** (Chinese common name: Xinjunan, Shandong Shenbon Greenland Chemical) is an aliphatic nitrogen fungicide<sup>64)</sup> that has been known since 1952 and was already commercialized in China,<sup>65)</sup> although its ISO common name was given in 2021. Seboctylamine inhibits ATP synthesis by affecting oxidative phosphorylation and TCA cycle pathways in bacteria.<sup>66)</sup>

**Chloroinconazide** (co-developed by Shandong Jingbo Agrochemicals Technology and Nankai University) is a tryptophan-derived analog of alkaloid isolated from *Peganum harmala*,

which has been reported to exhibit potent inhibitory activity on viruses and *Phytophthora*.<sup>67)</sup> It exhibits significant potential for controlling *P. syringae* pv. *tabaci*-induced tobacco wildfire disease, offering a potential alternative strategy for disease management. Chloroinconazide obtained its first registration in Cambodia.<sup>68)</sup>

**D-Tagatose** (Kagawa University, Mitsui Chemicals CLS, Shikoku Research Institute), a rare sugar (natural product) used mainly in food, controls a wide range of plant diseases such as downy mildew and powdery mildew.<sup>69)</sup> It has been shown that D-tagatose inhibits the first step of mannose metabolism, the phosphorylation of D-fructose to D-fructose 6-phosphate by fructokinase. Synthesis of mannan is essential for the development of fungi and oomycetes.<sup>69)</sup>

**Galquin** (Silvateam S.p.A.) is a complex mixture of esters, mainly of quinic acids with gallic acid extracted from pods of the legume *Tara spinosa* (*Caesalpinia spinosa*), and it exhibits fungicidal and nematocidal activity.<sup>70)</sup> The Silvateam group is headquartered in San Michele Mondovì (Northern Italy).

**Fluquinometoate** (Shandong United Pesticide Industry) is effective against bacterial diseases caused by pathogens such as *Pectobacterium* (causing soft rot in cruciferous vegetables) and Dickie's genus (causing sweet potato stem rot, corn bacterial stem rot, etc.).<sup>71)</sup> Additionally, it enhances crop growth and development by promoting plant height, stimulating chlorophyll synthesis, and increasing leaf area.

For fenepdamidoquin, which received its ISO common name

**Table 9.** Other fungicides with mode of action being novel or unknown

| Common name              | Company name                                                                        | Registration year in Japan | Remarks                                                                                                                                |
|--------------------------|-------------------------------------------------------------------------------------|----------------------------|----------------------------------------------------------------------------------------------------------------------------------------|
| Flumetylsulforim         | ADAMA                                                                               | 2021*                      | Novel pyrimidine fungicide having novel mode of action: target site in cereals is nucleic acid metabolism                              |
| Seboctylamine            | Shandong Shenbon Greenland Chemical                                                 | 2021*                      | Seboctylamine has been known since 1952 and commercialized as name of "xinjunan" in China. Mode of action: inhibition of ATP synthesis |
| Chloroinconazide         | Jingbo Agrochemicals Technology/Nankai University                                   | 2020*                      | A novel fungicide and antiviral agent, which is a tryptophan-derived analog of alkaloid                                                |
| Fenepdamidoquin          | Syngenta                                                                            | 2024*                      | A quinolinecarboxamide class fungicide and highly effective in controlling phytopathogenic fungi                                       |
| D-Tagatose <sup>a)</sup> | Kagawa University, Mitsui Chemicals Agro <sup>b)</sup> , Shikoku Research Institute | Under development          | Mode of action: inhibition of the first step of mannose (essential for development of fungi and oomycetes) metabolism on downy mildews |
| Galquin                  | Silvateam S.p.A.                                                                    | 2024*                      | A fungicidal and nematocidal plant extract from pods of the legume <i>Tara spinosa</i> .                                               |
| Fluquinometoate          | Shandong United Pesticide Industry <sup>c)</sup>                                    | 2024*                      | A quinolinone bactericide with potent activity against various bacterial pathogens in agriculture                                      |
| Quinaminoprole           | Jiangsu Yangnong Chemical                                                           | 2025*                      | A pyrazole compound containing pyrimidine, which has a broad-spectrum fungicidal, and acaricidal activity                              |
| Aminotipyr               | KingAgroot                                                                          | 2025*                      | New fungicide                                                                                                                          |
| Cyclobunofen             | KingAgroot                                                                          | 2025*                      | New carboxamide fungicide, effective against nematodes, Fusarium diseases, Botrytis cinerea, and Sclerotinia sclerotiorum              |
| Enprocymid               | Jiangsu Flag Chemical Industry                                                      | 2025*                      | Pyrazolecarboxamide fungicide                                                                                                          |
| Carneconazole            | Kureha Corporation                                                                  | 2025*                      | Triazole fungicide                                                                                                                     |

\*Year of ISO common name given. <sup>a)</sup> No ISO common name. <sup>b)</sup> Currently Mitsui Chemicals CLS. <sup>c)</sup> A wholly owned subsidiary of Shandong Sino-Agri United Biotechnology Co., Ltd.

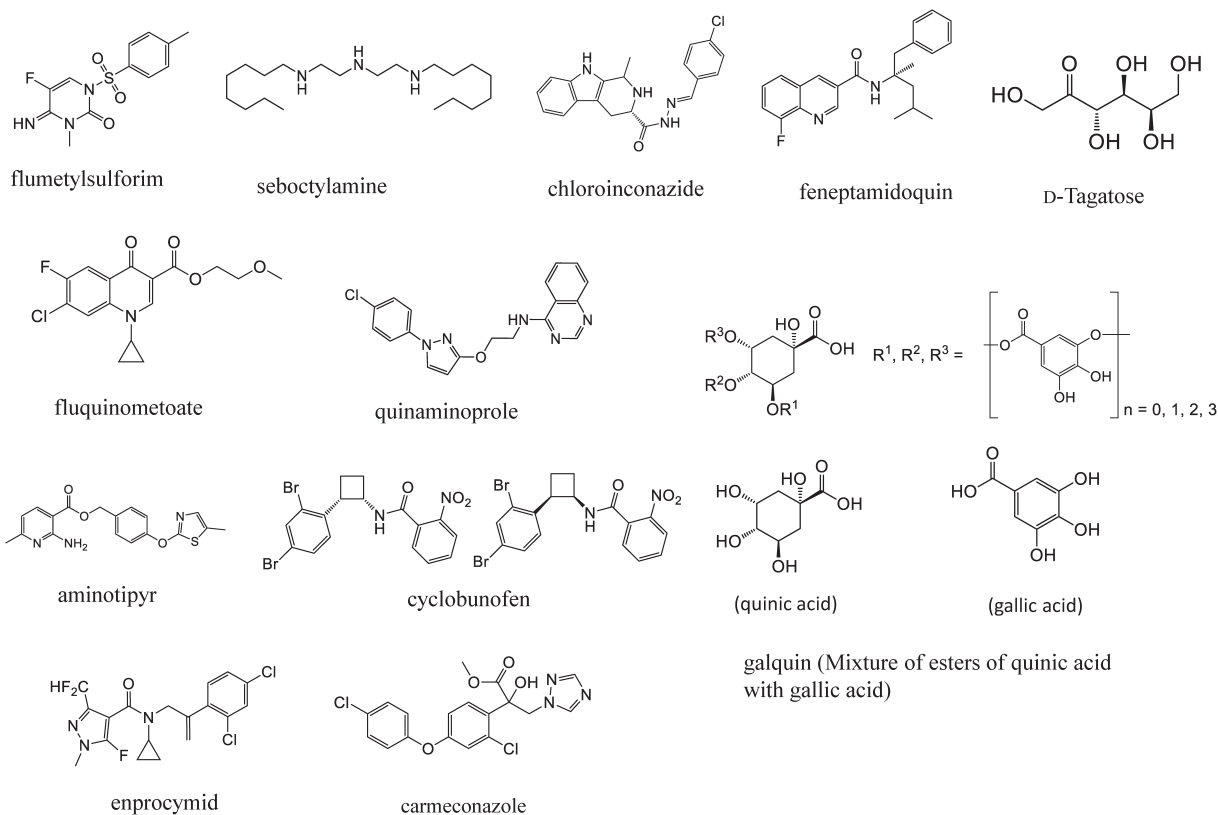


Fig. 7. Chemical structures of other fungicides with mode of action being novel or unknown.

in 2024, and five fungicides (quinaminoprople, aminotipyr, cyclobunofen, enprocymid, and carmeconazole), which received ISO common names in 2025, development status data are limited to the information presented in Table 9.

#### 4.2. Insecticides

##### 4.2.1. General trends in development

In the history of insecticide development, trends have changed from organophosphates, carbamates, and synthetic pyrethroids to neonicotinoids (recently, the whole group, including related compounds, is called nicotinic insecticides: nicotinic acetylcholine receptor competitive modulators)<sup>72,73</sup> and diamide insecticides. Since 2015, the first general trend in insecticide development has been progress in research and development of the four major classes of insecticides: nicotinic insecticides (7), diamide insecticides (7), GABA-gated chloride channel allosteric modulators (8), and insect behavior or growth regulators (4).

The second trend is the development of insecticides with various novel modes of action other than those of insecticides of the four major classes. Other trends include the development of peptide and RNAi-based insecticides. Insecticides with novel modes of action include inhibitors of vesicular acetylcholine transporter, inhibitors of the function of the chordotonal organs of pests, and interference with the insect's neurotransmission system, although the modes of action of some of these insecticides have not been clearly determined and are listed as

unknown by the IRAC.

Regarding the global development trends of new insecticides from 2015 to October 2022, please refer to the review by Nakano *et al.*,<sup>74</sup> "General trends in insecticide research and development," In *Trends in Research and Development of Chemical Pesticides, Biopesticides and Biostimulants*, N. Umetsu Supervised, CMC Publishing, pp. 69–83 (2023) (in Japanese).<sup>4)</sup>

##### 4.2.2. Insecticides recently launched or under development of four major classes of insecticides

###### 4.2.2.1. Nicotinic insecticides

Table 10 shows nicotinic insecticides launched or under development since 2015, and their chemical structures are shown in Fig. 8. The nicotinic insecticides currently under development belong to the third generation (the first generation consists of two pesticides, including nicotine, and the second generation consists of seven neonicotinoids). In the EU, the use of three pesticides belonging to the second generation, imidacloprid, clothianidin, and thiamethoxam, was banned in April 2013 as a preventive measure due to potential honeybee toxicity issues, and their use outdoors was officially banned in 2018<sup>2,75</sup> (such measures have not been taken in Japan or the USA).

**Sulfoxaflor** (Isoclast<sup>TM</sup> active, Transform<sup>TM</sup> flowable, Corteva Agriscience) is a new class of nicotinic acetylcholine receptors (nAChRs) competitive modulator (IRAC Sub-Group 4C) that provides control of a wide range of sap-feeding insect pests.<sup>76)</sup> Sulfoxaflor exhibits distinct interactions with nAChRs as com-

**Table 10.** Nicotinic insecticides launched or under development

| Common name     | Sub-group name | Company name                                    | Registration year in Japan | Remarks                                                                                           |
|-----------------|----------------|-------------------------------------------------|----------------------------|---------------------------------------------------------------------------------------------------|
| Sulfoxaflor     | sulfoximines   | Dow <sup>a)</sup>                               | 2017                       | US EPA banned its use in March 2016/Re-registered in February 2017                                |
| Flupyradifurone | butenolides    | Bayer                                           | 2015                       | Registered in many countries such as the USA, the EU, Canada and Japan, but not marketed in Japan |
| Triflumezopyrim | mesoiones      | Corteva Agriscience<br>In Japan With<br>ZEN-NOH | 2018                       | Launched in Japan as Zexalon™ in 2019, and as Pexalon™ in China, Vietnam, India <i>etc.</i>       |
| Dicloromezotiaz | mesoiones      | ZEN-NOH <sup>b)</sup>                           | 2021                       | Invented by DuPont. ZEN-NOH marketed in Japan                                                     |
| Fenmezoditiaz   | mesoiones      | BASF                                            | 2021*                      | Registered in India                                                                               |
| Flupyomezotiaz  | mesoiones      | KingAgroot                                      | 2025*                      | ISO common name was given in July 2025                                                            |
| Flupyrimin      | pyridylidenes  | Meiji Seika Pharma <sup>c)</sup>                | 2019                       | Launched in Japan and India                                                                       |

\*Year of ISO common name given. <sup>a)</sup> Currently Corteva Agriscience, <sup>b)</sup> National Federation of Agricultural Cooperative Associations, <sup>c)</sup> Currently Mitsui Chemicals CLS.

pared to other IRAC Group 4 insecticides, such as the neonicotinoids (Group 4A).

**Flupyradifurone** (Sivanto™, Buteo™, Bayer) belongs to the novel chemical class of butenolides (IRAC Sub-Group 4D), clearly different chemically from other insecticides, and shows excellent control of major sucking pests like aphids, leafhoppers, psyllids, and whiteflies.<sup>77)</sup> It was registered in many countries, including the USA, the EU, and Canada. The honeybee toxicity of flupyradifurone is very low (acute contact LD50: >100 µg/bee, acute oral LD50: 1.2 µg ai/bee).<sup>78)</sup>

**Triflumezopyrim** (Pyraxalt™ active, Zexalon™, Pexalon™, Lumispace™, DuPont, currently Corteva Agriscience) is the first mesoionic insecticide (IRAC Sub-Group 4E) that is chemically distinct from any other existing class of nicotinic insecticides. It provides outstanding and long-lasting control of planthoppers and leafhoppers in rice, providing excellent plant protection from direct pest damage and hopper transmitted virus

diseases.<sup>79,80)</sup>

**Dicloromezotiaz** (Field Mast® flowable, ZEN-NOH), the second mesoionic insecticide invented by DuPont, has the same mode of action as triflumezopyrim, *i.e.*, nAChR competitive modulator (IRAC Sub-Group 4E). In Japan, ZEN-NOH acquired the rights and has been proceeding with development and obtained registration in 2024 as Field Mast® flowable.<sup>81,82)</sup> It shows high activity against Lepidoptera, Hymenoptera, Diptera, and Coleoptera and is highly effective against pests resistant to existing insecticides. Dicloromezotiaz has not been registered in any other countries. In addition, termite control agents containing dicloromezotiaz as an active ingredient have been developed and marketed.<sup>83)</sup>

**Fenmezoditiaz** (Prexio® active, BASF) is a mesoionic insecticide (IRAC Sub-Group 4E) designed specifically to manage all four rice hopper species. BASF recently submitted regulatory dossiers in key Asia Pacific markets.<sup>84)</sup> Fenmezoditiaz has been

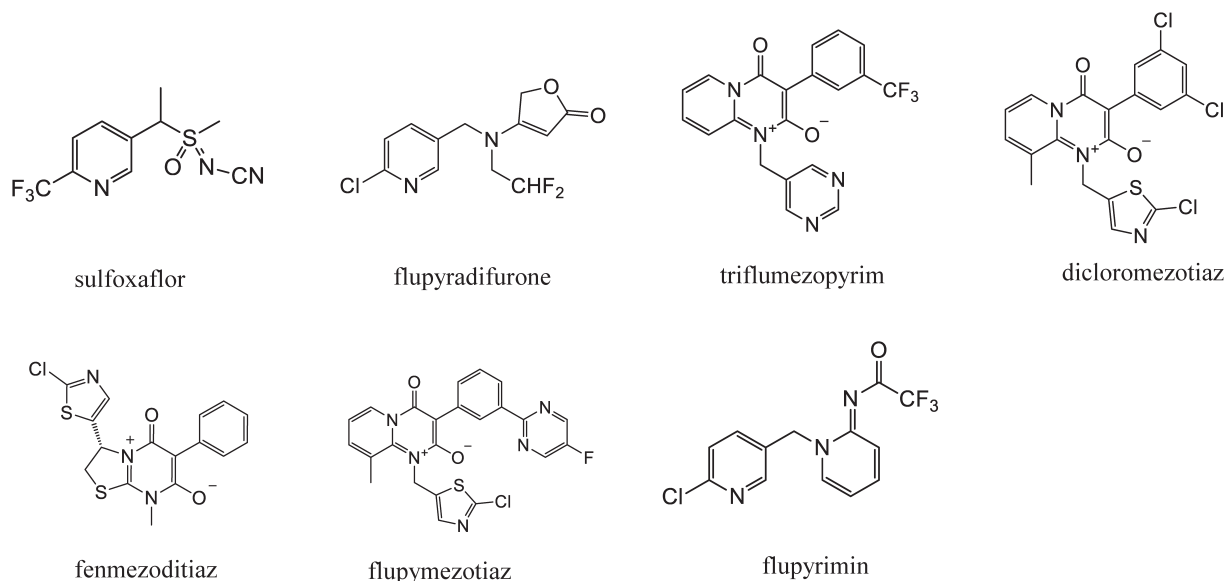
**Fig. 8.** Chemical structures of nicotinic insecticides.

**Table 11.** Diamide insecticides launched or under development since 2015

| Common name              | Company name                          | Registration year in Japan | Remarks                                                                                                                                       |
|--------------------------|---------------------------------------|----------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|
| Cyclaniliprole           | Ishihara Sangyo Kaisha                | 2017                       | Having an anthranilic diamide structure. Broader insecticidal spectrum compared with existing diamide insecticides                            |
| Tetraniliprole           | Bayer                                 | 2020                       | Having an anthranilic diamide structure. Effective in controlling a wide range of pests                                                       |
| Cyhalodiamide            | Hebei Chinally International          | 2015*                      | Developed by Zhejiang Chemical Industry Research Institute                                                                                    |
| Tetrachlorantraniliprole | Sinochem                              | 2018*                      | Already been marketed in China. Active against Lepidopteran pests                                                                             |
| Fluchlordiniliprole      | Hailir Pesticides and Chemicals Group | 2021*                      | Already been marketed in China. Patent is limited to China                                                                                    |
| Tiorantraniliprole       | Zhejiang Udragon Bioscience           | 2022*                      | Granted registration in 2021 before ISO common name given. For the prevention and control of Lepidopteran pests, such as the diamondback moth |
| Pioxaniliprole           | PI Industries                         | 2023*                      | Presumed to be diamide. It is believed to be India's first insecticide obtained ISO common name                                               |

\*Year of ISO common name given.

registered in India in 2023 for the first time in the world.<sup>85)</sup>

**Flupyomezotiaz** (KingAgroot), which was just given an ISO common name in 2025, is the fourth mesoionic insecticide. It effectively controls lepidopteran pests on rice, such as the striped rice stem borer and rice leaf roller, which have developed resistance to conventional insecticides.<sup>86)</sup>

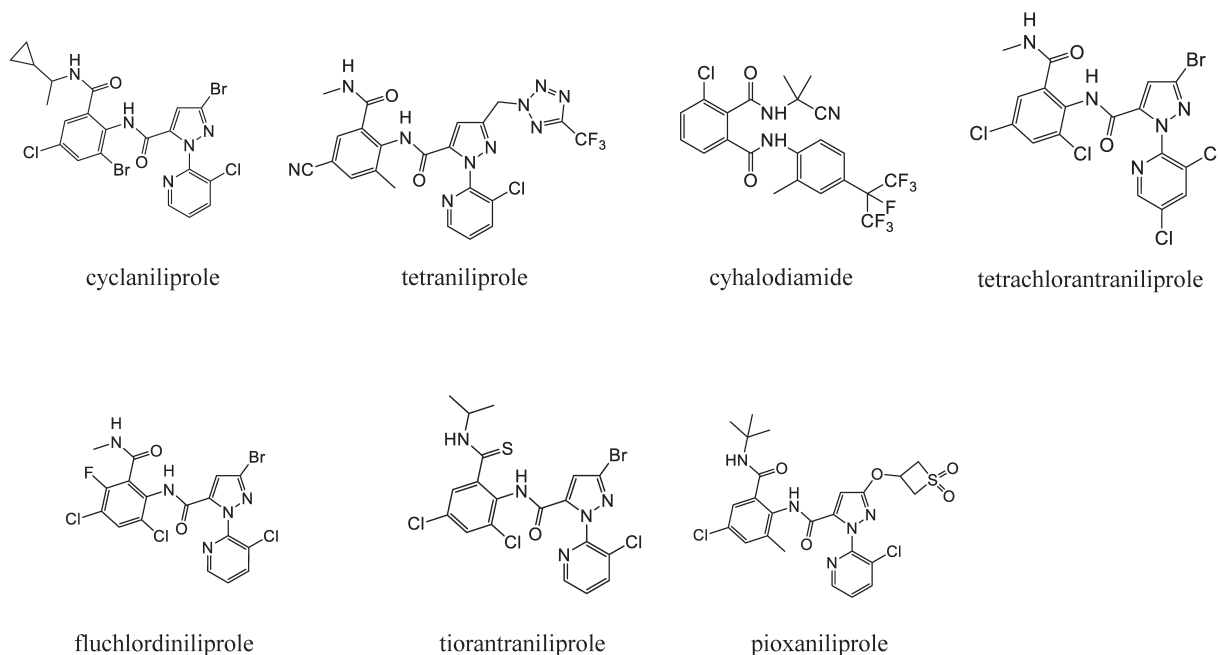
**Flupyrimin** (Lydia™, Emylia™, Meiji Seika Pharma: currently Mitsui Chemicals CLS) was launched in Japan in 2020 (registered 2019), followed by India (2022). It exhibits remarkable biological properties, featuring outstanding potency to neonicotinoid-insensitive rice insect pests and superior safety toward pollinators.<sup>87)</sup> Intriguingly, flupyrimin acts on insect nAChRs as an antagonist *via* a recognition manner different from those of other nicotinic insecticides<sup>73)</sup> and is classified as IRAC Sub-

Group 4F.

#### 4.2.2.2. Diamide insecticides

Table 11 shows diamide insecticides launched or under development since 2015, and their chemical structures are shown in Fig. 9. Since Nihon Nohyaku developed and registered the first diamide insecticide (flubendiamide) in 2007, many diamide insecticides have been developed; after 2015, seven diamide insecticides, including cyclaniliprole and tetraniliprole, have been developed.

These are not only effective against Lepidoptera pests but also other insect orders such as Hemiptera, Thysanoptera, Coleoptera, and Diptera. Chinese companies have obtained ISO common names for four compounds; however, information on their developmental status is limited. It is interesting to note that this

**Fig. 9.** Chemical structures of diamide insecticides.

is the first time an Indian company (PI Industries) has received an ISO common name (pioxaniliprole) as a development candidate.

**Cyclaniliprole** (Cyclapryn™ active, Teppan®, Muteki®, Harvanta®, etc., Ishihara Sangyo Kaisha) shows a broader spectrum of activity against not only Lepidopteran pests but also pests in other orders, including Coleoptera, Diptera, and Hemiptera, as compared with existing diamide insecticides.<sup>88,89)</sup> Ishihara Sangyo obtained initial registrations in South Korea, the USA, Canada, and Japan in 2017. Cyclaniliprole is now registered in 13 countries.<sup>89)</sup> Cyclaniliprole is classified as a ryanodine receptor modulator like other diamide insecticides.

**Tetraniliprole** (Vayego®, Yeoval®, Boon®, Leopard®, Bayer), belonging to the anthranilic diamide class of insecticides, is effective in controlling a wide range of pests, not only Lepidoptera, but also Hemiptera (such as aphids and whiteflies), Diptera, Coleoptera, Thysanoptera, and Orthoptera.<sup>90–92)</sup> It has been registered for use on a variety of agricultural crops, including corn, soybeans, potatoes, and several fruit and vegetable crops. It was registered in Japan in 2020 and has been marketed in many countries such as the USA, Canada, Australia, and China.

**Cyhalodiamide** (Hebei Chinally International) was developed by the Zhejiang Chemical Industry Research Institute in China, and the exclusive global product rights (10 years) were transferred to Hebei Chinally International in 2014. Cyhalodiamide is mainly used to control lepidopteran pests, including *Cnaphalocrocis medinalis*, *Chilo suppressalis*, *Pieris rapae*, *Plutella xylostella*, and *Scirpophaga incertulas*.<sup>93)</sup> Cyhalodiamide is presumed to be on the market in China.

There is limited information on the developmental status of the remaining three diamide insecticides of Chinese origins (**tetrachlorantraniliprole**, **fluchlordiniliprole**, **tiorantraniliprole**), although the first two are known to be already commercially available in China.<sup>74)</sup> Tiorantraniliprole was granted registra-

tion as both a technical and a formulation in China in 2021.<sup>94)</sup>

**Pioxaniliprole**, presumed to be a diamide insecticide, is being developed by an Indian company and obtained its ISO common name in 2023.

#### 4.2.2.3. GABA-gated chloride channel allosteric modulators

GABA-gated chloride channel allosteric modulators are new insecticides with a novel mode of action; therefore, they were classified into an independent group, IRAC Group 30. The first compound in Group 30, fluxametamide, is known to act *via* the distinctive antagonism of insect ligand-gated chloride channels.<sup>95)</sup> Table 12 shows eight GABA-gated chloride channel allosteric modulators launched or under development since 2015 (non-agricultural veterinary drugs are excluded from the list), and their chemical structures are shown in Fig. 10. Fluxametamide, broflanilide, isocycloseram, and cyproflanilide were classified officially as IRAC Group 30, and others are presumed to be GABA-gated chloride channel allosteric modulators due to their structural similarity to either fluxametamide or broflanilide. For information regarding the development of these types of insecticides, please refer to the review by Inada and Asahi.<sup>96)</sup>

**Fluxametamide** (Gracia®, Nissan Chemical), which possesses a novel isoxazoline skeleton, has a novel mode of action, *i.e.*, an allosteric modulator of the GABA-gated chloride ion-channel. It is highly effective against lepidopteran pests such as the diamondback moth, which has reduced sensitivity to existing pesticides, and against thrips, which are difficult to control with few effective pesticides. It also has practical effectiveness against a wide range of pest species, including Diptera, Acarina, Coleoptera, and some Hemiptera.<sup>97,98)</sup> Fluxametamide was launched in Japan in 2019 and in South Korea, India, and Indonesia.

**Broflanilide** (Tenebenal™ active, Brofrefya® SC, Vectron™, Mitsui Chemicals CLS) has a meta-diamide structure and is highly effective against agricultural pests, such as lepidopteran and leaf beetle, and insects affecting human health, such as

**Table 12.** GABA-gated chloride channel allosteric modulators launched or under development since 2015

| Common name    | Company name                        | Registration year in Japan | Chemical structure characteristics | Remarks: mode of action/action characteristics                                                                                       |
|----------------|-------------------------------------|----------------------------|------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|
| Fluxametamide  | Nissan Chemical                     | 2019                       | isoxazolines                       | Classified as IRAC Group 30. It is highly effective against many agricultural pests                                                  |
| Broflanilide   | Mitsui Chemicals Agro <sup>a)</sup> | 2020                       | meta-diamides                      | Classified as IRAC Group 30. Effective both for agricultural pests and insects affecting animal health                               |
| Isocycloseram  | Syngenta                            | 2018*                      | isoxazolines                       | Classified as IRAC Group 30. Marketed in many countries except for Japan                                                             |
| Cyproflanilide | CAC Nantong Chemical                | 2020*                      | meta-diamides                      | Classified as IRAC Group 30. Planning joint development with UPL Corp                                                                |
| Mivorilaner    | Eli Lilly                           | 2022*                      | isoxazolines                       | Insecticide/acaricide. This product can be used for researching veterinary medicine                                                  |
| Modoflaner     | Mitsui Chemicals Agro <sup>a)</sup> | 2022*                      | meta-diamides                      | Due to structural similarity, it may possess a similar insecticidal property to broflanilide, but probably for animal health purpose |
| Isoflualanam   | KingAgroot                          | 2023*                      | isoxazolines                       | According to KingAgroot this compound is a GABA-gated chloride channel allosteric modulator                                          |
| Piperflanilide | Jiangsu Yangnong Chemical           | 2023*                      | meta-diamides                      | Detailed data are not available                                                                                                      |

\* Year of ISO common name given, <sup>a)</sup> Currently Mitsui Chemicals CLS.

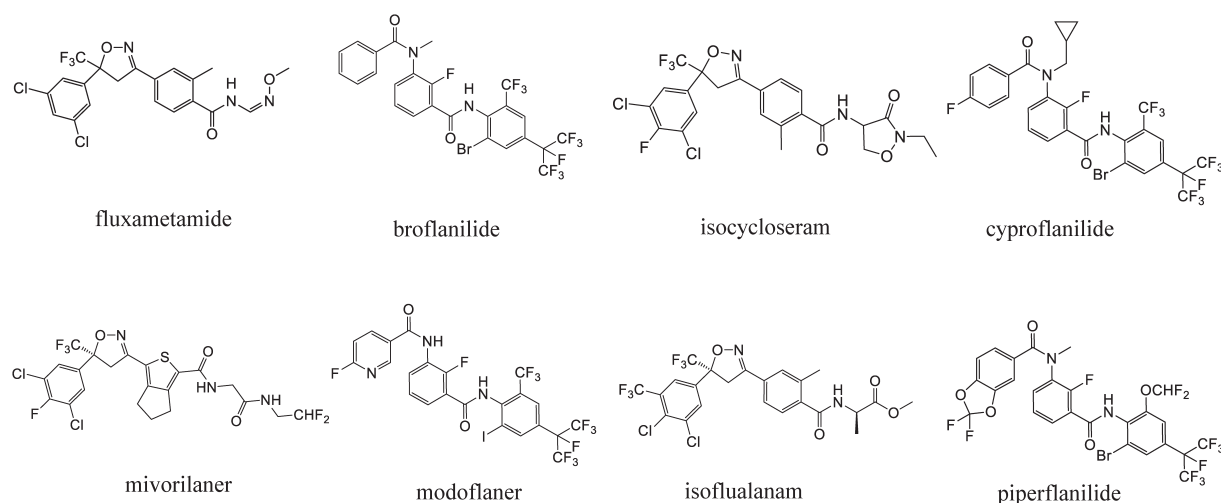


Fig. 10. Chemical structures of GABA-gated chloride channel allosteric modulators.

mosquito, cockroach, and bedbug.<sup>99–101</sup>) Vectron™ T500 has outstanding efficacy against malaria vector mosquitoes and has been prequalified by the WHO.<sup>102</sup>) Broflanilide was launched in 2021 in Japan, and subsequently launched in South Korea, China, India, the USA, Canada, Colombia, and other countries.<sup>100,101</sup>) Global market development is being carried out in collaboration with Germany's BASF.

**Isocycloseram** (Plinazolin® active, Virantra®, Incipio®, Atexzo®, Vykenda®, Vanecto®, etc., Syngenta) is a new member of the isoxazoline class of insecticides and has been approved for use in many countries, such as Argentina, Brazil, South Korea, India, and the USA, but not yet in Japan. Isocycloseram provides broad control of a range of crop-damaging pests, in particular, the orders of Lepidoptera, Hemiptera, Coleoptera, Thysanoptera, Diptera, and Acari.<sup>103</sup>) In the USA, Vykenda® is used for controlling thrips, mites, leaf miners, and flea beetles on ornamentals, Vanecto® is for cockroach control, and Atexzo® is for use on turf (annual bluegrass weevils, mole crickets, etc.).<sup>104</sup>)

**Cyproflanilide** (CAC Nantong Chemical) was registered in China in 2024 for export only to Cambodia. The product can effectively control lepidopteran pests such as *Spodoptera exigua*, diamondback moth, *Spodoptera litura* and *Chilo suppressalis*, Coleopteran pests such as longhorn beetle and leaf beetle, as well as thrips.<sup>105</sup>) CAC Nantong Chemical and UPL Corp will

jointly develop, register, and commercialize cyproflanilide products within their respective markets.<sup>106</sup>)

**Isoflualanam** (KingAgroot) is an isoxazoline insecticide that exhibits a broad insect spectrum. It is particularly effective against Lepidoptera, Acarina, and Homoptera, demonstrating no cross-resistance to other insecticides.<sup>107</sup>) Pesticide registration is expected soon in China, Cambodia, Kyrgyzstan, Indonesia, Cameroon, etc.

4.2.2.4. *Insect behavior regulators and insect growth regulators*  
Table 13 shows insect behavior regulators and insect growth regulators launched or under development since 2015, and their chemical structures are shown in Fig. 11. One insect behavior regulator and three growth regulators are listed.

**Acetylated glyceride** (AG, Bemidetach™ EC, Ishihara Sangyo Kaisha/RIKEN) is composed of food additives that regulate insect behaviors. Although AG does not show any direct insecticidal activity, it suppresses whitefly densities on tomato plants and inhibits the transmission of tomato yellow leaf-curl virus (TYLCV).<sup>108,109</sup>) AG has three types of action against tomato whiteflies: a repellent effect, a mating-inhibitory effect, and a sap-sucking-inhibitory effect; as a result, it suppresses four problems caused by whiteflies (population proliferation, transmission of plant pathogenic viruses, appearance of sooty blotches on fruits, and abnormal coloration of fruits). AG was marketed

Table 13. Insect behavior regulators and insect growth regulators launched or under development since 2015

| Common name                        | Company name                 | Registration year in Japan | Remarks: action characteristics and others                                                                                                                                |
|------------------------------------|------------------------------|----------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Acetylated glyceride <sup>a)</sup> | Ishihara Sangyo Kaisha/RIKEN | 2015                       | Regulates insect behavior. Registered crops are tomato and mini-tomato and sales started in 2019                                                                          |
| Spiropidion                        | Syngenta                     | 2017*                      | Inhibition of acetyl-CoA carboxylase, resulting in disruption of fatty acid biosynthesis, leading to poor growth, reduced egg production, and insufficient egg production |
| Spidoxamat                         | Bayer                        | 2021*                      |                                                                                                                                                                           |
| Benzpyrimoxan                      | Nihon Nohyaku                | 2020                       | Abnormal molting by disrupting the changes of ecdysteroids concentration in planthoppers (IRAC: unknown mode of action)                                                   |

\*Year of ISO common name given, <sup>a)</sup> No ISO common name.

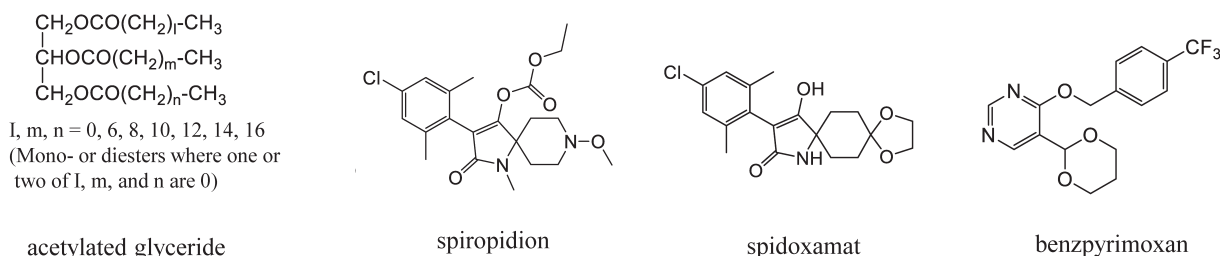


Fig. 11. Chemical structures of insect behavior regulators and growth regulators.

in 2019 in Japan. The registration of AG was expanded to the tea green leafhopper in 2022.

**Spiropidion** (Tinivion™, Elestal Neo (Spiropidion+acetamiprid), Syngenta) is a new tetramic acid family member (IRAC Group 23: inhibitor of acetyl-CoA carboxylase) that is effective against a wide range of important sucking insects, such as aphids, whiteflies, psyllids, scales, and various types of mites.<sup>110</sup> Spiropidion is for use in field crops, specialty crops, and vegetables. The first global registration of a formulated product (Elestal Neo) containing spiropidion was obtained in Guatemala in 2020, followed by Paraguay and Pakistan in 2021, Brazil in 2023,<sup>111</sup> and in some other countries.

**Spidoxamat** (Plenexos active, Bayer) is a novel ketoenol insecticide (IRAC Group 23: inhibitor of acetyl-CoA carboxylase) that targets sucking insects in general, such as aphids, whiteflies, and others. Its commercial launch is planned in 2026 in Australia, Brazil, and elsewhere.<sup>112</sup> Brazil is urgently evaluating spidoxamat for combating citrus greening disease, which is caused by the bacterium *Candidatus Liberibacter asiaticus*, spread by the insect vector *Diaphorina citri*.<sup>113</sup>

**Benzpyrimoxan** (Orchestra® SC, Orchestra® DL, Nihon Nohyaku) belongs to a novel chemical class, benzyloxy pyrimidines, and shows remarkable activity against nymphs of rice planthoppers (brown planthopper, white-backed planthopper), including strains resistant to existing insecticides.<sup>114</sup> Benzpyrimoxan has been shown to induce abnormal molting by disrupting the titer of ecdysteroids in the planthopper. Therefore, Nihon Nohyaku proposed a new group, “Ecdysone titer disrupters,” as an IRAC classification for benzpyrimoxan.<sup>115</sup> Benzpyrimoxan was registered in Japan in 2020, followed by India in 2021.

#### 4.2.3. Trends of novel insecticides other than the four major classes of insecticides

##### 4.2.3.1. Peptide insecticides

Development of useful peptide fungicides was described in the previous section 4.1.3.2; however, in the field of insecticides, two products have also been developed and marketed. Table 14 shows information on the two launched peptide insecticides, and their chemical structures are shown in Fig. 12.

**GS-omega/kappa-Hctx-Hv1a** (HXTX, Spear®-T, Vestaron), derived from the venom of the Australian Blue Mountains funnel web spider (*Hadronyche versuta*), is a biological insecticide for the treatment of thrips, whiteflies, two-spotted spider mites, and broad mites in vegetables and ornamentals in greenhouses.<sup>55,116</sup> HXTX is composed of 41 amino acid residues and forms by three disulfide bonds a three-dimensional structure called the inhibitor cystine-knot motif (ICK).<sup>55</sup> HXTX was initially thought to act on calcium and potassium channels, but it was later revealed that it acted as a positive allosteric modulator of insect nicotinic acetylcholine receptors (nAChRs) (IRAC Group 32).<sup>117</sup> HXTX has been marketed in the USA, Canada, and Mexico, followed by European countries.

**Clitoria ternatea Extract** (Sero-X®, Innovate Ag) is an insecticide whose active ingredient is an extract from the butterfly pea (*Clitoria ternatea*), a widespread tropical legume.<sup>55,118</sup> It contains more than 40 cyclotides that are remarkably effective in pest control and is active against several pests, including thrips, mites, and whiteflies. Clitoria ternatea Extract is currently registered and commercialized for use on cotton and several other crops in Australia.

##### 4.2.3.2. Various insecticides with novel or unknown modes of action

As shown in Table 15, 15 insecticides with novel or unknown

Table 14. Developmental status of peptide insecticides

| Active ingredient name    | Product name                | Company name            | Registration information | Remarks: structure/mode of action                                                                                                                                                                                                         |
|---------------------------|-----------------------------|-------------------------|--------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| GS-omega/kappa-Hctx-Hv1a  | Spear®-T Liquid Concentrate | Vestaron (the USA)      | 2018 (the USA)           | A peptide insecticide consists of 41 amino acid residues derived from spider venom. Nicotine acetylcholine receptor (nAChR) allosteric modulator                                                                                          |
| Clitoria Ternatea Extract | Sero-X®                     | Innovate Ag (Australia) | 2017 (Australia)         | An insecticide whose active ingredient is an extract from the legume plant, the Butterfly Pea. Exhibits not only direct toxicity, but also antifeedant, repellent, and oviposition inhibitory activities against pests such as whiteflies |

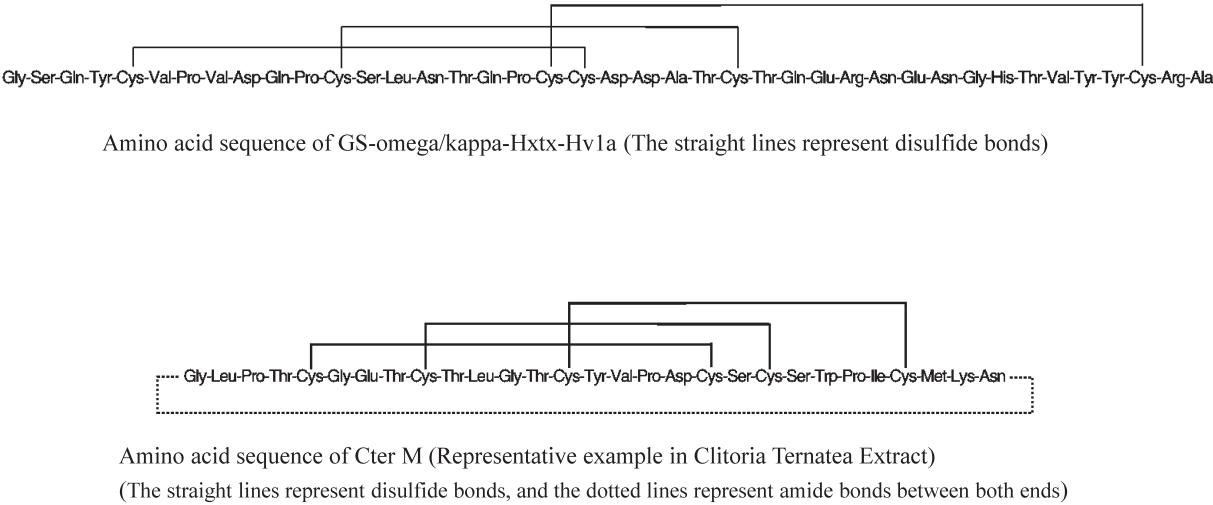


Fig. 12. Structures of peptide insecticides.

modes of action have been subjected to development since 2015. Their chemical structures are shown in Fig. 13 and Fig. 14. Of these insecticides, the development status and structure of led-prona (RNAi-based insecticide) will be mentioned in the next

section and those of sulflummin will be mentioned in the “Acaricide” section.  
**Flometoquin** (Finesave®, Gladius®, Kamui®, Masurao®, Nippon Kayaku/Meiji Seika Pharma, currently Mitsui Chemicals

Table 15. Other insecticides with novel or unknown modes of action

| Common name      | Company name                                        | Registration year in Japan | Remarks: mode of action                                                                                                                                                     |
|------------------|-----------------------------------------------------|----------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Flometoquin      | Meiji Seika Pharma <sup>a)</sup> /<br>Nippon Kayaku | 2018                       | Inhibits complex III by binding to the Qi site                                                                                                                              |
| Afidopropen      | Meiji Seika Pharma <sup>a)</sup> /<br>BASF          | 2022                       | Binds to the TRPV (Transient Receptor Potential Vanilloid) channel complex in chordotonal organs, disrupts channel gating, and inhibits normal signaling in sensory neurons |
| Oxazosulfyl      | Sumitomo Chemical                                   | 2021                       | Novel sulfyl class of insecticide. Vesicular acetylcholine transporter (VACHT) inhibitor                                                                                    |
| Cybenzoxasulfyl  | Nihon Nohyaku                                       | 2024*                      | Oxazosulfyl related compound. Probably Vesicular acetylcholine transporter (VACHT) inhibitor                                                                                |
| Tyclopyrazoflor  | Dow: Currently Corteva Agriscience                  | 2017*                      | Pyridinyl pyrazole compound. Interferes with the insect’s neurotransmission system, causing the insect to act out of order                                                  |
| Tiapyrachlor     | Corteva Agriscience                                 | 2024*                      | Tyclopyrazoflor related compound                                                                                                                                            |
| Indazapyroxamet  | FMC                                                 | 2021*                      | Novel 3-pyridinyl insecticide. Chordotonal organ TRPV (transient receptor potential Vanilloid) modulator                                                                    |
| Dimpropyridaz    | BASF                                                | 2018*                      | Pyridazine pyrazole carboxamide. Inhibits chordotonal organ function upstream of TRPV channels                                                                              |
| Nicofluprole     | Bayer                                               | 2020*                      | Phenylpyrazole class insecticide. Selective antagonistic activity on insect GABA receptors                                                                                  |
| Flupyroxystrobin | Syngenta                                            | 2022*                      | The first strobilurin insecticide. Probably respiratory inhibitor of Qo mitochondria                                                                                        |
| Sulflummin       | Bayer                                               | 2023*                      | Insecticides and acaricides. Listed in the “Acaricide” section                                                                                                              |
| Flumetnicam      | Syngenta                                            | 2024*                      | Metabolite of flonicamid and has insecticidal activity (nicotinamide insecticide.) Potent chordotonal organ modulator                                                       |
| Trioxylanilide   | Zhejiang Udragon Pesticides and Chemicals           | 2024*                      | Novel meta-diamide compound containing heptafluoroisopropyl group, structure being like broflanilide (GABA-gated chloride channel allosteric modulators)                    |
| Vinylfluthrin    | Jiangsu Yangnong Chemical                           | 2025*                      | Novel pyrethroid insecticide                                                                                                                                                |
| Ledprona         | GreenLight Biosciences                              | 2022*                      | RNAi-based insecticide, classified into IRAC Group 35 . See the “RNAi-based pesticides” section                                                                             |

\*Year of ISO common name given, <sup>a)</sup> Currently Mitsui Chemicals CLS. Note: Tigolaner and umifoxolaner obtained ISO common names in February 2022, but both are thought to be veterinary drugs (insecticides and acaricides).

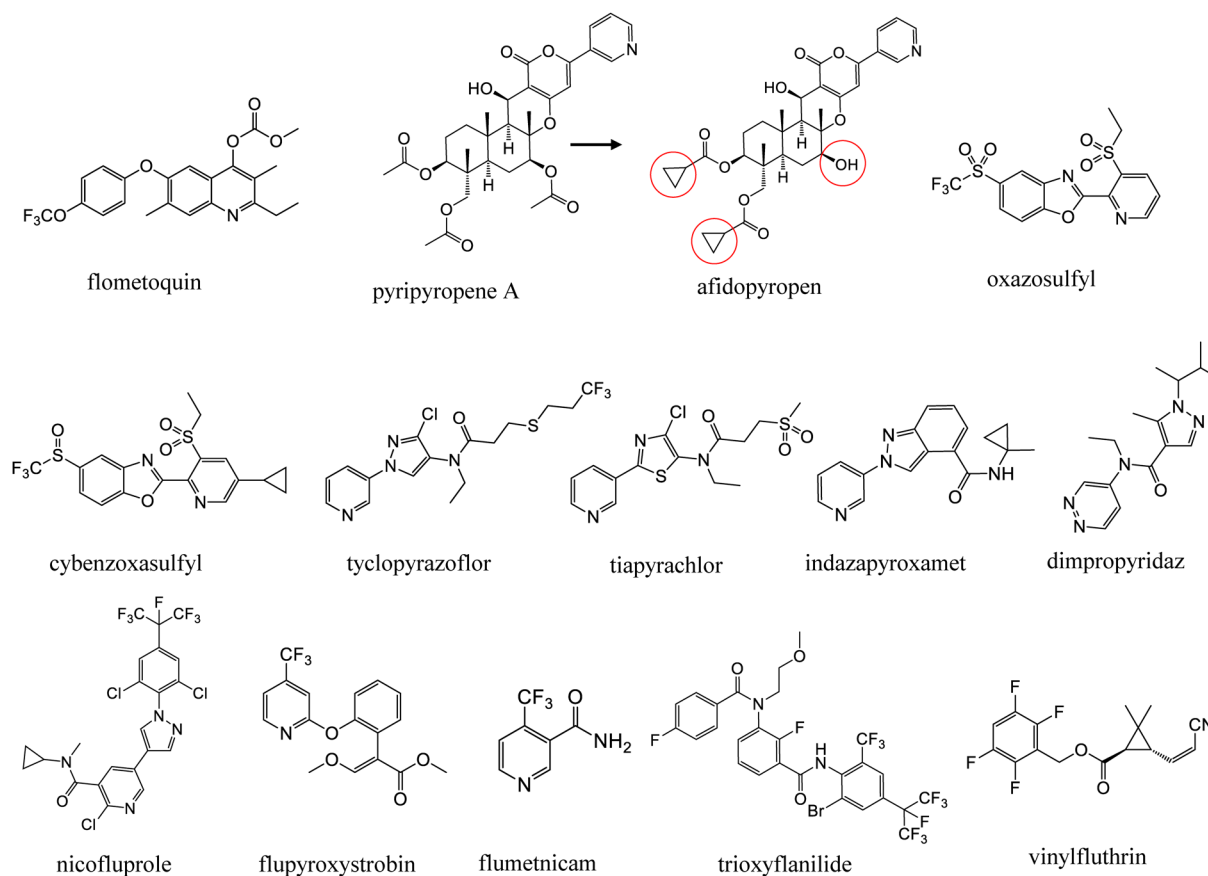


Fig. 13. Chemical structures of other insecticides with novel modes of action or unknown and their related compounds.

CLS) possesses a unique 6-phenoxy quinoline structure and demonstrates strong and quick insecticidal action against a variety of thrips species at the nymphal and adult stages through contact and feeding activity.<sup>119)</sup> Flometoquin is the first insecticide to inhibit the Qi site of mitochondrial respiratory chain complex III and is the only compound classified in Group 34.<sup>120)</sup> Flometoquin is registered in Japan, South Korea, and other countries.

**Afidopyropen** (Inscal<sup>®</sup>, Sefina<sup>®</sup>DC, Meiji Seika Pharma: currently Mitsui Chemicals CLS/BASF) is a structurally modified compound of pyripyropene A, isolated from the culture medium of *Aspergillus fumigatus* in 1992 by a group led by 2016 Nobel Prize winner Dr. Satoshi Omura of the Kitasato Institute. It shows a selective spectrum against sucking pests, such as aphids and whiteflies, and has low impact on non-target organisms.<sup>121,122)</sup> Afidopyropen has been registered in more than 23 countries, including Australia, India, the USA, and Japan. It is the only insecticide classified into Group 9D of chordotonal organ TRPV channel modulators in the IRAC.<sup>122)</sup>

**Oxazosulfl** (Alles<sup>®</sup> granule, Sumitomo Chemical) belongs to a new chemical class, the sulfl group, which is structurally characterized by its ethylsulfonyl moiety. It exhibits excellent control against a broad range of major rice insect pests, including Hemiptera, Coleoptera, Lepidoptera, and Orthoptera, through nursery-box treatment.<sup>123,124)</sup> Initially, the action

of oxazosulfl was reported to be linked to its interaction with the voltage-gated sodium channel; however, it was later revealed that the primary point of action is the inhibition of the vesicular acetylcholine transporter (IRAC Group 37).<sup>124,125)</sup> Oxazosulfl was registered in Japan in 2021.

**Cybenzoxasulfl** (Nihon Nohyaku) is a novel sulfl class of

#### Base sequence of sense strand

```
001 AGGUGCGGCA GACUGUGUUU AUUGGGACCG UGUACUGGCC AAACAAUGUA
051 GAAUGUAUGA AUUAAGGAAC AGGGAGCGUA UUCUGUAGC AGCUGCUUC
101 AAAUUGAUGG CAAACAUUGU AUACAAUUAAC AAGGGAUUGG GACUGUCAAU
151 GGGAAUGAUG UUAGCAGGAU GGGAUAAAAG AGUAAACUCC GAGGGUACCA
201 GAACACCUUG AAAAGUCUUU AGUGUGGGUU CAGGUUCAAU UUAUGCAUUU
251 GGUGUCUUGG AUUCCGGAUA CAAUUGGGAU UUGACGGAUG AGGAGGCUUA
301 CGAUUUGGGU CGCAGGGCGA UUUACCAUGC CACACACAGA GAUGCCUACU
351 CUGGAGGUUAU CGUGAGGGUU UAUACACAGA AGGAGACUGG UUGGAUACAU
401 AUUGAUACA AUGAUUGUAA UGAUUUACAU UAAAGUACC AGGCGAGAA
451 GGAAGAUUUG
```

#### Base sequence of antisense strand

```
001 UCCACGCCGU CUGACACAAA UAACCCUGGC ACAUGACCGG UUUUUUACAU
051 CUUACAUACU UAAUUCUUG UCCUCGCAU AAAGACAUCC UCGACGAAGG
101 UUUUACUACC GUUUGUACCA UAUUGUAAUG UUCUUUACC CUGACAGUUA
151 CCCUACUAC AAUCGUCCUA CCUUAUUUUC UCAUUUGAGG CUCCAUUGGU
201 CUUGUGGACC UUUUCAGAAA UCACACCCAA GUCCAAGUUA AAUACGUAAA
251 CCACAGAACC UAAGGCCUUA GUUUACCUA AACUGCCUAC UCCUCGGAU
301 GCUAAACCA GCGUCCGCU AAUUGGUACG GUGUGUGUCU CUACGGAUGA
351 GACCUCAUA GCACUCCAA AUAGUGUACU UCCUCUGACC AACCUAUGA
401 UACUAUUUGU UACUAACAUU ACUAAAUGUA AUUUUACUUG UCCGACUUCU
451 CCUUCUAAAC
```

Fig. 14. Structure of ledprona. \* A: adenine, C: cytosine, G: guanine, U: uracil.

insecticide that is highly effective against difficult-to-control pests of Lepidoptera and Coleoptera. It was shown that cybenzoxasulflor binds directly to the vesicular acetylcholine transporter (VACHT).<sup>126)</sup> Cybenzoxasulflor is scheduled to apply for Japanese pesticide registration in 2025.

**Tyclopyrazoflor** (Dow, currently Corteva Agriscience) is a pyridinyl pyrazole insecticide that has the best control effect on *Bemisia tabaci*, *Rhynophorus ferrugineus*, and nightshade aphids. It exhibits high insecticidal activity approaching that of imidacloprid against green peach aphids.<sup>74,127)</sup> It has been reported that tyclopyrazoflor mainly interferes with the insect's neurotransmission system, causing the insect to act out of order, ultimately killing the pest.<sup>128)</sup>

**Indazaproxamet** (FMC) is a novel 3-pyridinyl insecticide that targets aphids on high-value specialty crops (vegetables, potatoes, tree fruits, etc.) and row crops (cereals, cotton, corn, soybeans, etc.).<sup>129,130)</sup>

The mode of action of indazaproxamet is thought to be a chordotonal organ TRPV (transient receptor potential Vanilloid) channel modulator (IRAC Group 9).<sup>130,131)</sup>

**Dimpropyridaz** (Axalion® active, Efficon®, Durilon®, BASF) is a pyridazine pyrazolecarboxamide class insecticide that is effective against key piercing, sucking, and rasping pests, including whiteflies, aphids, leafhoppers, psyllids, mealybugs, scales, and thrips in a variety of crops, including fruits, vegetables, soybeans, cotton, corn, and cereals.<sup>132)</sup> Dimpropyridaz is metabolized in target insects to its active form, which inhibits chordotonal organ function upstream of TRPV channels (IRAC Group 36, targeting a new site in chordotonal organs).<sup>132,133)</sup> Dimpropyridaz (Efficon®) was first launched in Australia in 2023, followed by India in 2024.

**Nicofluprole** (Bayer) is a novel phenylpyrazole insecticide with selective antagonism against insect GABA receptors, which play a key role in inhibitory neurotransmission in the insect nervous system.<sup>134)</sup>

Information is limited on the development of **flupyroxystrobin** (Syngenta), **flumetnicam** (Syngenta), **trioxyflanilide** (Zhejiang Udragon Pesticides and Chemicals), and **vinylfluthrin** (Jiangsu Yangnong Chemical), which have acquired ISO common names since 2022. Only currently available information is shown in Table 15. Regarding **sulfluminal** (Bayer), since this product has acaricidal activity, it will be dealt with in the section on acaricides.

#### 4.2.3.3. RNAi-based pesticides

In recent years, efforts to develop pesticides using RNA interference (RNAi) have become more common. RNAi-based pesticides function by using the RNAi effect to inhibit the expression of a gene that is essential for the survival of the target crop pest, thereby suppressing the vital biology of the pest and even causing death.<sup>135)</sup> RNAi-based pesticides are considered promising novel pest management products that might reduce environmental impacts as compared to conventional pesticides. To date, two RNAi-based pesticides (one insecticide and one acaricide) have obtained ISO common names and are under development.

This section describes the RNAi-based insecticide currently under development (see Table 15). The RNAi-based acaricide will be discussed in the “Acaricide Development” section.

**Ledprona** (Calantha™, GreenLight Biosciences) is a double-stranded ribonucleic acid (dsRNA) that prevents the production of a specific protein in the Colorado potato beetle (*Leptinotarsa decemlineata*) by a process known as RNAi<sup>136)</sup> (classified into IRAC Group 35). Ledprona is a large molecule containing 490 base pairs, so the structure is presented as the sequence of the purine and pyrimidine bases adenine (A), cytosine (C), guanine (G), and uracil (U) (see the structure in Fig. 14). Sequences at the ends, known as ITS (internal transcript sequences), are needed to manufacture the dsRNA but have no pesticidal activity. Ledprona is a sprayable product that targets the Colorado potato beetle, a major pest of potato crops. Ledprona was registered for 3 years as a biopesticide product in December 2023 in the USA.<sup>137)</sup>

### 4.3. Acaricides

#### 4.3.1. General trends in development

Some acaricides have only acaricidal activity; however, many cases have been developed as acaricides/insecticides or acaricides/nematicides that also have insecticidal or nematocidal activity. The key acaricides have changed over time due to the development of resistance. Although there were only a limited number of modes of action for acaricides until the 1990s, since the 2000s, acaricides with various modes of action have been developed. This trend has become more pronounced since the 2010s. Acaricides developed since 2015 are classified as inhibitors of the mitochondrial electron transport chain complex II, acetyl-CoA carboxylase inhibitors, and acaricides possessing an unknown or novel mode of action. Non-chemically synthesized acaricides have also been developed.

#### 4.3.2. Recently launched or under development inhibitors of the mitochondrial electron transport chain complex II, acetyl-CoA carboxylase inhibitors, and non-chemically synthesized acaricides

As shown in Table 16, two inhibitors of mitochondrial electron transport chain complex II, two acetyl-CoA carboxylase inhibitors, and two non-chemically synthesized acaricides have been subjected to development since 2015. Their chemical structures are shown in Fig. 15.

**Pyflubumide** (Dani-Kong, Noblesse®, Nihon Nohyaku) is a new carboxanilide acaricide that exhibits excellent acaricidal activity against *Tetranychus* and *Panonychus* species, including strains that have developed resistance to conventional acaricides. Pyflubumide is classified as Group 25B in IRAC in mitochondrial complex II electron transport inhibitors, since its binding site is different from previous acaricides (*Beta*-ketonitrile derivatives: cyflumetofen and cyenopyrafen, IRAC Group 25A).<sup>138,139)</sup> Pyflubumide was registered and launched in Japan in 2015 and South Korea in 2017.

**Cyetypyrafen** (Sinochem) is a new acaricide that obtained an ISO common name in 2020, but it has been marketed in China since 2016.<sup>74)</sup> It is presumed to be an inhibitor of the mitochon-

**Table 16.** Recently launched or under development inhibitors of the mitochondrial electron transport chain complex II, acetyl-CoA carboxylase inhibitors, and non-chemically synthesized acaricides

| Common name or product name                                         | Company name                              | Registration year in Japan | Remarks                                                                                                                                  |
|---------------------------------------------------------------------|-------------------------------------------|----------------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| Inhibitors of the mitochondrial electron transport chain complex II |                                           |                            |                                                                                                                                          |
| Pyflubumide                                                         | Nihon Nohyaku                             | 2015                       | The mode of action is the same as the previous two acaricides, but the site of action is different                                       |
| Cyetypyrafen                                                        | Sinochem                                  | 2020*                      | Presumed to be an inhibitor of the mitochondrial electron transport chain complex II                                                     |
| Acetyl-CoA carboxylase inhibitors                                   |                                           |                            |                                                                                                                                          |
| Spiropidion                                                         | Syngenta                                  | 2017*                      | Listed in the “Insecticides” section                                                                                                     |
| Spirobudifen                                                        | Zhejiang Udragon Bioscience <sup>a)</sup> | 2022*                      | An analog of spiroadiclofen registered in Japan in 2003. Presumed to be an inhibitor of acetyl-CoA carboxylase                           |
| Non-chemically synthesized acaricides                               |                                           |                            |                                                                                                                                          |
| Formulated oil (safflower oil and cottonseed oil)                   | OAT Agrio/RIKEN                           | 2015                       | The mode of action is suffocation by spiracles blockage, but at the same time it inhibits larval escape behavior in eggs during hatching |
| Polyglycerol esters of fatty acids                                  | Nippon Kayaku                             | 2016                       | The mode of action is spiracles blockage                                                                                                 |

\*Year of ISO common name given. <sup>a)</sup> A subsidiary of Zhejiang Udragon Pesticides and Chemicals Co., Ltd.

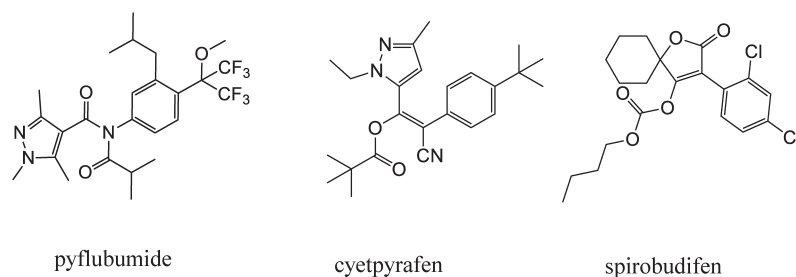
drial electron transport chain complex II based on the similarity in chemical structure to cyenopyrafen (IRAC Group 25A). Cyetypyrafen is effective against the agricultural mite pest (*T. cinnabarinus*) but not the natural enemy (*N. californicus*) of *T. cinnabarinus*.<sup>140)</sup>

**Spirobudifen** (Zhejiang Udragon Bioscience) is a tetrionic acid acaricide that obtained an ISO common name in 2022. The mode of action of spirobudifen is presumed to be the inhibition of acetyl-CoA carboxylase due to the similarity of its chemical structure with that of spiroadiclofen (IRAC Group 23).

**Formulated oil** (safflower oil and cottonseed oil 97%, Suf-

foil® emulsion, OAT Agrio/RIKEN) is an insecticide, acaricide, and fungicide, and it is effective against spider mites, whiteflies, aphids, rust mites, dust mites, and powdery mildew.<sup>141)</sup> It can be used at a relatively high dilution ratio of 300 to 500 times (compared to machine oil). Formulated oil has dual modes of action, i.e., spiracle blockage and killing mites by ovicidal activity. Formulated oil strongly adhered to *T. urticae* eggs, seeped through the chorion being cut during hatching, and inhibited the embryonic rotational movement necessary for cutting and hatching.<sup>142)</sup>

**Polyglycerol ester of fatty acid** (82.5% Emulsifiable Concentrate, Fumon®, Nippon Kayaku), which categorized in food ad-



pyflubumide

cyetypyrafen

spirobudifen

Diverse chemical structure composed of multiple fatty acids

Formulated oil

$\text{RO}-(\text{CH}_2-\text{CH}(\text{OR})-\text{CH}_2-\text{O})_n-\text{R}$

n-10 (Average degree of polymerization calculated from the hydroxyl value of the constituent polyglycerol)

R: Fatty acid residue or hydrogen atom (Approximately 10 moles of fatty acid are bonded to 1 mole of polyglycerol)

polyglycerol esters of fatty acid

**Fig. 15.** Chemical structures of inhibitors of mitochondrial electron transport chain complex II, acetyl-CoA carboxylase inhibitors and non-chemically synthesized acaricides.

**Table 17.** Other acaricides with novel or unknown modes of action

| Common name      | Company name                                     | Registration year in Japan | Remarks: structure/mode of action                                                                                                                                                   |
|------------------|--------------------------------------------------|----------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Fluxametamide    | Nissan Chemical                                  | 2019                       | Listed in the “Insecticides” section                                                                                                                                                |
| Isocycloseram    | Syngenta                                         | 2018*                      | Listed in the “Insecticides” section                                                                                                                                                |
| Acynonapyr       | Nippon Soda                                      | 2019                       | Block of $\text{TurKCa2}$ channels in a concentration-dependent manner                                                                                                              |
| Flupentiofenox   | Kumiai Chemical                                  | 2020*                      | Inhibition of the mitochondrial $\beta$ -oxidation pathway of fatty acids                                                                                                           |
| Sulflufumin      | Bayer                                            | 2023*                      | Similar chemical structure to flupentiofenox, having a trifluoroethyl phenylsulfoxide structure                                                                                     |
| Bisulflufen      | Jiangsu Yangnong Chemical <sup>a)</sup>          | 2023*                      | Similar chemical structure to flupentiofenox and sulflufumin                                                                                                                        |
| Bentioflumin     | Shandong Kangqiao Biotechnology                  | 2024*                      | Similar chemical structure to flupentiofenox, sulflufumin and bisulflufen                                                                                                           |
| Trifluenfurunate | Shandong United Pesticide Industry <sup>b)</sup> | 2021*                      | Since it also has nematocidal properties, it is listed in the “Nematicides” section                                                                                                 |
| Vadescana        | GreenLight Biosciences                           | 2025 (the USA)             | RNAi-based acaricide. Large molecule containing 372 base pairs                                                                                                                      |
| Sulfindoflufen   | Jiangsu Shaanxi Sunger Road Bio-Science          | 2025*                      | Aryltrifluoroethylsulfide-based acaricide and insecticide. Similar chemical structure to sulflufumin. It shows particularly high efficacy against <i>Tetranychus cinnabarinus</i> . |

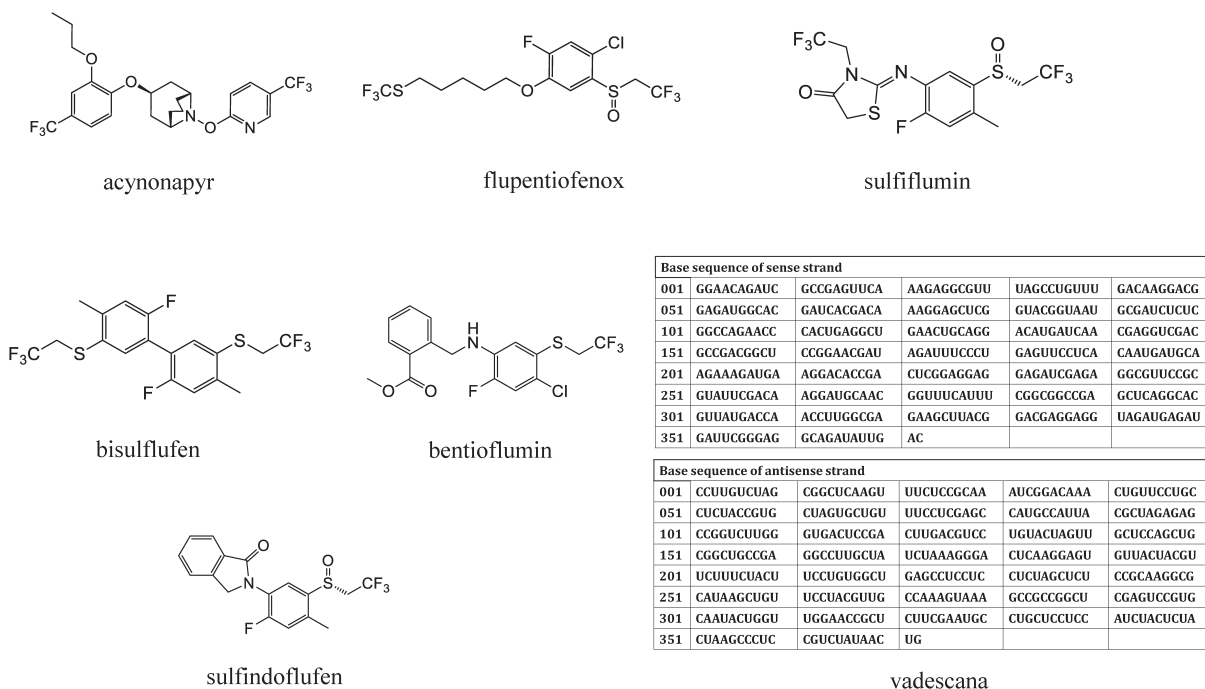
\* Year of ISO common name given, <sup>a)</sup> Subsidiary “Shenyang Sinochem Agrochemicals R&D Co., Ltd.” is in charge of the development, <sup>b)</sup> A wholly owned subsidiary of Shandong Sino-Agri United Biotechnology Co., Ltd.

ditives is an insecticide, acaricide, and fungicide.<sup>143)</sup> Its mode of action is spiracle blockage. Polyglycerol ester of fatty acid is registered and marketed only in Japan.

#### 4.3.3. Trends of various acaricides with novel or unknown modes of action

As shown in Table 17, ten acaricides with novel or unknown modes of action have been subjected to development since 2015.

Of these, two compounds (fluxametamide and isocycloseram) have been listed and described in the insecticide section because they have high insecticidal activity in addition to acaricidal activity. One compound (trifluenfurunate) will be listed and described in the nematocide section because it has high nematocidal activity. The chemical structures of the remaining seven acaricides are shown in Fig. 16.



\* A: adenine, C: cytosine, G: guanine, U: uracil

**Fig. 16.** Chemical structures of various acaricides with novel modes of action or unknown and structure of vadescana.

**Acynonapyr** (Cynazet™, Daniote Flowable®, Nippon Soda) is a novel acaricide with *N*-pyridyloxy azabicyclo as a unique core structure. It exhibits high activity against spider mite species in the genera *Tetranychus* and *Panonychus* on fruits and vegetable crops, with good efficacy at all life stages.<sup>144)</sup> Acynonapyr and its analogs block TurK<sub>Ca2</sub> channels in a concentration-dependent manner and were classified as members of a new group of IRAC (Group 33: calcium-activated potassium channel modulators) in 2021.<sup>144,145)</sup> Acynonapyr was marketed in October 2020 in Japan and South Korea for use on fruits and vegetable crops.

**Flupentiofenox** (Danimaster Wettable powder, Kumiai Chemical) has a unique trifluoroethyl phenylsulfoxide structure and is effective against spider mites *Tetranychus urticae* and *Panonychus citri* at all developmental stages, including those with resistance to multiple commercial acaricides.<sup>146)</sup> Flupentiofenox is assumed to have a new mode of action. It inhibits the mitochondrial fatty acid metabolic pathway between the uptake of long-chain acylcarnitine or medium-chain fatty acid and the synthesis of acetyl-CoA by  $\beta$ -oxidation, resulting in suppressed mitochondrial energy generation.<sup>147)</sup>

**Sulfiflumin** (Bayer), **bisulfufen** (Jiangsu Yangnong Chemical), and **bentioflumin** (Shandong Kangqiao Biotechnology), which have acquired ISO common names after 2023, are all similar in chemical structure to flupentiofenox. The mode of action of the three acaricides is assumed to be the same as that of flupentiofenox.

**Vadescana** (GreenLight Biosciences) is a double-stranded ribonucleic acid (dsRNA). It is a large molecule containing 372 base pairs<sup>148)</sup> that is designed to specifically control *Varroa destructor*, the Varroa mite which is an external parasitic mite that attacks and feeds on honey bees and is one of the most damaging honey bee pests in the world. The US EPA proposed registering vadescana in May 2025.<sup>149)</sup> Vadescana is expected to be ex-

empt from the requirement of a tolerance for residues.

**Sulfindoflufen** (Jiangsu Shaanxi Sunger Road Bio-Science) is a novel aryltrifluoroethylsulfide-based acaricide and insecticide that was just given an ISO common name in August 2025.

#### 4.4. Nematicides

##### 4.4.1. General trends in development

The methods of controlling plant-parasitic nematodes are largely divided into fumigant (gas) treatments and non-fumigant (contact agent) treatments. In recent years, agricultural chemical manufacturers have been actively developing safer non-fumigants. Table 18 summarizes ten non-fumigant nematicides that have been subjected to development since 2015. Of those, galquin has a fungicidal effect, so it is listed in the “fungicide” section. Figure 17 shows the chemical structures of nematicides except for galquin. The recent global developmental status of new nematicides is detailed in a review by Sasami.<sup>150)</sup>

**Fluopyram** (Velum™ Prime, Verango® Prime, NemaClean®, Bayer) was initially developed as a fungicide but was later patented for its nematocidal activity and was also developed as a nematicide.<sup>150)</sup> Fluopyram, an SDH inhibitor, impairs ATP generation and causes paralysis in plant-parasitic nematodes and *Caenorhabditis elegans*.<sup>151)</sup> It shows high control effects against root-knot nematodes, root-lesion nematodes, cyst nematodes, and potato rot nematodes, and it has excellent residual activity.<sup>150)</sup> Fluopyram has been marketed in many countries. In Japan, it was registered in 2017 as Velum™ Granules by Bayer and NemaClean® granules by Nihon Nohyaku.

**Tioxazafen** (NemaStrike™, Monsanto, currently Bayer) provides consistent broad-spectrum control of nematodes in corn, soy, and cotton with seed treatment. Tioxazafen obtained registration in the USA in 2017, but its sales were suspended in 2020 due to skin irritation in those handling NemaStrike.<sup>152)</sup>

**Table 18.** Recently launched or under development nematicides

| Common name or product name   | Company name                                       | Registration year in Japan | Remarks                                                                                                                                            |
|-------------------------------|----------------------------------------------------|----------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------|
| Fluopyram                     | Bayer                                              | 2017                       | Originally developed as a fungicide, but was later developed as a nematicide                                                                       |
| Tioxazafen                    | Monsanto <sup>a)</sup>                             | 2013*                      | Sales have been suspended due to skin irritation                                                                                                   |
| Fluensulfone                  | ADAMA/Bayer                                        | 2017                       | Inhibits development, egg-laying, egg-hatching, feeding, and locomotion, and mode of action is probably different from existing nematicides        |
| Fluazaindolizine              | Corteva Agriscience                                | 2015*                      | Mode of action is unknown but different from existing nematicides.                                                                                 |
| Garlic extract (Nemguard)     | Ecospray                                           | —                          | The active ingredients are allicin and polysulfides contained in garlic extract. Not developed in Japan                                            |
| Geraniol and thymol (Cedroz™) | Eden Research/Eastman Chemical (Joint development) | —                          | The active ingredients are geraniol and thymol, which are nature identical. Marketed in many countries, but not developed in Japan                 |
| Cyclobutrifluram              | Syngenta                                           | 2020*                      | Has different modes of action for acaricidal and fungicidal activities, <i>i.e.</i> , IRAC Group N-3 for nematicide and FRAC Class 7 for fungicide |
| Trifluenfuronate              | Shandong United Pesticide Industry <sup>b)</sup>   | 2021*                      | A novel nematicide with low toxicity                                                                                                               |
| Sulfoxamyl                    | Ningxia HugeRise Chemical                          | 2024*                      | Oxime carbamate. Highly effective against root-knot nematodes                                                                                      |
| Galquin                       | Silvateam S.p.A                                    | 2024*                      | Listed in “Fungicide” section                                                                                                                      |

\*Year of ISO common name given, <sup>a)</sup> Currently Bayer, <sup>b)</sup> A subsidiary of Shandong Sino-Agri United Biotechnology.

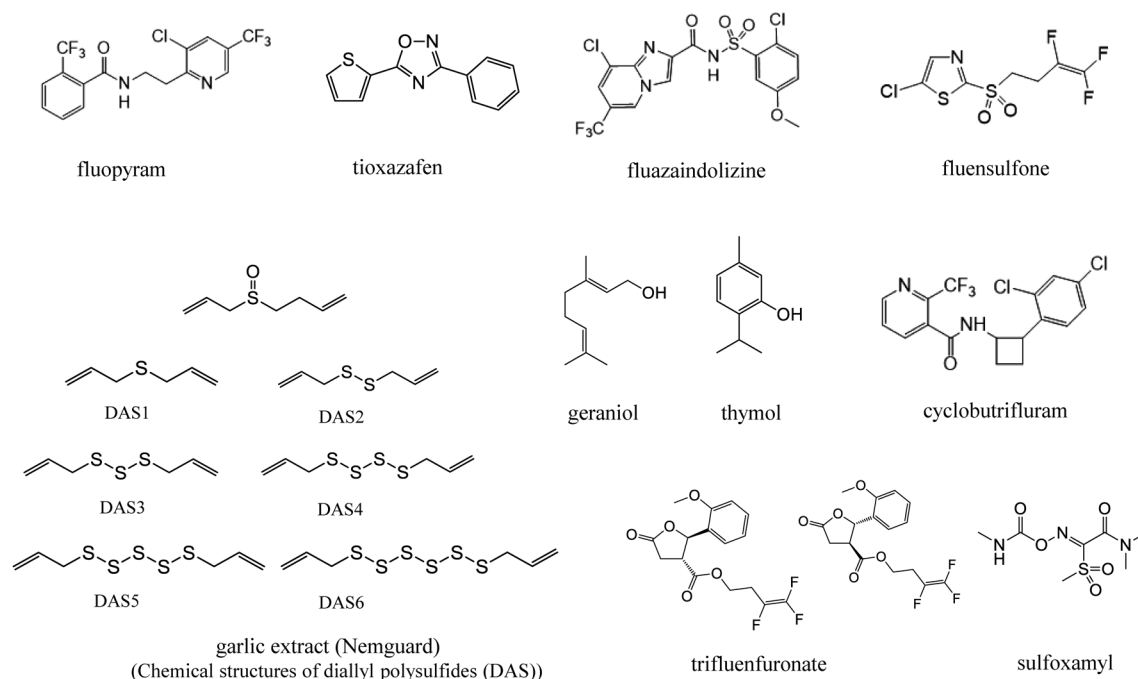


Fig. 17. Chemical structures of recently launched or under development nematicides.

**Fluazaindolizine** (Reklemel™ active, Salibro®, Corteva Agriscience) is the first sulfonamide nematicide, which is a chemical group different from other commercial nematicides. Fluazaindolizine has excellent activity on root-knot nematodes and many other important plant-parasitic nematode species on vegetables and some fruits.<sup>150,153</sup> The mode of action of fluazaindolizine is unknown, but it appears to be different from all other currently available nematicides.<sup>153</sup> Fluazaindolizine was registered in Australia, Canada, and the USA in 2021.

**Fluensulfone** (Nimitz®, Nemashot®, ADAMA and Bayer) is a new nematicide of the fluoroalkenyl thioether group that has an excellent effect on root-knot nematodes and significantly reduces environmental impact with low toxicity to non-target insects and mammals.<sup>154,155</sup> It was registered in the USA and Israel in 2014 for fruits and vegetables. In Japan, it was registered in 2017 as Nemashot® granules by ADAMA Japan and SDS Biotech but not marketed. Fluensulfone inhibits development, egg-laying, egg-hatching, feeding, and locomotion.<sup>154</sup>

**Garlic extract** (Nemguard SC, NEMguard®, Ecospray) is a non-chemically synthesized soil-applied nematicide. It contains biologically active ingredients such as allicin and the diallyl polysulfides, containing one to six sulfur atoms in a linear chain<sup>156</sup> (see chemical structures in Fig. 17). Diallyl polysulfide molecules penetrate through the cuticle, and a lethal biochemical chain reaction begins, which causes the nematode to die due to oxidative stress. Nemguard (garlic extract) has been registered for use on a range of crops, including carrots, potatoes, and tomatoes in many countries, such as the UK, EU countries (Italy, France, Spain, etc.), the USA, and South Korea but not Japan.

**Geraniol and Thymol** (Cedroz™, Eden Research/Eastman

Chemical) are two active ingredients that have excellent nematocidal properties together. Cedroz™ is a new post-planting, terpene-based nematicide for the control of root-knot nematodes in fruit and vegetables.<sup>157</sup> The two active compounds, geraniol and thymol (nature identical), together have a synergistic mode of action that increases their efficacy in treated soil. The primary mode of action of thymol and geraniol is to accumulate in cell membranes, causing the loss of integrity of the membranes due to a change in the composition of fatty acids and phospholipids with consequent lysis, release of cellular substances, and ultimately the death of the cell.<sup>150,157</sup> Cedroz™ is registered in many EU countries such as Italy, Spain, and France, as well as Mexico and the USA.

**Cyclobutrifluram** (Tymirium® active, Victrato®, Vaniva®, Syngenta), a chiral phenyl-cyclobutyl-pyridineamide, demonstrates wide-ranging effectiveness against all economically important plant parasitic nematodes and several soil-borne diseases, particularly those caused by *Fusarium* species. It is highly effective against root-knot nematodes and beet cyst nematodes on cucumber, tomato, corn, and sugar beet.<sup>158,159</sup> Regarding the mode of action, cyclobutrifluram is now classified as IRAC Group N-3 (mitochondrial complex II electron transport inhibitors, succinate-coenzyme Q reductase) for nematicide action and FRAC Class 7 (complex II succinate dehydrogenase inhibitor: SDHI) for fungicidal action.<sup>158</sup> Cyclobutrifluram was already registered in many countries such as Argentina, Brazil, and China and will be soon in the USA (in 2025).

**Trifluenfuramate** (Shandong United Pesticide Industry) is a fluoroalkenyl nematicide and acaricide. As compared to traditional chemical nematicides, trifluenfuramate exhibits three

**Table 19.** Year of marketing and period of elucidation of the mode of action of herbicides by the site of action<sup>a)</sup>

| HRAC classification | Site of action                                      | Active ingredient | Year of marketing | Period of elucidation of mode of action |
|---------------------|-----------------------------------------------------|-------------------|-------------------|-----------------------------------------|
| 1                   | Acetyl-CoA carboxylase (ACCase)                     | diclofop-methyl   | 1970              | 1987                                    |
| 2                   | Acetolactate synthase (ALS)                         | chlorsulfuron     | 1980              | 1984                                    |
| 3                   | Microtubule assembly                                | trifluralin       | 1960              | 1977                                    |
| 4                   | Auxin mimics                                        | 2,4-D             | 1940              | 1944                                    |
| 5                   | Photosynthesis                                      | atrazine          | 1950              | 1956–1975                               |
| 9                   | 5-Enolpyruvylshikimate-3 phosphate synthase (EPSPS) | glyphosate        | 1970              | 1984                                    |
| 10                  | Glutamine synthetase (GS)                           | glufosinate       | 1980              | 1982–1986                               |
| 12                  | Phytoene desaturase (PDS)                           | norflurazon       | 1970              | 1980                                    |
| 13                  | 1-Deoxy-d-xylulose-5-phosphate synthase (DXPS)      | clomazone         | 1980              | 2000                                    |
| 14                  | Protoporphyrinogen IX oxidase (PPO)                 | nitrofen          | 1960              | 1982–1986                               |
| 15                  | Very long-chain fatty acid synthesis (VLCFA)        | propachlor        | 1960              | 1993–2000                               |
| 18                  | Dihydropteroate synthase (DHPS)                     | asulam            | 1960              | 1977                                    |
| 19                  | Auxin transport                                     | naptalam          | 1950              | 1973                                    |
| 22                  | PSI electron diversion                              | paraquat          | 1960              | 1964                                    |
| 27                  | 4-Hydroxyphenyl pyruvate dioxygenase (HPPD)         | pyrazolynate      | 1970              | 1992–1993                               |
| 28                  | Dihydroorotate dehydrogenase (DHODH)                | tetflupyrolimet   | Under development | 2020                                    |
| 29                  | Cell wall (cellulose) synthase                      | dichlobenil       | 1960              | 1974                                    |
| 30                  | Fatty acid thioesterase (FAT)                       | cinmethylin       | 1980              | 2018                                    |
| 31                  | Serine threonine protein phosphatase (STPP)         | endothall         | 1960              | 2020                                    |
| 32                  | Solanesyl diphosphate synthase (SDPS)               | aclonifen         | 1980              | 2020                                    |
| 33                  | Homogentisate solanesyltransferase (HST)            | cyclopyrimorate   | 2020              | 2021                                    |
| 34                  | Lycopene cyclase                                    |                   |                   |                                         |

<sup>a)</sup> The table made by Murakami *et al.*<sup>162)</sup> was revised and modified with reference to the 2024 HRAC Global Herbicide MOA Classification.<sup>163)</sup>

advantages, *i.e.*, low toxicity, no development of pest resistance (it can kill both insects and its eggs), and growth regulation to improve crop quality.<sup>160)</sup> Registration was expected in China by the end of 2023.

**Sulfoxamyl** (Ningxia HugeRise Chemical), which just obtained an ISO common name in 2024, is an oxime carbamate nematicide that is effective against root-knot nematodes.

#### 4.5. Herbicides

##### 4.5.1. General trends in development

Since the 1940s, many herbicides with different modes of action have been developed and provided for commercial use. Table 19 shows the history of the discovery of herbicides with different modes of action, *i.e.*, the year of marketing and period of elucidation of the mode of action by the site of action.

After the launch of clomazone (DXPS inhibitor in the MEP pathway) in the late 1980s, there were no reports on herbicides

with novel modes of action until 2017—approximately 30 years. However, two new herbicides with novel modes of action have appeared since 2018. In addition, several herbicides that have been used for a long time have been shown to have novel modes of action. In 2020, the herbicide RAC code (HRAC) was revised for the first time in 10 years, changing the code from an alphabetical to a numerical notation.<sup>161)</sup> This revision added four new modes of action: fatty acid thioesterase (FAT) inhibition (cinmethylin), homogentisate solanesyltransferase (HST) inhibition (cyclopyrimorate), solanesyl diphosphate synthase (SDPS) inhibition (aclonifen), and serine threonine protein phosphatase (STPP) inhibition (endothall). Furthermore, one novel mode of action, dihydroorotate dehydrogenase (DHODH) inhibition (tetflupyrolimet), was added in HRAC 2022.

The herbicides launched or under development since 2015 will be described based on the review by Murakami *et al.*,<sup>162)</sup> summarizing the herbicide discovery studies up to 2023 and the

**Table 20.** Recently launched or under development ALS-inhibiting herbicides

| Common name    | Company name                | Target crop | Registration year in Japan | Remarks                          |
|----------------|-----------------------------|-------------|----------------------------|----------------------------------|
| Triafamone     | Bayer                       | Paddy rice  | 2016                       | sulfonanilides, Dose: 40–50 g/ha |
| Pyriflubenoxim | Jiangsu Agrochem Laboratory | Paddy rice  | 2022*                      | pyrimidinylsalicylic acids       |

\*Year of ISO common name given.

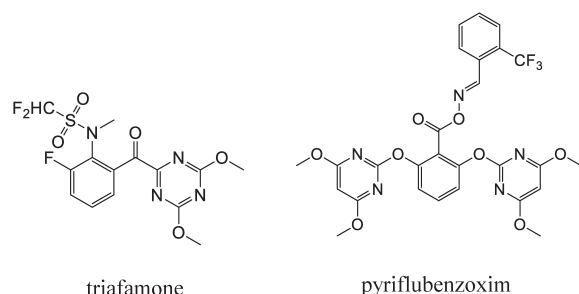


**Fig. 18.** Chemical structures of ALS-inhibiting herbicides.

latest information as of August 2025. Since EPSPS-, GS-, PDS-, DHPS-, and photosynthesis inhibitors and others have not been developed during this period, descriptions of these herbicides have been omitted.

#### 4.5.2. Herbicides developed since 2015

##### 4.5.2.1. Acetolactate synthase (ALS) inhibitors

ALS-inhibiting herbicides include compounds of various classes, such as sulfonylureas, triazolinones, triazolopyrimidines, pyrimidinylsalicylic acids, imidazolinones, and sulfonanilides. Due to resistance issues, the number of ALS-inhibiting herbicides being developed has been declining, and little explorative research has been conducted recently.<sup>162</sup> Table 20 summarizes the ALS-inhibiting herbicides that have been subjected to development since 2015. Their chemical structures are shown in Fig. 18.

**Triafamone** (Council active, Council® Complete (triafamone+tefuryltrione), etc., Bayer) is an herbicide for paddy rice that is highly effective against grass weeds, such as barnyard grass, as well as Cyperaceous weeds.<sup>164</sup> Triafamone was registered and marketed in Japan in 2016 and marketed in many countries such as Indonesia, China, and India.

**Pyrflubenzoxim** (Jiangsu Agrochem Laboratory), which just obtained an ISO common name in 2022, is an herbicide for paddy fields that is effective for controlling not only grass weeds such as barnyard grass, junglerice, knotgrass, and late watergrass but also various broadleaf weeds.<sup>162</sup>

##### 4.5.2.2. 4-Hydroxyphenyl pyruvate dioxygenase (HPPD) inhibitors

Recently, exploratory research has been most actively conducted in the field of HPPD-inhibiting herbicides, and many compounds are currently in the development stage. See Fig. 26 for their mode of action. HPPD inhibitors include triketones, pyrazoles, and isoxazoles, which are classified based on the structure of the acidic moiety and bicyclo ring types (classified as other). In addition, compounds with keto groups at the 1 and 3 positions of the cyclohexane ring are called cyclohexanedione types. These HPPD-inhibiting herbicides offer a high degree of structural flexibility, can be used in both paddy and field crops, and are applicable to a wide range of crops. Furthermore, because there are few reports of resistant weed development, many companies are actively conducting exploratory research. Table 21 summarizes the HPPD-inhibiting herbicides that have been subjected to development since 2015. Their chemical structures are shown in Fig. 19.

**Fenquinotrione** (Effeeda®, Kumiai Chemical) is an HPPD-inhibiting herbicide that can control a wide range of broadleaf and sedge weeds with excellent rice selectivity at 30 g a.i./10 a. It is as effective as the wild type on ALS inhibitor-resistant weeds.<sup>165</sup> Many fenquinotrione mixture products have been developed for paddy use. It is interesting that fenquinotrione has been found to be applicable to a wide variety of rice plants, including forage rice, due to its safety against not only edible rice but also forage rice. The potent demethylating metabolism of

**Table 21.** Recently launched or under development HPPD-inhibiting herbicides

| Common name        | Company name                                            | Target crop | Registration year in Japan | Remarks                                                        |
|--------------------|---------------------------------------------------------|-------------|----------------------------|----------------------------------------------------------------|
| Fenquinotrione     | Kumiai Chemical                                         | Paddy rice  | 2018                       | Cyclohexanedione type compound (triketones) Dose: 250–300 g/ha |
| Lancotrione-sodium | Ishihara Sangyo Kaisha                                  | Paddy rice  | 2019                       | Cyclohexanedione type compound (triketones) Dose: 210 g/ha     |
| Tolpyralate        | Ishihara Sangyo Kaisha                                  | Corn        | 2016                       | Pyrazole-type compound, Dose: 40–50 g/ha                       |
| Dioxopyrithione    | Syngenta                                                | Unknown     | 2021*                      | Cyclohexanedione type compound                                 |
| Bipyrazone         | KingAgroot                                              | Wheat       | 2021*                      | Pyrazole-type compound, Registered in China in 2018            |
| Cypyafluone        | KingAgroot                                              | Wheat       | 2021*                      | Pyrazole-type compound, Registered in China in 2018            |
| Fenpyrazone        | KingAgroot                                              | Corn        | 2021*                      | Pyrazole-type compound, Registered in China in 2019            |
| Tripyrasulfone     | KingAgroot                                              | Paddy rice  | 2021*                      | Pyrazole-type compound, Registered in China in 2019            |
| Benquitrione       | Central China Normal University/Shandong Cynda Chemical | Sorghum     | 2021*                      | Cyclohexanedione type compound, Registered in China in 2020    |
| Ipatriazopyrid     | Nissan Chemical                                         | Paddy rice  | 2022*                      | Possess a novel azole carboxamide structure                    |
| Flusulfenam        | KingAgroot                                              | Paddy rice  | 2022*                      | Structurally like ipatriazopyride                              |
| Pyraquinat         | Central China Normal University/Shandong Cynda Chemical | Paddy rice  | 2023*                      | Benzoylpyrazole compound. Launched in China                    |

\*Year of ISO common name given.

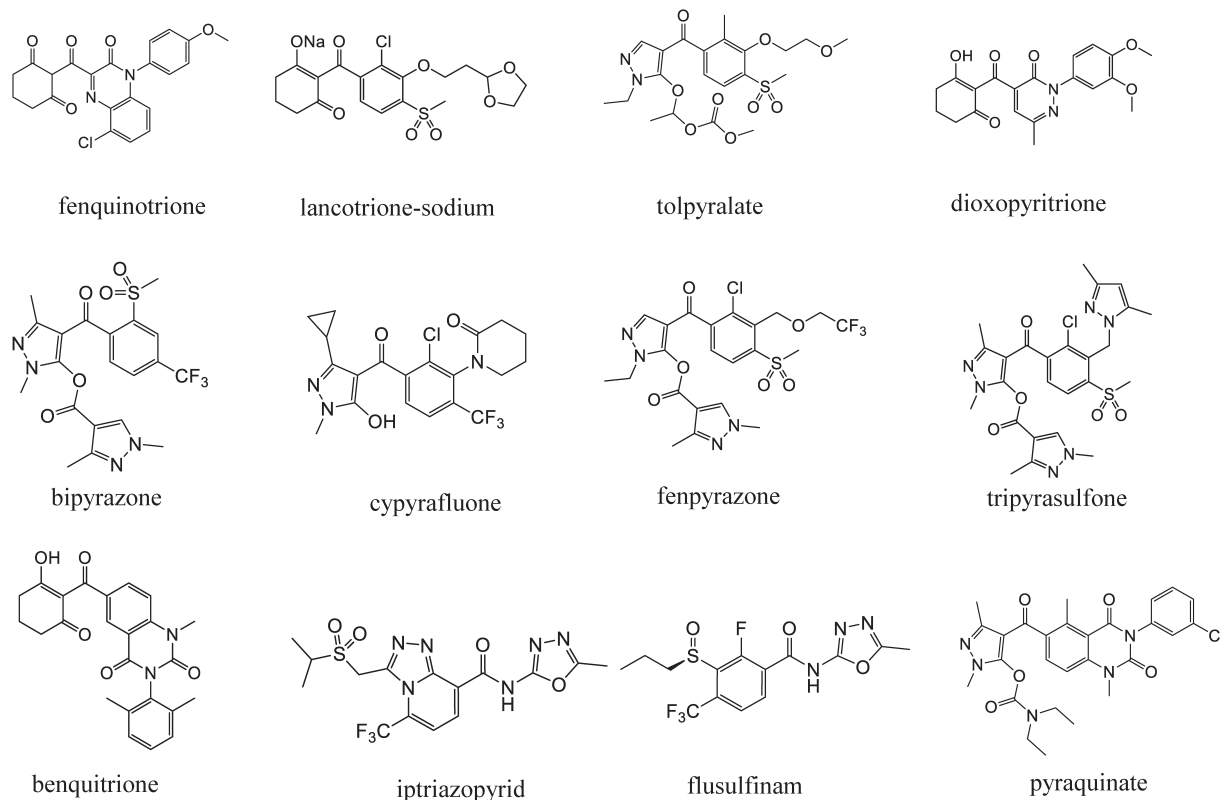


Fig. 19. Chemical structures of HPPD-inhibiting herbicides.

fenquitrione, followed by glucose conjugation in rice, is responsible for the rice selectivity of fenquitrione.<sup>166)</sup>

**Lancotrione-sodium** (Promise® GR, Ishihara Sangyo Kaisha) shows high herbicidal activity against major paddy field weeds such as *Scirpus juncoides*, *Lindernia procumbens*, *Sagittaria pygmaea*, and *Cyperus serotinus* from pre-emergence to the growing stage. It is effective against ALS-resistant *Scirpus juncoides*, even in individuals with high leaf age. It is also effective against difficult-to-control weeds such as arrowhead (*Eleocharis kuroguwai* Ohwi) and sea clubrush (*Bolboschoenus maritimus* (L.) Palla).<sup>162,167)</sup> Lancotrione-sodium was registered in Japan in 2019, and subsequently, a mixture with another herbicide (propyrisulfuron) was marketed (The registration of Promise® GR has expired).

**Tolpyralate** (Brucia® flowable, Shieldex, Raker, *etc.*, Ishihara Sangyo Kaisha) is a new selective post-emergence herbicide developed for weed control in corn. It exhibited excellent herbicidal activity against annual grass and broadleaf weeds at a rate of 30–50 g a.i./ha. Furthermore, it shows high herbicidal activity against glyphosate-resistant weeds, providing an important tool for managing resistant weeds, which has become a major issue worldwide.<sup>168)</sup> Tolpyralate was registered in Japan and many other countries such as South Korea, the Philippines, Argentina, Canada, Chile, Mexico, and the USA.<sup>169)</sup>

**Dioxopyrtrione** (Syngenta) is an arolylcyclohexanedione herbicide and is presumed to be an HPPD inhibitor. Details such as target crops, herbicide spectrum, and developmental progress

are unknown.

The next four herbicides—bipyrazone, cypyrfluone, fenpyrazone, and tripyrasulfone—are all pyrazole HPPD inhibitors, for which KingAgroot (China) simultaneously obtained ISO common names in March 2021. All of these herbicides were registered and marketed in China before ISO common names were obtained.

**Bipyrazone** (KingAgroot), developed as a foliar herbicide for wheat, greatly improves the prevention and control of resistant broad leaves in wheat fields.<sup>162,170)</sup> It is effective against annual broadleaf weeds at the 2 to 5 leaf stage such as *Descurainia sophia* L., *Capsella bursa-pastoris* (L.) Medic., and *Lithospermum arvense* L. The recommended dose rate is 30–37.5 g a.i./ha.

**Cypyrfluone** (KingAgroot) is also an HPPD-inhibiting herbicide in wheat, and it is able to selectively control many annual grasses and some broadleaf weeds by post-emergence application. It targets resistant weeds such as *Alopecurus aequalis*, *Alopecurus japonicus*, *Alopecurus myosuroides*, *Phalaris* spp., and *Snowdenia polystachya*. It is effective on some broad-leaved weeds like *Stellaria media*, *Capsella bursa-pastoris*, and *Brassica campestris*.<sup>171)</sup> Outside of China, cypyrfluone was registered in Pakistan in 2021.

**Fenpyrazone** (Jinyuying®, Jinwenyu®, KingAgroot) is a post-emergence corn herbicide that has a broadened spectrum, including key grasses like *Digitaria sanguinalis*, *Echinochloa crus-galli*, *Eleusine indica*, and *Panicum miliaceum*, along with annual broad-leaved weeds like *Chenopodium album* and *Abutilon theo-*

*phrasti*. The new fluorine structure is more active, more stable, and faster in controlling weeds, with excellent crop selectivity and crop rotation flexibility. The recommended dose rate is 90–135 g a.i./ha.<sup>162,172)</sup>

**Tripyrasulfone** (Daoyu<sup>®</sup>, Daoguying<sup>®</sup>, Jingjie<sup>®</sup>, KingAg-root) is a novel herbicide for post-emergence foliar application in rice that targets *Echinochloa crusgalli*, *Echinochloa oryzicola*, *Leptochloa chinensis*, and other annual grasses. It also suppresses some sedges and *Monochoria vaginalis*. The recommended dose rate is 105–225 g a.i./ha.<sup>162,173)</sup> Outside of China, tripyrasulfone is scheduled to obtain registration in Cambodia, Pakistan, Myanmar, and Indonesia.

**Benquitrione** (Central China Normal University/ Shandong Cynda Chemical) is a novel HPPD-inhibiting herbicide for sorghum. Benquitrione was discovered by Central China Normal University, and the manufacturer is Shandong Cynda Chemical. It showed high activity toward the major weeds in sorghum fields of *S. viridis*, *Chenopodium album*, *Panicum miliaceum*, and *Amaranthus retroflexus*. Field trial studies demonstrated that benquitrione exhibited sufficient and stable crop safety in field conditions with excellent weed control (especially toward *S. viridis* and *P. miliaceum*) in sorghum fields at spraying concentrations of 75–150 g a.i./ha.<sup>174)</sup>

**Ipatriazopyrid** (Nissan Chemical) possesses a novel azole carboxamide structure that is different from those of existing HPPD inhibitors.<sup>175)</sup> Ipatriazopyrid exhibits a strong herbicidal effect without being metabolized by barnyard grass plants, whereas it is rapidly metabolized by rice plants and therefore is highly safe for rice crops.<sup>176)</sup> Ipatriazopyrid is expected to be the first foliar-applied herbicide for paddy rice classified as HRAC Group 27. It is suitable for the direct-seeded rice system. Nissan Chemical aims to launch the product in 2027 (Expected peak sales: 10 billion yen).

**Flusulfenam** (Dao Wu<sup>®</sup>, Dao Pu Rui<sup>®</sup>, KingAgroot) is a new generation of HPPD-inhibiting class-selective herbicides for paddy fields. It effectively controls resistant annual grasses and most broadleaf weeds and sedges, with good rice selectivity. Flu-

sulfenam is an excellent resistance-management tool for rice. The recommended application rate is 60–120 g a.i./ha.<sup>177)</sup> It is suitable for various cultivation models such as wet direct seeded, dry direct seeded, machine transplanting, hand throwing seeding, and manual transplanting. Flusulfenam obtained registration in Cambodia in 2022 and China in 2024.

**Pyraquinat** (Daoqingyang, Central China Normal University/Shandong Cynda Chemical) is an HPPD-inhibiting herbicide for post-emergence stem and leaf treatment in paddy fields. It can effectively prevent and control weeds such as the resistant moleplant seed, *Leptochloa panicea*, young barnyard grass, *Eragrostis japonica*, *Leersia oryzoides*, *Paspalum distichum*, and *Echinochloa crus-galli*, while being highly safe for indica, japonica, waxy rice, and hybrid rice.<sup>178,179)</sup> Pyraquinat obtained registration in China in 2024.

**4.5.2.3. Protoporphyrinogen IX oxidase (PPO) inhibitors**  
Existing PPO-inhibiting herbicides can be divided into diphenyl ether and diaryl types. Currently, diphenyl ether types are hardly being developed, while diaryl types are the focus of development due to their structural diversity. Four diaryl PPO-inhibiting herbicides have been subjected to development since 2015. In addition, exploratory research into pyrazole PPO inhibitors has been conducted in recent years, with one being put into development since 2015. Table 22 summarizes the PPO-inhibiting herbicides that have been subjected to development since 2015. Their chemical structures are shown in Fig. 20.

**Tiafenacil** (Terrador<sup>®</sup>, Terrador Plus<sup>®</sup> (tiafenacil+glyphosate), FarmHannong, Korea) is a non-selective herbicide for foliar application in field crops. It is highly effective against grass weeds and exhibits not only foliar treatment activity but also some soil treatment activity and residual activity, making it suitable for use as a complement to glyphosate and glufosinate during burndown treatment before sowing crops.<sup>162,180)</sup> Tiafenacil demonstrated outstanding performance against glyphosate-resistant weeds amaranth, ragweed, copperleaf, and dayflower. Tiafenacil was registered in 2018 in South Korea, followed by Sri Lanka in 2019 and the USA in 2021.

**Table 22.** Recently launched or under development PPO-inhibiting herbicides

| Common name     | Company name                                                       | Target crop                 | Registration year in Japan | Remarks: Dose, Main target weeds, Development and launch status                                                          |
|-----------------|--------------------------------------------------------------------|-----------------------------|----------------------------|--------------------------------------------------------------------------------------------------------------------------|
| Tiafenacil      | FarmHannong                                                        | Non-selective               | 2013*                      | Dose: 75 g/ha, Target weeds: Grass weeds, broadleaf weeds<br>Mixture with glyphosate was marketed in South Korea in 2018 |
| Trifludimoxazin | BASF                                                               | Non-selective Corn, soybean | 2014*                      | Dose: 37.5–150 g/ha, Target weeds: Grass weeds, broadleaf weeds. Registered in Australia in 2020                         |
| Epyrifenacil    | Sumitomo Chemical                                                  | Non-selective GM crops      | 2020*                      | Dose: 20–40 g/ha, Target weeds: Grass weeds, broadleaf weeds                                                             |
| Flufenoximacil  | KingAgroot                                                         | Non-selective               | 2022*                      | Target weeds: Grass weeds, broadleaf weeds                                                                               |
| Cyclopyranil    | Kyoyu Agri                                                         | Rice                        | 2017*                      | Grass weeds, annual weeds in paddy fields                                                                                |
| Isoxafenacil    | Shenyang Sinochem Pesticide Chemical/Jiangshan Stock <sup>a)</sup> |                             | 2024*                      | An analog of this well-known class of PPO inhibitors                                                                     |

\*Year of ISO common name given, <sup>a)</sup> Nantong Jiangshan Agrochemical and Chemicals Co., Ltd.

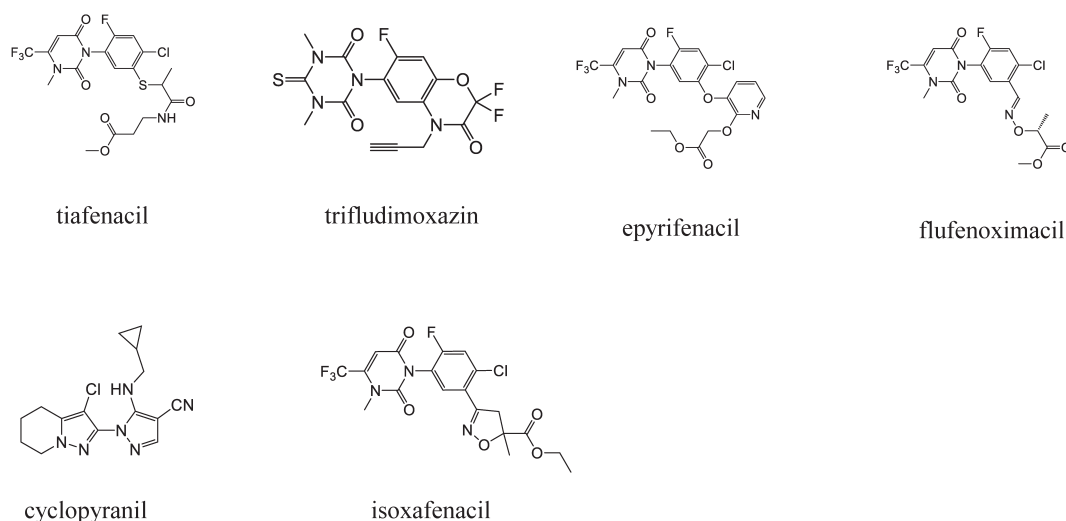


**Fig. 20.** Chemical structures of PPO-inhibiting herbicides.

**Trifludimoxazin** (Tirexor<sup>®</sup>, BASF) is a PPO-inhibiting herbicide for field crops. It has high soil and foliar treatment activity against a wide range of weeds, from broadleaf weeds to grass weeds. It shows relatively low mobility in the soil and good residuality, resulting in potent activity in pre-emergence application on shallow and variable emerging small-seeded broadleaf weeds such as *Amaranthus* species. In addition, trifludimoxazin shows outstanding control of weeds already resistant to existing PPO inhibitors.<sup>162,181</sup> It was registered in Australia in 2020 and in Canada in 2021. It was also registered in the USA, but BASF stopped selling trifludimoxazin in response to a lawsuit filed by the Center for Food Safety and Center for Biological Diversity.<sup>182</sup> In June 2025, the US EPA proposed registration of trifludimoxazin.<sup>183</sup>

**Epyrifenacil** (Rapidicil<sup>®</sup> active, Sumitomo Chemical) is a novel PPO-inhibiting foliar application herbicide, belonging to the pyrimidinedione chemical class. It is systemically active on a broad range of weeds, including grass weeds and some target-site-based PPO-inhibiting-resistant broadleaf weeds.<sup>184</sup> It obtained registration in Argentina in 2024, and registrations were planned in the USA, Canada, Brazil, and Japan. Rapidicil<sup>®</sup> is particularly suitable for no-till farming due to its fast acting and high efficacy. Sumitomo Chemical will strive to achieve annual revenue of 100 billion yen from the sale of herbicides for non-till farming, including Rapidicil<sup>®</sup>, combined with the PPO-inhibitor tolerant crops currently being developed by Bayer.<sup>185</sup>

**Flufenoximacil** (Kuairufeng, KingAgroot) functions as a

contact-based, non-selective herbicide. It boasts higher efficacy and a broader spectrum of weed control, effectively managing glyphosate- and glufosinate-resistant weeds. It is widely applicable in plantations, orchards, tea gardens, row crops, and non-cropland.<sup>186</sup> Flufenoximacil obtained registration in Cambodia in 2022 and China in 2024.

**Cyclopyranil** (Kyoyu Agri) is a novel pyrazole PPO-inhibiting herbicide. It is a close analog of pyraclonil used to control weeds in paddy-field rice. Details such as the herbicidal spectrum of cyclopyranil are unknown.

#### 4.5.2.4. Very long-chain fatty acid synthesis (VLCFA)-inhibiting herbicides

VLCFA-inhibiting herbicides (formerly called very long-chain fatty acid elongase (VLCFAE)-inhibiting herbicides) initially were mainly chloroacetamides and oxyacetamides; however, various structures have since been identified. Recently, the number of patent applications for VLCFA-inhibiting herbicides has been declining. Since 2015, two products have been launched on the market. Table 23 summarizes the VLCFA-inhibiting herbicides that have been subjected to development since 2015. Their chemical structures are shown in Fig. 21.

**Fenoxasulfone** (HIE-CUT, SPADA, *etc.*, Kumiai Chemical) is a rice herbicide. It displays excellent herbicidal activity against *Echinochloa* spp. and other annual weeds at 150–200 g a.i./ha with long residual activity and has favorable toxicological, ecotoxicological, and environmental profiles. It showed stable herbicidal efficacy even under overflow conditions in paddy fields,

**Table 23.** Recently launched or under development VLCFA-inhibiting herbicides

| Common name   | Company name    | Target crop | Registration year in Japan | Remarks                                                                                |
|---------------|-----------------|-------------|----------------------------|----------------------------------------------------------------------------------------|
| Fenoxasulfone | Kumiai Chemical | Paddy rice  | 2014                       | Marketed in 2015. Dose: 200 g/ha, Target weed: barnyard grass, broadleaf weeds         |
| Dimesulfazet  | Nissan Chemical | Paddy rice  | 2024                       | Dose: 150 g/ha Target weed: <i>S. juncoides</i> , <i>E. kuroguwai</i> Ohwi <i>etc.</i> |

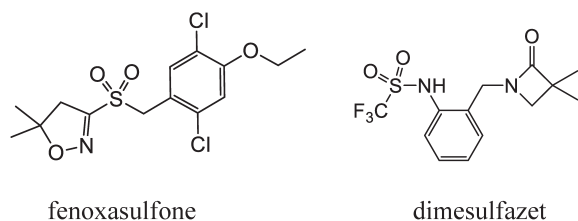


Fig. 21. Chemical structures of VLCFA-inhibiting herbicides.

though in general, overflow reduces efficacy to some extent. Various products containing fenoxasulfone have been launched since 2015.<sup>187)</sup>

**Dimesulfazet** (Verdad<sup>®</sup> active, Nissan Chemical) is a new herbicide used in rice paddy fields. Dimesulfazet at a field application rate of 150 g a.i./ha is highly efficient against Cyperaceae weeds, such as *Schoenoplectiella juncooides* (Roxb.), *Eleocharis kuroguwai* Ohwi, and *Bolboschoenus koshevnikovii* (Litv. ex Zinger) A. E. Kozhev. Dimesulfazet selectivity was clearly observed between rice and *S. juncooides*, whose resistance to ALS inhibitors has been reported previously.<sup>188)</sup> Dimesulfazet obtained registration in 2024 in Japan as mixtures with other herbicides. Expected peak sales will be 6.0 billion yen.<sup>189)</sup>

#### 4.5.2.5. Auxin herbicide

Herbicides that exhibit auxin-like activity include phenoxycarboxylic acids, benzoic acids, pyridine/pyrimidinecarboxylic acids, and quinolinecarboxylic acids; however, in recent years, pyridine/pyrimidinecarboxylic acid compounds have been marketed and developed. Table 24 summarizes the auxin herbicides that have been subjected to development since 2015. Their chemical structures are shown in Fig. 22.

**Halauxifen-methyl** (Arylex<sup>™</sup> active, Belkar<sup>™</sup>, Quelex<sup>™</sup>,

Zypar<sup>™</sup>, etc., Dow, currently Corteva Agriscience) is a new structural class of synthetic auxin herbicide. It is highly effective against major broadleaf weeds such as henbit, corn poppy, flxweed, and chickweed at low application rates of 5–7.5 g a.i./ha in key crops, including cereals, winter oilseed rape, sunflowers, and olive and citrus trees.<sup>190,191)</sup> Halauxifen-methyl even effectively controls glyphosate-resistant and ALS-resistant weeds. It obtained registration in 2015 in Japan and in many countries.

**Florpyrauxifen-benzyl** (Rinskor<sup>™</sup> active, Loyant<sup>™</sup>, Novlect<sup>™</sup>, Novoxid<sup>™</sup>, etc., Corteva Agriscience) is a member of the arylpicolinate family of chemistry and a new structural class of synthetic auxin herbicide. It provides excellent broad-spectrum (grass, broadleaf, and sedges) weed control in rice and aquatic environments at very low rates. It provides effective control of target-site resistance populations to ALS, ACCase, propanil, and quinclorac herbicides.<sup>192)</sup> Rinskor holds 93 registrations in 44 countries as of August 2022.

**Indolauxipyr-cyanomethyl** (Bexoveld<sup>™</sup> active, Corteva Agriscience), a novel class of auxin herbicide, demonstrates outstanding control of broadleaf weeds, including key resistant species in cereal crops. It is effective at low usage rates against *Kochia*, as well as poppy, *Veronica*, and wild mustard. Indolauxipyr-cyanomethyl is expected to launch in North America in 2028 and in Europe in 2030.<sup>193,194)</sup>

**Fluchloraminopyr-tefuryl** (KingAgroot) is a non-selective systemic and long-acting burndown auxin herbicide. It is of a broad herbicidal spectrum for effectively controlling a large variety of glyphosate-resistant and tolerant weeds such as horseweed herbs, dayflower, field bindweed, *Eleusine indica*, *Leersia oryzoides*, and reed. Its effect remains stable even under low-temperature weather conditions, while effect lasts 1.5 to two times longer

Table 24. Recently launched or under development auxin herbicides

| Common name              | Company name        | Target crop                                            | Registration year in Japan | Remarks                                                            |
|--------------------------|---------------------|--------------------------------------------------------|----------------------------|--------------------------------------------------------------------|
| Halauxifen-methyl        | Dow <sup>a)</sup>   | Cereals, oilseed rape, sunflowers, olive, citrus trees | 2015                       | Dose: 5–7 g/ha Target weed: broadleaf weeds                        |
| Florpyrauxifen-benzyl    | Corteva Agriscience | Paddy rice                                             | 2020                       | Dose: 5–50 g/ha Target weed: grass weeds, broadleaf weeds          |
| Indolauxipyr-cyanomethyl | Corteva Agriscience | Cereals                                                | 2022*                      | Structurally like halauxifen-methyl Target weed: broadleaf weeds   |
| Fluchloraminopyr-tefuryl | KingAgroot          | Non-selective                                          | 2022*                      | Dose: 162–360 g a.i./ha. Target weed: grass weeds, broadleaf weeds |

\*Year of ISO common name given, <sup>a)</sup> Currently Corteva Agriscience.

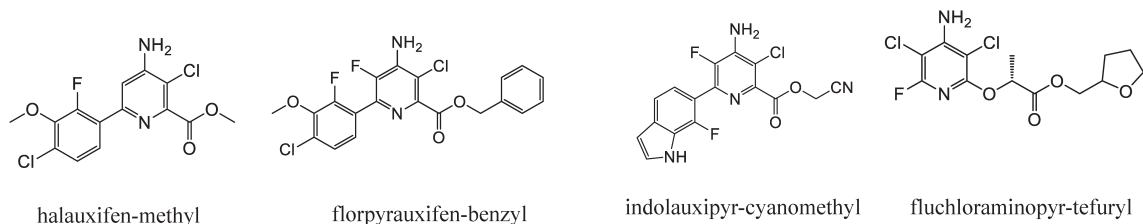
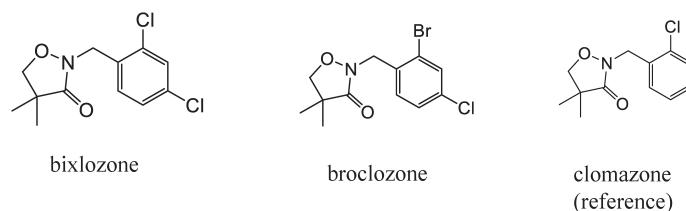


Fig. 22. Chemical structures of auxin herbicides.

**Table 25.** DXPS-inhibiting herbicides launched or under development since 2015

| Common name | Company name | Target crop                                                  | Registration year in Japan | Remarks                                   |
|-------------|--------------|--------------------------------------------------------------|----------------------------|-------------------------------------------|
| Bixlozone   | FMC          | Cereals, corn, legumes, rapeseed, sugarcane                  | 2018*                      | Target weed: grass weeds, broadleaf weeds |
| Broclozone  | KingAgroot   | Corn, wheat, cotton, peanut, sugar beet, soybean <i>etc.</i> | 2022*                      | Target weed: grass weeds, broadleaf weeds |

\*Year of ISO common name given.

**Fig. 23.** Chemical structure of DXPS inhibiting herbicides.

than glyphosate.<sup>195,196)</sup> Fluchloraminopyr-tefuryl was first registered in Cambodia in April 2022.

#### 4.5.2.6. 1-Deoxy-d-xylulose-5-phosphate synthase (DXPS) inhibitors

DXPS-inhibiting herbicides inhibit DXPS, which exists in the non-mevalonate pathway upstream of carotenoid biosynthesis (see Fig. 26). Clomazone was the only herbicide known to have this type of action; however, recently, FMC developed bixlozone, which is thought to have a similar activity to clomazone. In addition, broclozone, which was given an ISO common name in 2022, is also thought to be a DXPS inhibitor due to its structural similarity to bixlozone (the only difference is the substituent on the benzene ring). Table 25 summarizes the DXPS-inhibiting herbicides that have been subjected to development since 2015. Their chemical structures are shown in Fig. 23.

**Bixlozone** (Isoflex<sup>TM</sup> active, Overwatch<sup>®</sup>, FMC) has a structure in which a chloro group is introduced at the para position of the benzene ring of clomazone (see Fig. 23). It shows excellent activity against annual grass weeds (including those with developed resistance to other modes of action herbicides) such as ryegrass (*Lolium* spp.), barnyardgrass (*Echinochloa* spp.), and crabgrass (*Digitaria* spp.), as well as key broadleaf weeds such as common chickweed (*Stellaria media*), speedwells (*Veronica* spp.), and shepherd's purse (*Capsella bursa-pastoris*). Target

crops are cereals, corn, legumes, rapeseed, and sugarcane.<sup>197)</sup> Bixlozone was registered in many countries, such as Australia, Argentina, Brazil, China, the UK, and India.

**Broclozone** (KingAgroot) is a new DXPS-inhibiting systemic selective herbicide for pre- and post-emergence applications. It effectively targets *Lolium multiflorum*, *Beckmannia syzigachne*, *Alopecurus myosuroides*, and other grasses and broadleaf weeds, and it is applicable to various dryland crops (corn, wheat, cotton, peanut, sugar beet, and soybean). The recommended dose rate is 150–300 g a.i./ha. It exhibits high efficacy against weeds resistant to various modes of action, including ALS and ACCase inhibitors.<sup>198)</sup>

#### 4.5.2.7. Plant growth regulators

Plant growth regulators are chemicals used to control the growth and development of useful plants such as agricultural crops to improve quality, increase yields, stabilize yields even under poor conditions, and reduce production labor. Since 2015, only one growth regulator, anisiflupurin, has been developed. Table 26 shows the development status and chemical structure of anisiflupurin.

**Anisiflupurin** (Syngenta) is a 6-anilinopurine derivative, which inhibits cytokinin oxidase/dehydrogenase and possesses plant growth regulator activity. Anisiflupurin is less toxic yet more efficacious than the other known analogs. The application

**Table 26.** Development status and chemical structure of anisiflupurin

| Common name   | Company name | Target crop                                       | Year of ISO common name given | Remarks (Chemical structure) |
|---------------|--------------|---------------------------------------------------|-------------------------------|------------------------------|
| Anisiflupurin | Syngenta     | Not certain (rice: under testing, tobacco callus) | 2021                          |                              |

**Table 27.** Recently launched or under development other herbicides

| Common name       | Company name    | Target crop                     | Registration year in Japan | Remarks: mode of action               |
|-------------------|-----------------|---------------------------------|----------------------------|---------------------------------------|
| Metproxybicyclone | Syngenta        | soybean, cotton, and sugar beet | 2023*                      | Fourth generation of ACCase-inhibitor |
| Feproxydim        | Shandong Xianda | Paddy rice                      | 2023*                      | ACCase inhibitor                      |
| Icafolin-methyl   | Bayer           | non-selective                   | 2023*                      | Inhibition of tubulin polymerization  |

\*Year of ISO common name given.

of anisiflupurin secures seed setting by protecting pollen development and enhances grain weight under heat stress conditions in rice.<sup>199)</sup> Although there is little information on the use of this compound, Syngenta India is aiming to develop a tobacco callus stimulator.<sup>200)</sup>

#### 4.5.2.8. Herbicides with other modes of action

Three herbicides with other modes of action have been developed since 2015, *i.e.*, two ACCase inhibitors (metproxybicyclone, feproxydim) and one tubulin polymerization inhibitor (icafolin-methyl).

Table 27 summarizes the herbicides with other modes of action that have recently been launched or are under development. Their chemical structures are shown in Fig. 24.

**Metproxybicyclone** (Syngenta) is the first carbocyclic arylidione ACCase-inhibiting herbicide for soybean, cotton, and sugar beet, among other crops. It is effective on a variety of key grass weeds, including *Eleusine indica*, *Digitaria insularis*, *Sorghum halepense*, and *Echinochloa crus-galli*. It killed resistant grass weed populations more efficaciously than current ACCase herbicides.<sup>201)</sup> Metproxybicyclone is the fourth generation of ACCase-inhibitor (the third generation is pinoxaden, launched in 2006).<sup>202)</sup> The herbicide is expected to be launched in Argentina in 2026.

**Feproxydim** (Shandong Xianda) is a cyclohexanedione oxime

ACCase-inhibiting herbicide. It can effectively control grass weeds resistant to ALS inhibitors, ACCase inhibitors, and hormonal herbicides in paddy fields. It has special effects on barnyard grass, moleplant seed, and *Paspalum distichum*.<sup>203)</sup> It has no cross-resistance with penoxsulam, cyhalofop-butyl, metamifop, quinclorac, *etc.* It was expected to launch in China in 2024.

**Icafolin-methyl** (Bayer) is a novel non-selective herbicide with an established mode of action (plant-specific inhibitor of tubulin polymerization), but with a superior potency and spectrum, specifically after foliar application. This makes icafolin-methyl fundamentally different from existing tubulin polymerization-inhibiting herbicides.<sup>204)</sup> Icafolin-methyl has been developed for initial use in soybean, cereals, pulses, and oil seed crops, as well as pome and stone fruits, tree nuts, grapes, and citrus.<sup>205)</sup> Bayer expects icafolin-methyl will be launched from 2028 onward with initial availability in Brazil.

#### 4.5.2.9. Herbicides with novel modes of action

As already mentioned, no herbicides with novel modes of action had been developed for nearly 30 years after clomazone was launched in the late 1980s. However, since 2018, a total of eight herbicides with novel modes of action have appeared, as well as the elucidation of novel modes of action for existing herbicides. These are fatty acid thioesterase (FAT) inhibitors (cinmethylin, methiozolin: both existing herbicides; cinflubrolin: an analog of

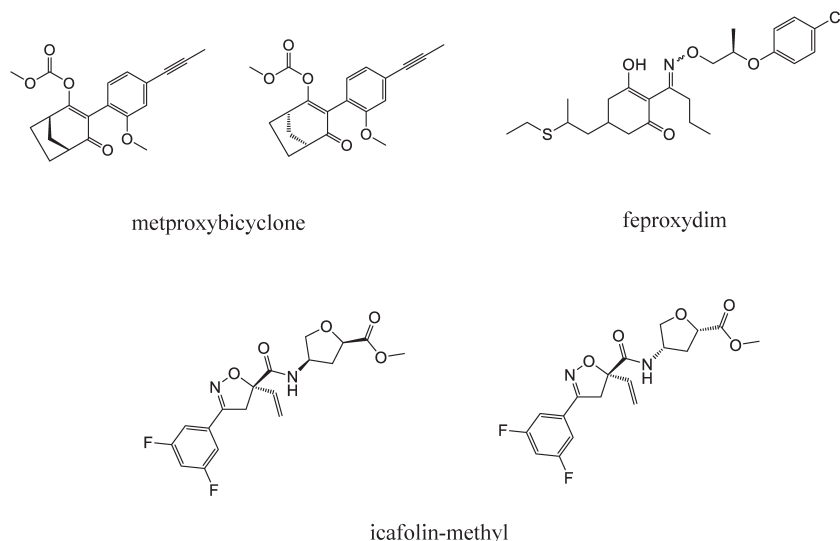
**Fig. 24.** Chemical structure of herbicides with other modes of action.

**Table 28.** Developmental status of herbicides with novel modes of action

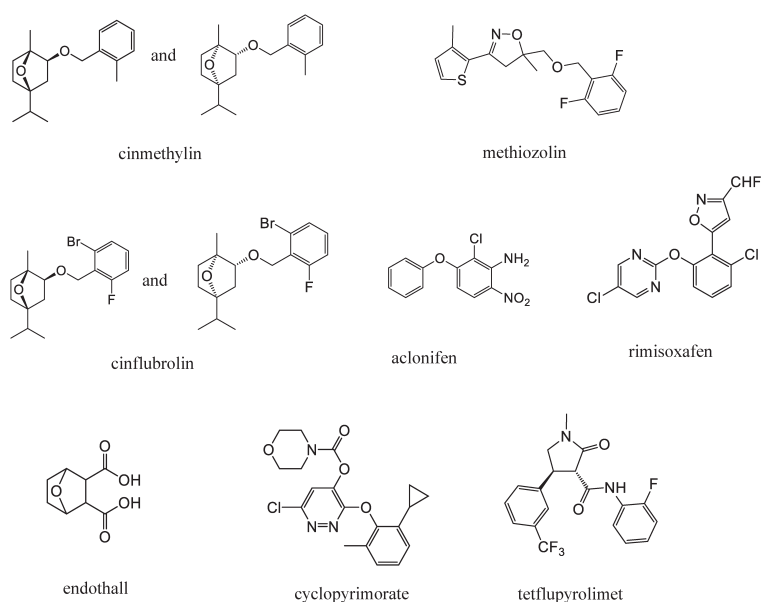
| Common name     | Company name                                                      | Mode of action<br>(site of action)                | Registration<br>year in Japan | Remarks                                                                     |
|-----------------|-------------------------------------------------------------------|---------------------------------------------------|-------------------------------|-----------------------------------------------------------------------------|
| Cinmethylin     | BASF                                                              | Fatty acid thioesterase<br>(FAT)                  | 2025                          | Registered and marketed overseas in the 1980s, since 1994<br>in Japan       |
| Methiozolin     | Moghu Research Center<br>(SDS Biotech)                            | Fatty acid thioesterase<br>(FAT)                  | 2016                          | Herbicide for lawn use. Marketed since 2010 in South Korea                  |
| Cinflubrolin    | KingAgroot                                                        | Fatty acid thioesterase<br>(FAT)                  | 2024*                         | Structurally like cinmethylin                                               |
| Aclonifen       | Bayer                                                             | Solanesyl diphosphate<br>synthase (SDPS)          | —                             | Agricultural use since 1980s                                                |
| Rimisoxafen     | FMC                                                               | Solanesyl diphosphate<br>synthase (SDPS)          | 2021*                         | A novel pyrimidinyloxy benzene class herbicide                              |
| Endothall       | Pennwalt Corporation<br>(Mitsui Chemicals<br>Agro <sup>a)</sup> ) | Serine threonine<br>protein phosphatase<br>(STPP) | 2017                          | Used as a terrestrial and aquatic weed control herbicide<br>since the 1960s |
| Cyclopyrimorate | Mitsui Chemicals<br>Agro <sup>a)</sup>                            | Homogentisate solane-<br>syltransferase (HST)     | 2019                          | New herbicides for paddy rice                                               |
| Tetflupyrolimet | FMC                                                               | Dihydroorotate<br>dehydrogenase<br>(DHODH)        | 2019*                         | New herbicides for paddy rice under development                             |

\*Year of ISO common name given, <sup>a)</sup> Currently Mitsui Chemicals CLS.

cinmethylin), solanesyl diphosphate synthase (SDPS) inhibitors (aclonifen: existing herbicide; rimisoxafen: new herbicide), serine threonine protein phosphatase (STPP) inhibitor (endothall: existing herbicide), homogentisate solanesyltransferase (HST) inhibitor (cyclopyrimorate: new herbicide), and dihydroorotate dehydrogenase (DHODH) inhibitor (tetflupyrolimet: new herbicide). It appears that leading pesticide discovery companies around the world are actively exploring herbicides with novel modes of action. Table 28 shows the developmental status of herbicides with novel modes of action, and their chemical structures are shown in Fig. 25.

#### 4.5.2.9.1. Fatty acid thioesterase (FAT) inhibitors

**Cinmethylin** (Luximo<sup>®</sup> active, Luximax<sup>®</sup>, Luxinum<sup>®</sup> Plus, BASF) is an herbicide that was registered in Japan more than 30 years ago, in 1994, and mixtures containing cinmethylin have been on the market. However, Campe *et al.* recently revealed that cinmethylin inhibits FAT in the fatty acid biosynthesis pathway, inhibiting fatty acid biosynthesis in plants.<sup>206)</sup> BASF developed cinmethylin for the control of major grass weeds in cereals. It was registered in Australia as Luximax<sup>®</sup> in November 2019.<sup>207)</sup> Registration has been applied for in the EU. In the UK, it was registered as Luxinum<sup>®</sup> Plus.<sup>208)</sup> It was registered in Japan in 2025. Due to its

**Fig. 25.** Chemical structures of herbicides with novel modes of action.

novel mode of action, Luximo® has no known cross-resistance. It provides soil residual control against a broad range of grasses in cereal crops, including resistant and difficult-to-control black grass and ryegrass.<sup>209)</sup>

**Methiozolin** (PoaCure®, Moghu Research Center) is a turf herbicide discovered by Moghu Research Center, a South Korean company founded in 2007. It has been marketed in South Korea as a golf course turf herbicide since 2010.<sup>162)</sup> It received unconditional registration for golf course turf in the USA in 2019. In Japan, a turf soil treatment (emulsion) was marketed under the brand name PoaCure®.<sup>210)</sup> It is effective against annual bluegrass and crabgrass on greens. Brabham *et al.* demonstrated that the mechanism of action of this agent is FAT inhibition, like that of cinmethylin.<sup>211)</sup>

**Cinflubrolin** (KingAgroot), an analog of cinmethylin, is a new systemic pre-emergence herbicide with FAT-inhibiting activity, exhibiting both pre-emergence soil activity and early post-emergence foliar activity. It demonstrates no cross-resistance and effectively controls annual grasses, sedges, and some broad-leaf weeds.<sup>212)</sup>

#### 4.5.2.9.2. Solanesyl diphosphate synthase (SDPS) inhibitors

**Aclonifen** (Pestanal®, Bayer) is a diphenyl ether herbicide that has been used in agriculture since the 1980s. It was primarily used as a pre-emergence treatment for potatoes, sunflowers, dry beans, and wheat in Europe. Its mode of action has been uncertain, with evidence (observation of whole-plant effect of bleaching) suggesting it might interfere with carotenoid biosynthesis or inhibit PPO. However, in 2020, Kahlau *et al.* in Bayer revealed that aclonifen has a different and novel mode of action, targeting

solanesyl diphosphate synthase, which would also cause bleaching (see Fig. 26).<sup>213)</sup>

**Rimisoaxafen** (FMC) is a new pyrimidinyloxy benzene class herbicide whose ISO common name was given in 2021. Rimisoaxafen induces a characteristic leaf-bleaching phenotype. Kang *et al.* demonstrated that rimisoaxafen inhibits both PDS and SDPS, two key enzymes essential for carotenoid and plastoquinone biosynthesis, respectively.<sup>214)</sup> The HRAC classified rimisoaxafen as Group 12 for the inhibition of PDS (see Fig. 26) and Group 32 for the inhibition of SDPS. Rimisoaxafen maintains herbicidal activity against weed strains resistant to either PDS or SDPS inhibitors in key row crops such as corn and soybeans. The single-molecule dual inhibition approach offers potential for reducing herbicide load in the field, especially in corn and soybean cropping systems.

#### 4.5.2.9.3. Serine threonine protein phosphatase (STPP) inhibitors

**Endothall** (Pennwalt Corporation) has been used as a terrestrial and aquatic weed control herbicide since the 1960s. In Japan, official efficacy testing has been conducted since the 1980s, and the product was registered and marketed by Mitsui Chemicals Agro (currently Mitsui Chemicals CLS) as a new pesticide in 2017. In 2011, endothall's mode of action was reported to be the inhibition of plant protein phosphatases 1 (PP1) and 2A (PP2A).<sup>215)</sup> However, in the 2020 revision of the RAC code for herbicides, endothall was classified as having a new mode of action (HRAC Group 31).

#### 4.5.2.9.4. Homogentisate solanesyltransferase (HST) inhibitors

**Cyclopyrimorate** (Cyra®, Mitsui Chemicals CLS) is a selective

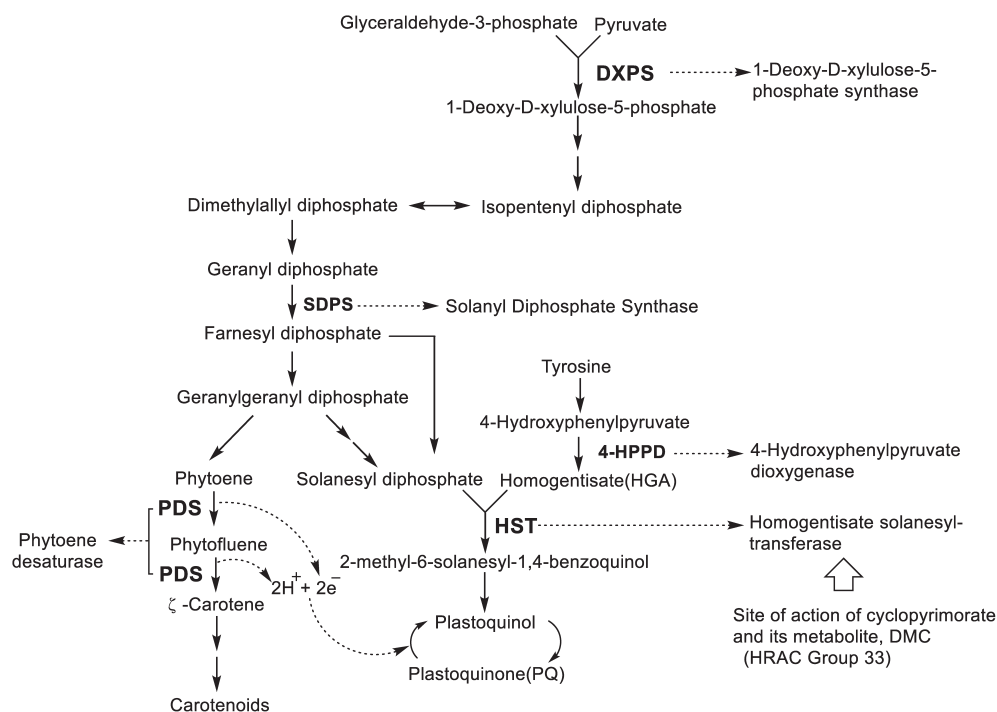


Fig. 26. Carotenoids and plastoquinone biosynthesis pathways (Drawn based on Ref. 216).

**Table 29.** Herbicides that received ISO common names in 2025

| Common name      | Company name                | Registration year in Japan | Remarks: Description in “New pesticides for BCPC’s global database” <sup>222)</sup>                                                                               |
|------------------|-----------------------------|----------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Dimepyroliomet   | KingAgroot                  | 2025*                      | An analog of tetflupyroliomet from FMC; the latter represents a new class of dihydroorotate dehydrogenase (DHODH) inhibitors                                      |
| Flufenazopyr     | KingAgroot                  | 2025*                      | The mode of action is not known but likely an inhibitor of phytoene desaturase (PDS)                                                                              |
| Prochlorosulfone | Shandong Binnong Technology | 2025*                      | An analog of this well-known class of HPPD inhibitors                                                                                                             |
| Flufenauxirim    | KingAgroot                  | 2025*                      | An analog of the pyrimidinecarboxylic acid auxinic herbicides pioneered by Corteva Agriscience                                                                    |
| Fendioxypyracil  | BASF                        | 2025*                      | An interesting twist on the classic N-phenylimide series of PPO inhibitors in which the pyrimidinone is now attached to a pyridine instead of the typical benzene |
| Toxapyzone       | Shandong Dehao Chemical     | 2025*                      | A benzoylpyrazole herbicide from Shandong Dehao Chemical Co., Ltd. Yet another example of this well-known class of HPPD inhibitors                                |

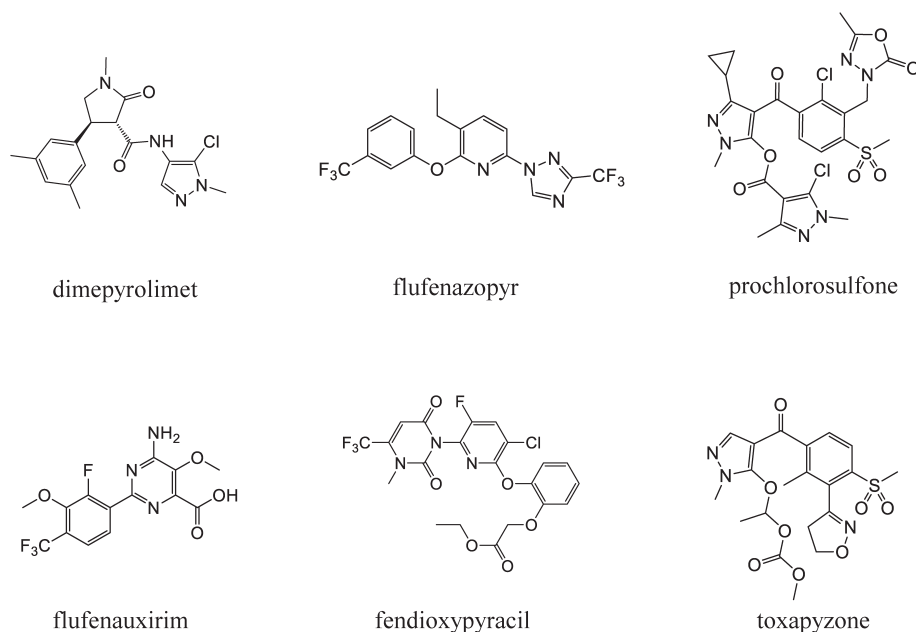
\*Year of ISO common name given.

pyridazine rice herbicide that exhibits a broad herbicidal spectrum against Cyperaceae weeds and broadleaf weeds.<sup>216,217)</sup> It is also highly effective against weeds that have acquired resistance to ALS inhibitors. Further, it can be applied simultaneously to rice plantings and direct sowing cultivation in paddy fields. The site of action of cyclopyrimorate is HST (the first member of HRAC Group 33), a downstream enzyme of HPPD (see Fig. 26).<sup>216,217)</sup> In *in vitro* assays, HST was inhibited strongly by DMC (a metabolite of cyclopyrimorate) and weakly by cyclopyrimorate. Although it has already been reported that HST inhibitors have herbicidal activity,<sup>218)</sup> cyclopyrimorate is the first commercial herbicide having this mode of action. Cyclopyrimorate obtained registration in 2019 in Japan.

**4.5.2.9.5. Dihydroorotate dehydrogenase (DHODH) inhibitor Tetflupyroliomet** (Dodhylex™ active, FMC) is a novel aryl pyrolidinone anilide class herbicide under development. It has

demonstrated excellent season-long control of grass weeds, such as *Echinochloa* and *Leptochloa* species, and some broadleaf and sedge weeds. It can control major weeds in global rice production, including direct-seeded and transplanted *japonica* and *indica* varieties.<sup>219)</sup> Tetflupyroliomet inhibits the enzyme dihydroorotate dehydrogenase (DHODH), the fourth step in the *de novo* pyrimidine biosynthesis pathway, and has been classified by HRAC as Group 28.<sup>219,220)</sup> It is effective on weeds that have developed increased tolerance or resistance to herbicide classes such as ALS, ACCase, HPPD, and glyphosate. FMC and Syngenta have signed an agreement for the joint development of tetflupyroliomet in the Asian rice market.<sup>221)</sup> Tetflupyroliomet has been submitted for review in many countries.<sup>219)</sup>

**4.5.2.10. Herbicides that received ISO common names in 2025** Six new herbicides have been given ISO common names in 2025. Of those, five are by Chinese companies, and one is by

**Fig. 27.** Chemical structures of herbicides that received ISO common names in 2025.

BASF. Since information on these compounds is limited, the data listed in “new pesticides for BCPC’s global database”<sup>222)</sup> are presented in Table 29. The chemical structures of these compounds are shown in Fig. 27.

### 5. Concluding remarks

During the past decade (between 2015 and 2025), 156 varieties of useful pesticides that are safe to humans and environmentally friendly have been subjected to development. Most of them are chemical pesticides, and some, such as RNAi-based pesticides and peptide pesticides, are classified as biopesticides or biological pesticides. In the field of fungicides, insecticides, acaricides, and nematocides, new chemicals that have or are likely to have a novel mode of action and unique chemical structure have been continuously developed. This is extremely important for avoiding the development of pesticide resistance and enabling sustainable agricultural production. It is of interest that, although no herbicides possessing novel modes of action were developed between the late 1980s and 2017, eight herbicides with novel modes of action have appeared since 2018, including the elucidation of novel modes of action for existing herbicides. This is significant for dealing with herbicide-tolerant weeds that have recently become a problem.

Chemical pesticides developed over the past decade have played an important role in crop protection and are expected to play an important role in the future. However, it is true that in recent years, the trend of global pesticide development has been gradually shifting from chemical pesticides to biopesticides, GM crops, seeds, RNAi-based pesticides, and abiotic stress control agents. Of those, biopesticides are gaining popularity as lower-environmental-impact alternatives to conventional synthetic pesticides.

Recently, practical RNAi-based pesticides (one insecticide and one acaricide) have appeared. The US EPA described that, unlike conventional chemical pesticides, which often present higher risks to human health and the environment, an RNAi-based insecticide (ledprona) offers a safer, more sustainable alternative, since its mode of action is highly specific to the Colorado potato beetle.<sup>223)</sup> It will be necessary for us to closely monitor future developments in RNAi-based pesticides in terms of their effectiveness and safety to humans and the environment. It is of interest that although the RNAi-based insecticide obtained registration as a biopesticide in the USA, it obtained an ISO common name, which is usually given to chemical pesticides. It is also noteworthy that peptide pesticides (fungicides and insecticides) with relatively large molecular weights have been developed and marketed as a new category of pesticides.

Over the past decade, the number of European, American, and Japanese companies, especially those in the West, involved in discovery research into new pesticides has decreased due to mergers and acquisitions; however, many Chinese companies have become involved in discovery studies of new pesticides. At present, most of the pesticides created in China are analogs of products made by other companies overseas, and original pesti-

cides are limited; however, in the future, first-in-class pesticides made in China are likely to appear.

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### References

- 1) J. Unsworth, Y. Nakagawa, C. Harris and G. Kleter: Chapter 2—The Battelle for a Sustainable Food Supply. In “Sustainable Agrochemistry: A Compendium of Technologies,” ed. by S. Vaz Jr., Springer Nature Switzerland, pp. 13–84, 2019.
- 2) N. Umetsu and Y. Shirai: Development of novel pesticides in the 21st century. *J. Pestic. Sci.* **45**, 54–74 (2020).
- 3) N. Umetsu and Y. Shirai: Trend in pesticide discovery studies in the 21st century. In “Discover of New Pesticides and Key Intermediate 2022,” CMC Publishing, pp. 333–369, 2022 (in Japanese).
- 4) N. Umetsu (su.): “Trend in Research and Development of Chemical Pesticides, Biopesticides and Biostimulants,” CMC Publishing, 2023 (in Japanese).
- 5) N. Umetsu: Recent trend in agrochemical development focusing on fungicides, insecticides, acaricides, and nematocides. *Plant Protection* **77**, 666–674 (2023), and **78**, 56–63 (2024) (in Japanese).
- 6) N. Umetsu and Y. Shirai: Recent trend in herbicide discovery studies. *Fine Chemicals* **53**, 38–47, 57–66 (2024) (in Japanese).
- 7) T. Yoneda, Y. Nakamura, S. Tsukuda, Y. Abe, M. Matsumoto and S. Mitani: Isofetamid: Discovery and optimization of a novel fungicide. In “Recent Highlights in the Discovery and Optimization of Crop Protection Products,” ed. by P. Maiefisch and S. Mangelinckx, Academic Press, pp. 391–399, 2021.
- 8) K. Kikutake, T. Furuya, M. Hasebe, H. Nagai and M. Oda: Development of a novel fungicide, pyraziflumid. *J. Pestic. Sci.* **45**, 184–190 (2020).
- 9) <https://investors.fmc.com/news/news-details/2021/FMC-Corporations-fluindapyr-fungicide-receives-U.S.-EPA-registration/default.aspx> (Accessed June 6, 2025)
- 10) <https://www.fmc.com/en/articles/fmc-corporation-and-corteva-agriscience-collaborate-provide-fluindapyr-fungicide> (Accessed 6 June, 2025)
- 11) Sumitomo Chemical News Release, Feb. 25, 2019. <https://www.sumitomo-chem.co.jp/english/news/detail/20190225e.html> (Accessed 4 June, 2025)
- 12) S. Kiguchi, T. Inoue, Y. Matsuzaki, F. Iwahashi and H. Sakaguchi: Discovery and biological profile of inpyrfluxam: A new broad-spectrum succinate dehydrogenase inhibitor fungicide. In “Recent Highlights in the Discovery and Optimization of Crop Protection Products,” ed. by P. Maiefisch and S. Mangelinckx, Academic Press, pp. 381–389, 2021.
- 13) A. Bartholomaeus, P. Dahmen, P. Desbordes, B. Essigmann, S. Gary, O. Gutbrod, J. Kleemann, P. Lancashire, M. Maue, H.-G. Schwarz and H. Tinwell: Isoflucypram—the next-generation succinate dehydrogenase inhibitor fungicide. In “Recent Highlights in the Discovery and Optimization of Crop Protection Products,” ed. by P. Maiefisch and S. Mangelinckx, Academic Press, pp. 367–380, 2021.
- 14) D. Stierli, H. U. Haas, R. Rajan, D. Bartlett, H. Sierotzki, F. Cederbaum, H. Walter and C. Lamberth: ADEPIDYN—The first *N*-methoxy-substituted carboxamide among the succinate dehydrogenase inhibitors. In “Recent Highlights in the Discovery and Optimization of Crop Pro-

- tection Products,” ed. by P. Maiefisch and S. Mangelinckx, Academic Press, pp. 357–366, 2021.
- 15) Adepidyn® technology: a new generation fungicide–Syngenta. <https://www.syngenta.com/products/protecting-crops/adepidyn> (Accessed 5 June, 2025)
  - 16) F. Ji, J. Zhang, X. Chen, B. Liu, A. Zhou, Y. Feng, J. Zhao, L. Huang, Z. Kang and G. Zhan: Effects of flubeneteram on inhibiting the development of *Puccinia striiformis* f. sp. *tritici* in wheat leaves. *J. Agric. Food Chem.* **71**, 5162–5171 (2023).
  - 17) A. Nishimura: Characteristics of the versatile fungicide picoxystrobin. *Plant Protection* **70**, 836–838 (2016) (in Japanese).
  - 18) K. Imanishi: Characteristics and usage of the fungicide mandestrobin. *Plant Protection* **70**, 710–711 (2016) (in Japanese).
  - 19) D. Hiroto, N. Ueda, S. Kiguchi, M. Hirota, K. Iwashita and R. Kodaka: Research and development of a novel fungicide ‘Mandestrobin.’ *Sumitomo Kagaku* **2016**, 4–16 (2016) (in Japanese).
  - 20) Y. Masuzaki, Y. Yoshimoto, S. Arimori, F. Iwahashi, M. Kurahashi, T. Toriumi, R. Ito, M. Kondo and M. Tabuchi: Discovery and development of a novel fungicide, Metyltetraprole, *Sumitomo Kagaku* (English Edition) **2024**, Report 2, 1–14 (2024). [https://www.sumitomo-chem.co.jp/english/rd/report/2024E\\_2.pdf](https://www.sumitomo-chem.co.jp/english/rd/report/2024E_2.pdf) (Accessed 7 June, 2025)
  - 21) Y. Matsuzaki, Y. Yoshimoto, S. Arimori and F. Iwahashi: The discovery of metyltetraprole: Reconstruction of the quinone outside inhibitor extended pharmacophore to overcome QoI-resistant Strains. In “Recent Highlights in the Discovery and Optimization of Crop Protection Products,” ed. by P. Maiefisch and S. Mangelinckx, Academic Press, pp. 425–432, 2021.
  - 22) <https://chemrobotics.in/agrochemical-discovery-update-june-2024-sumitomo-new-strobilurin-fungicide-bifemetstrobil-granted-provisional-iso-status/> (Accessed 9 June, 2025)
  - 23) <https://chemrobotics.in/new-iso-may-2025-metcyclofenstrobil-a-strobilurin-fungicide-by-syngenta/> (Accessed 9 June, 2025)
  - 24) W. J. Owen, C. Yao, K. Myung, G. Kemmitt, A. Leader, K. G. Meyer, A. J. Bowling, T. Slanec and V. J. Kramer: Biological characterization of fenpicoxamid, a new fungicide with utility in cereals and other crops. *Pest Manag. Sci.* **73**, 2005–2016 (2017).
  - 25) <https://www.corteva.co.uk/news-and-resources/Corteva-Agriscience-Inatreq-Active-Approved-in-UK.html> (Accessed 9 June, 2025)
  - 26) K. G. Meyer, C. Yao, Y. Lu, K. Bravo-Altamirano, Z. Buchan, J. F. Daeuble, K. DeKorever, J. DeLorbe, R. Heemstra, J. Herrick, D. Jones, B. A. Loy, J. Rigoli, N. X. Wang, J. Wilmot and D. Young: The discovery of florylpicoxamid, a new picolinamide for disease control. In “Recent Highlights in the Discovery and Optimization of Crop Protection Products,” ed. by P. Maiefisch and S. Mangelinckx, Academic Press, pp. 433–442, 2021.
  - 27) March 28, 2023/PRNewswire. <https://investors.corteva.com/news-releases/news-release-details/corteva-agriscience-launches-adaveltm-active-bringing-farmer> (Accessed 11 June, 2025)
  - 28) EPA 2025/1/16. <https://www.epa.gov/pesticides/epa-announces-proposed-registration-new-pesticide-florylpicoxamid> (Accessed 11 June, 2025)
  - 29) Corteva News release 2022/2/10. <https://www.corteva.com/resources/media-center/corteva-announces-haviza-active-as-global-trademark-for-newest-active-ingredient-in-its-innovation-pipeline.html> (Accessed 11 June, 2025)
  - 30) <https://homologa.com/blog/news/argentina-new-fungicide/> (Accessed June 11, 2025)
  - 31) Y. Kuchii: The biological property on a new fungicide, mefentriiflucanazole (Belanty® Flowable). *Plant Protection* **78**, 175–177 (2024) (in Japanese).
  - 32) M. Semar, D. Strobel, M. Coquiller, G. Stammeler, J. Barnes, L. de Paula Collette and J. Lee: Revysol®: The new broad-spectrum fungicide of BASF SE. *Comm. Appl. Biol. Sci. Ghent University* **84**, 251 (2019).
  - 33) S. Uchida: Properties of prothioconazole, a novel fungicide. *Plant Protection* **77**, 230–235 (2023) (in Japanese).
  - 34) B. Jiao, Y. Zhu, J. Xu, F. Dong, X. Wu, X. Liu and Y. Zheng: Identification and ecotoxicity prediction of pyrisoxazole transformation products formed in soil and water using an effective HRMS workflow. *J. Hazard. Mater.* **424**(Pt A), 127223 (2022).
  - 35) R. Kuwahara: Characteristics of the fungicide picarbutrazox. *Plant Protection* **72**, 208–211 (2018) (in Japanese).
  - 36) S. Watanabe, I. Urihara, T. Fujii, H. Yamanaka and H. Sano: Picarbutrazox: A novel fungicide for the control of oomycete disease. *Comm. Appl. Biol. Sci. Ghent University* **84**, 321 (2019).
  - 37) H. Hagiwara, R. Ezaki, T. Hamada, M. Tsuda and K. Ebihara: Development of a novel fungicide, tolprocarb. *J. Pestic. Sci.* **44**, 208–213 (2019).
  - 38) Y. Kuchii: Characteristics of the fungicide oxathiapiprolin. *Plant Protection* **70**, 418–419 (2016) (in Japanese).
  - 39) Zorvec™ active Technical Bulletin. <https://www.corteva.com/content/dam/dpagco/corteva/global/corporate/general/files/active-ingredients/ZOR.035.Corteva.Zorvec.Global.Technical.Bulletin.pdf> (Accessed 17 May, 2025)
  - 40) <https://news.agropages.com/News/NewsDetail---42499.htm#:~:text=Bayer Australia and New Zealand&text=The Australian Pesticides and Veterinary, in a suspension concentrate formulation> (Accessed 17 June, 2025)
  - 41) N. Myojo: Properties of dichlobentiazox (DISARTA™), a novel fungicide. *Plant Protection* **74**, 671–674 (2020) (in Japanese).
  - 42) Agricultural Chemicals and Agriculture-Related Business (Japan). [https://ir.kumiai-chem.co.jp/en/library/csr/main/00/teaserItems1/06/linkList/04/link/P37-38\\_en.pdf](https://ir.kumiai-chem.co.jp/en/library/csr/main/00/teaserItems1/06/linkList/04/link/P37-38_en.pdf) (Accessed 17 June, 2025)
  - 43) S. Fujii: Characteristics of KINOPROL® (ipflufenquin), a novel fungicide. *Plant Protection* **77**, 164–166 (2023) (in Japanese).
  - 44) Nisso Press Release, Oct. 2023. <https://www.nikkan.co.jp/releases/view/163440> (in Japanese) (Accessed 17 June, 2025)
  - 45) US EPA: Pesticide Product Label, Kinoprol 20 SC, 03/29/2022. [https://www3.epa.gov/pesticides/chem\\_search/ppls/008033-00139-20220329.pdf](https://www3.epa.gov/pesticides/chem_search/ppls/008033-00139-20220329.pdf) (Accessed 17 June, 2025)
  - 46) H. Ito, T. Takada, M. Morimoto, H. Komai, F. Kajino, T. Ohara, Y. Tamagawa, M. Tsuda and S. Banba: Design and biological activity of a novel fungicide, quinofumelin. *J. Pestic. Sci.* **48**, 22–27 (2023).
  - 47) N. Higashimura, A. Hamada, T. Ohara, S. Sakurai, H. Ito and S. Banba: The target site of the novel fungicide quinofumelin, *Pyricularia oryzae* class II dihydroorotate dehydrogenase. *J. Pestic. Sci.* **47**, 190–196 (2022).
  - 48) N. Higashimura, A. Hamada and S. Banba: Novel fungicide quinofumelin shows selectivity for fungal dihydroorotate dehydrogenase over the corresponding human enzyme. *J. Pestic. Sci.* **48**, 17–21 (2023).
  - 49) Mitsui Chemical News Release. [https://jp.mitsuichemicals.com/jp/release/2025/2025\\_0212/index.htm](https://jp.mitsuichemicals.com/jp/release/2025/2025_0212/index.htm) (in Japanese) (Accessed 17 June, 2025)
  - 50) M. Kurahashi, Y. Matsuzaki, A. Manabe, M. Kawamura, F. Iwahashi, M. Yamane, R. Matsuyama and Y. Handa: Discovery and development of pyridachlometyl. *SUMITOMO KAGAKU* (English Edition) **Report 3**, 1–14 (2023).
  - 51) Y. Matsuzaki, M. Kurahashi, S. Watanabe, S. Kiguchi, T. Harada and F. Iwahashi: Discovery and development of pyridachlometyl. *Pest*

- Manag. Sci.* **81**, 2442–2449 (2025).
- 52) Trade News, June 2, 2025. <https://www.basf.com/global/en/media/news-releases/2025/06/p-25-100> (Accessed 17 June, 2025)
  - 53) Fluopimomide—PubChem. <https://pubchem.ncbi.nlm.nih.gov/compound/Fluopimomide>
  - 54) Fluopimomide—AERU—University of Hertfordshire. <https://sitem.herts.ac.uk/aeru/ppdb/en/Reports/3204.htm> (Accessed 17 June, 2025)
  - 55) M. Miyashita: Trends in exploratory study on peptide pesticides. In “Trend in Research and Development of Chemical Pesticides, Biopesticides and Biostimulants,” supervised by N. Umetsu, CMC Publishing, pp. 303–311, 2023 (in Japanese).
  - 56) CEV, SA. <https://www.agropages.com/companydirectory/Detail-18394.htm> (Accessed 14 July, 2025)
  - 57) ProBlad® Verde—SymAgro. <https://sym-agro.com/our-products/problad> (Accessed 14 July, 2025)
  - 58) CEV and Ceradis Sign Biofungicide R&D Agreement. <https://ceradis.com/2020/09/29/cev-and-ceradis-sign-biofungicide-rd-agreement/> (Accessed 13 July, 2025)
  - 59) Products-Plant Health Care plc. <https://www.planthealthcare.com/products> (Accessed 19 June, 2025)
  - 60) Plant Health Care: Biofungicide PHC279 Approved by US EPA. <https://www.fmp-tv.co.uk/2023/03/01/plant-health-care-biofungicide-phc279-approved-by-us-epa/> (Accessed 19 June, 2025)
  - 61) Saori-Plant Health Care plc. <https://www.planthealthcare.com/products/Saori> (Accessed 19 June, 2025)
  - 62) C.-Y. Huang, K. Araujo, J. N. Sánchez, G. Kund, J. Trumble, C. Roper, K. E. Godfrey and H. Jin: A stable antimicrobial peptide with dual functions of treating and preventing citrus Huanglongbing. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2019628118 (2021).
  - 63) ADAMA Media Releases 06 May, 2025. <https://www.adama.com/en/media-releases/novel-active-ingredient-gilboa-introduces-new-mode-action> (Accessed 22 June, 2025)
  - 64) <https://www.bcp.org/latest-news/technical-news/new-pesticide-names-added-to-bcps-online-pesticide-manual> (Accessed 22 June, 2025)
  - 65) <https://chemrobotics.in/iso-update-march-2021-9-new-agrochemical-candidates-published-including-benquitrione-shandong-cynda-herbicide-bipyrazone-qingdao-qingyuan-herbicide-cyprafuone-kingagroot-herbicide/> (Accessed 22 June, 2025)
  - 66) L. Jin, X. Chen, C. Pang, L. Zhou, Y. Liu, Y. Sun, L. Xu, Y. Wang and Y. Chen: Investigation of the antibacterial mechanism of the novel bactericide dioctyldiethylenetriamine (Xinjunan). *Pest Manag. Sci.* **79**, 2780–2791 (2023).
  - 67) F. Li, K. Wang, X. Zhu, W. Liu, Y. Wu, D. Lv, Y. Han, X. Wang, D. Cheng, T. Chen, C. Xu and X. Sun: Chloroinconazole inhibits *Pseudomonas syringae* pv. *tabaci* causing tobacco wildfire disease by directly destroying bacteria and inducing oxidative damage. *Pestic. Biochem. Physiol.* **213**, 106476 (2025).
  - 68) <https://news.agropages.com/news/NewsDetail---52971.htm> (Accessed 22 June, 2025)
  - 69) S. Mochizuki, T. Fukumoto, T. Ohara, K. Ohtani, A. Yoshihara, Y. Shigematsu, K. Tanaka, K. Ebihara, S. Tajima, K. Gomi, K. Ichimura, K. Izumori and K. Akimitsu: The rare sugar d-tagatose protects plants from downy mildews and is a safe fungicidal agrochemical. *Commun. Biol.* **3**, 423 (2020).
  - 70) <https://chemrobotics.in/agrochemical-discovery-1update-silvateams-new-pesticide-galquin-granted-provisional-iso-status/> (Accessed 24 June, 2025)
  - 71) <https://chemrobotics.in/agrochemical-discovery-update-july-2024-shandong-uniteds-new-quinolinone-bactericide-fluquinomatoate-granted-provisional-iso-status-chemrobo/> (Accessed 23 June, 2025)
  - 72) R. Horikoshi and M. Tomizawa: Trend in development of nicotinic insecticides. In “Trend in Pesticide Discovery Research—Development of Safer and Environmentally Friendly Pesticides—,” supervised by N. Umetsu, CMC Publishing, pp. 104–112, 2018 (in Japanese).
  - 73) Y. Onozaki, R. Horikoshi, I. Ohno, S. Kitsuda, K. A. Durkin, T. Suzuki, C. Asahara, N. Hiroki, R. Komabashiri, R. Shimizu, M. Furutani, M. Ihara, K. Matsuda, M. Mitomi, S. Kagabu, K. Uomoto and M. Tomizawa: Flupyrimin: A novel insecticide acting at the nicotinic acetylcholine receptors. *J. Agric. Food Chem.* **65**, 7865–7873 (2017).
  - 74) M. Nakano, K. Fukatsu, R. Tanaka, H. Inui and Y. Yamashita: General trends in insecticide research and development. In “Trend in Research and Development of Chemical Pesticides, Biopesticides and Biostimulants,” supervised by N. Umetsu, CMC Publishing, pp. 69–83, 2023 (in Japanese).
  - 75) Neonicotinoids—European Commission. [https://food.ec.europa.eu/plants/pesticides/approval-active-substances-safeners-and-synergists/renewal-approval/neonicotinoids\\_en](https://food.ec.europa.eu/plants/pesticides/approval-active-substances-safeners-and-synergists/renewal-approval/neonicotinoids_en) (Accessed 30 June, 2025)
  - 76) G. B. Watson, M. W. Siebert, N. X. Wang, M. R. Loso and T. C. Sparks: Sulfoxaflor—A sulfoximine insecticide: Review and analysis of mode of action, resistance and cross-resistance. *Pestic. Biochem. Physiol.* **178**, 104924 (2021).
  - 77) Let's Talk About Flupyradifurone, Bayer Global. <https://www.bayer.com/en/agriculture/lets-talk-about-flupyradifurone> (Accessed 30 June, 2025)
  - 78) R. Nauen, P. Jeschke, R. Velten, M. E. Beck, U. Ebbinghaus-Kintscher, W. Thielert, K. Wölfel, M. Haas, K. Kunz and G. Raupach: Flupyradifurone: A brief profile of a new butenolide insecticide. *Pest Manag. Sci.* **71**, 850–862 (2015).
  - 79) Pyrexalt™ active Technical Bulletin. [https://www.corteva.com/content/dam/dpagco/corteva/global/corporate/general/files/active-ingredients/Pyrexalt\\_Tech\\_Bulletin\\_2019\\_FINAL.pdf](https://www.corteva.com/content/dam/dpagco/corteva/global/corporate/general/files/active-ingredients/Pyrexalt_Tech_Bulletin_2019_FINAL.pdf) (Accessed 30 June, 2025)
  - 80) [https://www.corteva.jp/content/dam/dpagco/corteva/as/jp/ja/files/flyer/DOC-Lumispace\\_brochure\\_AP-JP.pdf](https://www.corteva.jp/content/dam/dpagco/corteva/as/jp/ja/files/flyer/DOC-Lumispace_brochure_AP-JP.pdf) (in Japanese) (Accessed 12 Sep., 2025)
  - 81) T. Yamaga: Characteristics of the new insecticide “Dichloromezo-thiaz.” *Plant Protection* **79**, 172–176 (2025) (in Japanese).
  - 82) <https://www.zennoh.or.jp/operation/nouyaku/fieldmast/index.html> (in Japanese) (Accessed 12 Sep., 2025)
  - 83) Notice regarding launch of termite control agent “Nexus® Z800”. <https://www.nichino.co.jp/contents/000003556.pdf> (in Japanese)
  - 84) Trade News|February 6, 2025. <https://www.basf.com/global/en/media/news-releases/2025/02/p-25-002> (Accessed 1 July, 2025)
  - 85) India Makes Landmark Registration of FENMEZODITIAZ. <https://homologa.com/blog/news/india-makes-landmark-registration-of-fenmezoditiaz-a-novel-technical-active-ingredient/> (Accessed 1 July, 2025)
  - 86) <https://www.kingagroot.com/En/html/news-25Aug05.html> (Accessed 2 Sep., 2025)
  - 87) Flupyrimin/Mitsui Chemicals Crop & Life Solutions, Inc. <https://www.mc-croplifesolutions.com/en/randd/active-ingredients/flupyrimin/> (Accessed 1 July, 2025)
  - 88) M. Tsukamoto, T. Hamamoto, M. Morita, K. Nakamoto, A. Hisamatsu and T. Koyanagi: Cyclaniliprole: A novel diamide insecticide. In “Recent highlights in the Discovery and Optimization of Crop Protection Products,” ed. by P. Maiefisch and S. Mangelinckx, Academic Press, pp. 213–219, 2021.

- 89) Insecticide-Cyclaniliprole (CYCLAPRYN™). [https://www.iskweb.co.jp/eng/products/pdf/international\\_Cyclaniliprole.pdf?0418](https://www.iskweb.co.jp/eng/products/pdf/international_Cyclaniliprole.pdf?0418) (Accessed 1 July, 2025)
- 90) M. Ataka: Characteristics of tetraniliprole, a novel insecticide. *Plant Protection* **74**, 545–550 (2020) (in Japanese).
- 91) R. Fischer, C. Funke, E. R. Gesing, N. Godley, C. Grondal, M. Heil, A. Hense, S. Kuebbeler, P. Loesel, O. Malsam, *et al.*: Discovery, synthesis and structure-activity relationship of tetraniliprole (Vayego™), a novel diamide insecticide. *Comm. Appl. Biol. Sci. Ghent University* **84**, 227 (2019).
- 92) Tetraniliprole—Minnesota Department of Agriculture. <https://www.mda.state.mn.us/sites/default/files/docs/2023-10/tetraniliprolereview.pdf> (Accessed 1 July, 2025)
- 93) Y. Liu, Y. Zhang, S. Liu, Y. Lü, R. Lin, M. Li, X. Liao and X. Li: Distribution and degradation kinetics of cyhalodiamide in Chinese rice field environment. *Chin. J. Chem. Eng.* **26**, 2185–2191 (2018).
- 94) <https://news.agropages.com/News/NewsDetail---45768.htm>
- 95) M. Asahi, M. Kobayashi, T. Kagami, K. Nakahira, Y. Furukawa and Y. Ozoe: Fluxametamide: A novel isoxazoline insecticide that acts via distinctive antagonism of insect ligand-gated chloride channels. *Pestic. Biochem. Physiol.* **151**, 67–72 (2018).
- 96) M. Inada and M. Asahi: Development trends of GABA-gated chloride channel allosteric modulators. In “Trend in Research and Development of Chemical Pesticides, Biopesticides and Biostimulants,” supervised by N. Umetsu, CMC Publishing, pp. 98–107, 2023 (in Japanese).
- 97) M. Ando and H. Haruyama: Characteristics of the new insecticide, fluxametamide. *Plant Protection* **73**, 465–468 (2019) (in Japanese).
- 98) T. Mita, Y. Furukawa, M. Iwasa, T. Kikuchi and M. Komoda: Studies on a novel insecticide, fluxametamide. In “Recent highlights in the Discovery and Optimization of Crop Protection Products,” ed. by P. Maienfisch and S. Mangelinckx, Academic Press, pp. 157–163, 2021.
- 99) T. Nakao, H. Katsuta, M. Nomura, T. Wakita, H. Daido, Y. Kobayashi, A. Kawahara and S. Banba: Discovery and optimization of a novel insecticide, broflanilide. In “Recent Highlights in the Discovery and Optimization of Crop Protection Products,” ed. by P. Maienfisch and S. Mangelinckx, Academic Press, pp. 145–155, 2021.
- 100) A. Naoi: Features of TENEBENAL® (broflanilide), A novel insecticide. *Plant Protection* **75**, 462–467 (2021) (in Japanese).
- 101) Tenebenal™/Mitsui Chemicals Crop & Life Solutions, Inc. <https://www.mc-croplifesolutions.com/en/randd/active-ingredients/tenebenal/> (Accessed 5 July, 2025)
- 102) Mitsui Chemicals, Inc. Press Releases. [https://jp.mitsuichemicals.com/en/release/2020/2020\\_0917/index.htm](https://jp.mitsuichemicals.com/en/release/2020/2020_0917/index.htm) (Accessed 5 July, 2025)
- 103) J. Cassayre, T. Smejkal, J. Blythe, P. Hoegger, P. Renol, T. Pitterna, C. S. Prasanna, H. Smits, E. Godineau, T. Luksch, G. Berthon, G. Rawal, R. Patre, M. Lal, M. Boussemghoune, S. Masala, F. Barreateau, M. Flaeschel, J. Vogt and M. E. Qacemi: The discovery of isocycloseram: A novel isoxazoline insecticide. In “Recent Highlights in the Discovery and Optimization of Crop Protection Products,” ed. by P. Maienfisch and S. Mangelinckx, Academic Press, pp. 165–212, 2021.
- 104) Syngenta US News. [https://www.syngenta-us.com/newsroom/news\\_release\\_detail?id=227926](https://www.syngenta-us.com/newsroom/news_release_detail?id=227926) (Accessed 6 July, 2025)
- 105) <https://news.agropages.com/News/NewsDetail---50726.htm#:~:text=Cyproflaniide was granted a patent,with a promising market prospect> (Accessed 6 July, 2025)
- 106) [https://www.uplcorp.com/files/corp\\_press\\_pdfs/cd25b014150107183f55969d5cdfab37.pdf](https://www.uplcorp.com/files/corp_press_pdfs/cd25b014150107183f55969d5cdfab37.pdf) (Accessed 6 July, 2025)
- 107) Isoflualanam—KingAgroot. <https://www.kingagroot.com/en/html/pdfShow.html?pdfUrl=Isoflualanam> (Accessed 6 July, 2025)
- 108) T. Kashima, T. Kitamura, J. Ohnishi and T. Furuie: A novel insect behavior regulator, the feature and usage of acetylated glyceride. *Plant Protection* **73**, 594–597 (2019) (in Japanese).
- 109) T. Kashima: Development of acetylated glyceride. In “Trend in Research and Development of Chemical Pesticides, Biopesticides and Biostimulants,” supervised by N. Umetsu, CMC Publishing, pp. 282–293, 2023 (in Japanese).
- 110) M. Muehlebach, J. Schaetzer, A. Buchholz, A. J. Flemming, C. R. Godfrey, E. Godineau, M. Hamer, F. Vock-Hatt, O. Hueter, D. P. Kloer and Peter Maienfisch, S. Oliver, F. Perruccio, T. Pitterna, C. Popp, R. Senn, R. Slater, Tomas Smejkal, D. Stafford, J. Wenger, L. Wildsmith and W. Zambach: Spiropidion discovery: Broad spectrum control of sucking insects and mites for multicrop utility. In “Recent Highlights in the Discovery and Optimization of Crop Protection Products,” ed. by P. Maienfisch and S. Mangelinckx, Academic Press, pp. 241–260, 2021.
- 111) <https://www.syngenta.com/media/media-releases/2020/syngenta-crop-protection-announces-launch-spiropidion-new-insecticide> (Accessed 7 July, 2025)
- 112) The first ketoenol crop protection product for foliar and soil uses. <https://www.bayer.com/en/agriculture/plenexos> (Accessed 7 July, 2025)
- 113) Brazil’s MAPA requests urgent review of Spidoxamat for citrus greening control. <https://news.agropages.com/News/Detail-51897.htm> (Accessed 7 July, 2025)
- 114) E. Satoh, R. Kasahara, K. Fukatsu, T. Aoki, H. Harayama and T. Murata: Benzpyrimoxan: Design, synthesis, and biological activity of a novel insecticide. *J. Pestic. Sci.* **46**, 109–114 (2021).
- 115) Mode of Action of Benzpyrimoxan/IRAC. <https://irac-online.org/content/uploads/Mode-of-Action-of-Benzpyrimoxan-for-IRAC-proposal.pdf> (Accessed 7 July, 2025)
- 116) T. Spear: Bioinsecticide-Evergreen Growers Supply, LLC. <https://www.evergreengrowers.com/spear-t-bioinsecticide.html> (Accessed 8 July, 2025)
- 117) C. Chambers, P. Cutler, Y.-H. Huang, J. A. Goodchild, J. Blythe, C. K. Wang, A. Bigot, Q. Kaas, D. J. Craik, D. Sabbadin and F. G. Earley: Insecticidal spider toxins are high affinity positive allosteric modulators of the nicotinic acetylcholine receptor. *FEBS Lett.* **593**, 1336–1350 (2019).
- 118) Sero-X-Innovate Ag. <https://innovate-ag.com.au/sero-x/> (Accessed 16 July, 2025)
- 119) T. Kobayashi, H. Hotta, T. Miyake, M. Nomura, R. Horikoshi and K. Yamamoto: Discovery of flometoquin, a novel quinoline insecticide. *J. Pestic. Sci.* **48**, 168–174 (2023).
- 120) H. Takeuchi, M. Nomura, R. Horikoshi, S. Aasano, T. Miyake, T. Kobayashi, M. Murai, Y. J. Chen, F. Earley, J. Mina and A. Crossthwaite: Y.-Ju Chen, F. Earley, J. Mina, J. Mina and A. Crossthwaite: Flometoquin, a novel insecticide, acts on mitochondrial complex III as a Qi inhibitor. *J. Pestic. Sci.* **49**, 203–209 (2024).
- 121) C. Koradin, H. Schröder, K. Oyama and S. Ōmura: Chemistry and biology connected: The development of Inscalis. In “Recent Highlights in the Discovery and Optimization of Crop Protection Products,” ed. by P. Maienfisch and S. Mangelinckx, Academic Press, pp. 231–239, 2021.
- 122) R. Horikoshi, K. Goto, M. Mitomi, T. Sunazuka and S. Ōmura: Research and development of an insecticide, afidopyropen. *J. Pestic. Sci.* **50**, 14–17 (2025).
- 123) M. Kamezaki, J. Otsuki and K. Natsuhara: Insecticidal activity against rice pest of oxazosulfyl, a novel sulfyl insecticide. *J. Pestic.*

- Sci.* **49**, 31–37 (2024).
- 124) M. Ito, Y. Nokura, M. Takahashi, M. Kamezaki, E. Sakamoto and S. Nishimura: Development of the insecticide oxazosulfonyl. *J. Pestic. Sci.* **50**, 96–101 (2025).
  - 125) J. Goodchild, Y. J. Chen, J. Blythe, L. C. Firth, E. Hirst, K. Bess, J. Bristow, J. Willis, R. Baines, F. Cash, M. Muehlebach, A. Buchholz, S. Rendler, F. Earley and A. Crossthwaite: A novel class of insecticidal alkylsulfones are potent inhibitors of vesicular acetylcholine transport. *Pestic. Biochem. Physiol.* **201**, 105854 (2024).
  - 126) R. Yasunaga, M. Nakano, T. Kyuma, K. Fujii, H. Inui, J. Akutsu, I. Yonemura, T. Inoue, A. Suwa, T. Yoshizane, A. Nakao and Y. Mori: A novel insecticide cybenzoxasulfonyl potently binds to vesicular acetylcholine transporter and disrupts the storage and release of acetylcholine in insects. *Biochem. Biophys. Res. Commun.* **763**, 151792 (2025).
  - 127) J. D. Eckelbarger, M. H. Parker, M. C. Yap, A. M. Buysse, J. M. Babcock, R. Hunter, Y. Adelfinskaya, J. G. Samaritoni, N. Garizi and T. K. Trullinger: Synthesis and biological activity of a new class of insecticides: the N-(5-aryl-1,3,4-thiadiazol-2-yl)amides. *Pest Manag. Sci.* **73**, 761–773 (2017).
  - 128) Tyclopyrazoflor is expected to do very well when it comes to market. <https://www.echemi.com/cms/1747858.html> (Accepted 22 May, 2025)
  - 129) W. Zhang, R. D. Slack, M. A. Rossi, J. Hamm, D. Cordova, D. Clark, G. Lahm, M. Kar, K. Sana, M. Xu, A. DeAngelis and B. Frag: The discovery of indazaproxamet: A novel 3-pyridinyl insecticide targeting piercing/sucking insects. *Pest Manag. Sci.* **81**, 2419–2423 (2024).
  - 130) FMC highlights new products in meeting with shareholders. <https://revistacultivar.com/news/fmc-highlights-new-products-in-meeting-with-shareholders> (Accepted 22 May, 2025)
  - 131) P. Maienfisch and K. Koerber: Recent innovations in crop protection research. *Pest Manag. Sci.* **81**, 2406–2418 (2025).
  - 132) D. Hodges: Discovery, research and development of axalion® active insecticide: Dimpropridaz. *Pest Manag. Sci.* **81**, 2529–2534 (2025).
  - 133) C. Spalthoff, V. L. Salgado, N. Balu, M. D. David, P. Hehlert, H. Huang, J. E. Jones, R. Kandasamy, G. A. Knudsen, K. R. Lelito, J. B. Machamer, A. Nesterov, M. Tomalski, G. D. Wahl, B. J. Wedel and M. C. Göpfert: The novel pyridazine pyrazolecarboxamide insecticide dimpropridaz inhibits chordotonal organ function upstream of TRPV channels. *Pest Manag. Sci.* **79**, 1635–1649 (2023).
  - 134) C. Parmentier, A. Baze, M. Untrau, A. Kampkoetter, D. Lasserre and L. Richert: Evaluation of human relevance of nicofluprole-induced rat thyroid disruption. *Toxicol. Appl. Pharmacol.* **435**, 115831 (2022).
  - 135) S. Hashiro and H. Yasueda: RNA interference-based pesticides and antiviral agents: Microbial overproduction systems for double-stranded RNA for applications in agriculture and aquaculture. *Appl. Sci. (Basel)* **12**, 2954 (2022).
  - 136) Index of New ISO Common Names “ledprona”. [http://www.bcp-pesticidecompendium.org/index\\_new\\_frame.html](http://www.bcp-pesticidecompendium.org/index_new_frame.html) (Accepted 22 Jun, 2025)
  - 137) <https://www.epa.gov/pesticides/epa-registers-novel-pesticide-technology-potato-crops> (Accessed 1 July, 2025)
  - 138) T. Furuya, K. Machiya, S. Fujioka, M. Nakano and K. Inagaki: Development of a novel acaricide, pyflubumide. *J. Pestic. Sci.* **42**, 132–136 (2017).
  - 139) Technical information. <https://www.nichino.co.jp/contents/000003079.pdf> (Accessed 16 July, 2025)
  - 140) J. Ouyang, Y. Tian, C. Jiang, Q. Yang, H. Wang and Q. Li: Laboratory assays on the effects of a novel acaricide, SYP-9625 on *Tetranychus cinnabarinus* (Boisduval) and its natural enemy, *Neoseiulus californicus* (McGregor). *PLoS One* **13**, e0199269 (2018).
  - 141) N. Hayashi: Development of formulated oil. In “Trend in Research and Development of Chemical Pesticides, Biopesticides and Biostimulants,” supervised by N. Umetsu, CMC Publishing, pp. 294–302, 2023 (in Japanese).
  - 142) N. Takeda, A. Takata, Y. Arai, K. Sasaya, S. Noyama, S. Wakisaka, N. A. Ghazy, D. Voigt and T. Suzuki: A vegetable oil-based biopesticide with ovicidal activity against the two-spotted spidermite, *Tetranychus urticae* Koch. *Eng. Life Sci.* **20**, 525–534 (2020).
  - 143) Agrochemicals Business. <https://www.nipponkayaku.co.jp/english/business/life-science/agrochemicals/> (Accessed 25 July, 2025)
  - 144) I. Hamamoto, M. Kawaguchi, T. Nakamura, M. Yano, K. Koizumi and J. Takahashi: Discovery of a novel acaricide, acynonapyr. *J. Pestic. Sci.* **48**, 202–210 (2023).
  - 145) K. Hirata, K. Kudo, T. Amano and M. Kawaguchi: Effects of the novel acaricide acynonapyr on the calcium-activated potassium channel. *Pestic. Biochem. Physiol.* **204**, 106074 (2024).
  - 146) S. Yoshimura and S. Mukawa: Characteristics biological activities of the novel acaricide flupentiofenox against phytophagous mites. *J. Pestic. Sci.* **48**, 211–217 (2023).
  - 147) C. Uchiyama, S. Yoshimura, S. Yamamoto, M. Ogawa and K. Kawai: Acaricide flupentiofenox inhibits the mitochondrial  $\beta$ -oxidation pathway of fatty acids. *J. Agric. Food Chem.* **72**, 18391–18400 (2024).
  - 148) Index of New ISO Common Names “vadescana”. [http://www.bcppesticidecompendium.org/index\\_new\\_frame.html](http://www.bcppesticidecompendium.org/index_new_frame.html) (Accessed 25 July, 2025)
  - 149) EPA Proposes to Register New Pesticide for Varroa Mite Control. <https://www.epa.gov/pesticides/epa-proposes-register-new-pesticide-varroa-mite-control> (Accessed 10 Aug., 2025)
  - 150) T. Sasami: Trends in the development of nematicides and the practice of nematode control. In “Trend in Research and Development of Chemical Pesticides, Biopesticides and Biostimulants,” supervised by N. Umetsu, CMC Publishing, pp. 140–160, 2023 (in Japanese).
  - 151) A. S. S. Schleker, M. Rist, C. Matera, A. Damijonaitis, U. Collien, K. Matsuoka, S. S. Habash, K. Twelker, O. Gutbrod, C. Saalwächter, M. Windau, S. Matthiesen, T. Stefanovska, M. Scharwey, M. T. Marx, S. Geibel and F. M. W. Grundler: Mode of action of fluopyram in plant-parasitic nematodes. *Sci. Rep.* **12**, 11954 (2022).
  - 152) Bayer stops sale of NemaStrike for 2020. <https://www.farmprogress.com/business/bayer-stops-sale-of-nemastrike-for-2020> (Accessed 28 July, 2025)
  - 153) Reklmel active Technical bulletin. [https://www.corteva.com/content/dam/dpagco/corteva/global/corporate/files/products-and-services/DOC-Reklmel\\_active\\_tech\\_bull\\_2022\\_Final\\_Print-Global.pdf](https://www.corteva.com/content/dam/dpagco/corteva/global/corporate/files/products-and-services/DOC-Reklmel_active_tech_bull_2022_Final_Print-Global.pdf) (Accessed 28 July, 2025)
  - 154) J. Kearns, E. Ludlow, J. Dillon, V. O'Connor and L. Holden-Dye: Flusulfone is a nematicide with a mode of action distinct from anticholinesterases and macrocyclic lactones. *Pestic. Biochem. Physiol.* **109**, 44–57 (2014).
  - 155) NIMITZ®-ADAMA Ltd. [https://www.adama.com/new-zealand/sites/adama\\_new\\_zealand/files/product-documents/2024-08/Nimitz\\_TechNote\\_Final\\_24.pdf](https://www.adama.com/new-zealand/sites/adama_new_zealand/files/product-documents/2024-08/Nimitz_TechNote_Final_24.pdf) (Accessed 28 July, 2025)
  - 156) Nemguard SC, Ecospray. <https://ecospray.com/wp-content/uploads/2019/07/Ecospray-Nemguard-SC-Brochure.pdf> (Accessed 28 July, 2025)
  - 157) Cedroz/Eastman. <https://www.eastman.com/en/products/product-detail/71111396/cedroz> (Accessed 28 July, 2025)
  - 158) H. Thompson, F. J. Peris-Felipo, N. Peranginangin, M. Pocock and

- A. L. Gayan-Quijano: Cyclobutirfluram (TYMIRIUM® technology): Low risks of a soil applied nematicide and fungicide to non-target soil invertebrates and bees. *Crop Prot.* **184**, 106822 (2024).
- 159) A. Flemming, M. Guest, T. Luksch, A. O'Sullivan, C. Screpanti, R. Dumeunier, M. Gaberthüel, E. Godineau, P. Harlow, A. Jeanguenat, B. Kurtz, P. Maienfisch, R. Mondière, A. Pierce, B. Slaats, T. Smejkal and O. Loiseleur: The discovery of Cyclobutirfluram, a new molecule with powerful activity against nematodes and diseases. *Pest Manag. Sci.* **81**, 2480–2490 (2025).
  - 160) <https://news.agropages.com/News/Detail-47875.htm> (Accessed 28 July, 2025)
  - 161) The new HRAC Mode of Action Classification System for Herbicides. [https://hracglobal.com/europe/files/HRAC-Classification-System-2021\\_English.pdf](https://hracglobal.com/europe/files/HRAC-Classification-System-2021_English.pdf) (Accessed 3 Aug., 2025)
  - 162) S. Murakami, D. Itaya, Y. Lyu and Ki. Kawai: Trend of herbicide development. In “Trend in Research and Development of Chemical Pesticides, Biopesticides and Biostimulants,” supervised by N. Umetsu, CMC Publishing, pp.161–192, 2023 (in Japanese).
  - 163) 2024-hrac-global-herbicide-moa-classification. <https://hracglobal.com/files/2024-HRAC-GLOBAL-HERBICIDE-MOA-CLASSIFICATION-POSTERold.pdf> (Accessed 3 Aug., 2025)
  - 164) K. Sugiura, T. Yamaoka, M. Ito, R. Okabayashi, S. Shirakura and B. Shakudo: Development of a rice herbicide, triafamone. *J. Weed Sci. Tech* **66**, 72–76 (2021) (in Japanese).
  - 165) A. Nagamatsu, K. Ueda, R. Tamai, S. Tani and S. Yamamoto: Development of a rice herbicide, fenquinotrione. *J. Pestic. Sci.* **47**, 139–145 (2022).
  - 166) S. Yamamoto, Y. Tanetani, C. Uchiyama, A. Nagamatsu, M. Kobayashi, M. Ikeda and K. Kawai: Mechanism of action and selectivity of a novel herbicide, fenquinotrione. *J. Pestic. Sci.* **46**, 249–257 (2021).
  - 167) M. Miyashita, T. Suganuma, Y. Kobayashi, K. Izakura and M. Sano: Studies on a new herbicide, lancotrione-sodium salt, Part 1. *Abstracts of the 45th Annual Meeting of the Pesticide Science Society of Japan*, p. 79 (2020) (in Japanese).
  - 168) M. Tsukamoto, H. Kikugawa, S. Nagayama, T. Suganuma, T. Okita and H. Miyamoto: Discovery and structure optimization of a novel corn herbicide, tolypyralate. *J. Pestic. Sci.* **46**, 152–159 (2021).
  - 169) Tolpyralate. [https://www.iskweb.co.jp/eng/products/pdf/international\\_Tolpyralate.pdf?0418](https://www.iskweb.co.jp/eng/products/pdf/international_Tolpyralate.pdf?0418) (Accessed 12 Aug., 2025)
  - 170) Bipyrzone—KingAgroot. <https://www.kingagroot.com/en/html/pdfShow.html?pdfUrl=Bipyrzone> (Accessed 13 Aug., 2025)
  - 171) Cypirafluone—KingAgroot. <https://www.kingagroot.com/en/assets/pdf/Cypirafluone.pdf> (Accessed 13 Aug., 2025)
  - 172) Fenpyrzone—KingAgroot. <https://www.kingagroot.com/en/assets/pdf/Fenpyrzone.pdf> (Accessed 15 Aug., 2025)
  - 173) Tripyrasulfone—KingAgroot. <https://www.kingagroot.com/en/assets/pdf/Tripyrasulfone.pdf> (Accessed 15 Aug., 2025)
  - 174) R.-Yu Qu, J.-Xu Nan, Y.-Chao Yan, H.-Yan Lin, W.-Chao Yang and G.-Fu Yang: “Quinazoline-2,4-dione: A promising scaffold for herbicide discovery. In “Recent Highlights in the Discovery and Optimization of Crop Protection Products,” ed. by P. Maienfisch and S. Mangelinckx, Academic Press, pp. 483–499, 2021.
  - 175) T. Nishio, N. Nishijima, T. Kubota, Y. Furuhashi, Y. Nanao, H. Permana, T. Furuhashi and Y. Kato: Mechanism of herbicidal action and rice selectivity of iptriazopyrid: A novel azole carboxamide-based inhibitor of 4-hydroxyphenylpyruvate dioxygenase. *J. Agric. Food Chem.* **73**, 15950–15958 (2025).
  - 176) Mechanism of action of the rice herbicide “iptriazopyrid” elucidated. [https://www.nissanchem.co.jp/eng/news\\_release/release/en2025\\_06\\_11.pdf](https://www.nissanchem.co.jp/eng/news_release/release/en2025_06_11.pdf) (Accessed 15 Aug., 2025)
  - 177) Flusulfenam—KingAgroot. <https://www.kingagroot.com/en/assets/pdf/Flusulfenam.pdf> (Accessed 15 Aug., 2025)
  - 178) <https://news.agropages.com/News/NewsDetail---47391.htm> (Accessed 15 Aug., 2025)
  - 179) Cynda's patented herbicide pyraquinate released to market. <https://news.agropages.com/News/NewsDetail---53281.htm> (Accessed 15 Aug., 2025)
  - 180) FarmHannong launches novel nonselective herbicide Tiafenacil in South Korea. <https://news.agropages.com/News/NewsDetail---28263.htm> (Accessed 16 Aug., 2025)
  - 181) M. Witschel, R. Aponte, G. Armel, P. Bowerman, T. Mietzner, T. Newton, A. Porri, A. Simon and T. Seitz: Tirezor®—design of a new resistance breaking protoporphyrinogen IX oxidase inhibitor. In “Recent Highlights in the Discovery and Optimization of Crop Protection Products,” ed. by P. Maienfisch and S. Mangelinckx, Academic Press, pp. 501–509, 2021.
  - 182) <https://biologicaldiversity.org/w/news/press-releases/basf-to-stop-selling-pesticide-trifludimoxazin-rather-than-continue-litigation-2022-02-23/> (Accessed 16 Aug., 2025)
  - 183) <https://www.epa.gov/pesticides/epa-announces-proposed-registration-pesticide-trifludimoxazin> (Accessed 16 Aug., 2025)
  - 184) Y. Sada, Y. Jin, M. Hikosaka and K. Ido: Epyrifenacil, a new systemic PPO-inhibiting herbicide for broad-spectrum weed control. *Pest Manag. Sci.* **81**, 2463–2468 (2024).
  - 185) Business & Products/SUMITOMO CHEMICAL. <https://www.sumitomo-chem.co.jp/english/news/detail/20240725e.html> (Accessed 17 Aug., 2025)
  - 186) Flufenoximacil—KingAgroot. <https://www.kingagroot.com/en/assets/pdf/Flufenoximacil.pdf> (Accessed 17 Aug., 2025)
  - 187) M. Fujinami, Y. Takahashi, Y. Tanetani, M. Ito and M. Nasu: Development of a rice herbicide, fenoxasulfone. *J. Pestic. Sci.* **44**, 282–289 (2019).
  - 188) T. Furuhashi, M. Otani and M. Iwasa: Dimesulfazet, a novel rice paddy herbicide, is an inhibitor of very long-chain fatty acid biosynthesis. *J. Pestic. Sci.* **49**, 77–86 (2024).
  - 189) Presentation for R&D. [https://www.nissanchem.co.jp/eng/news\\_release/release/en2025\\_06\\_16.pdf](https://www.nissanchem.co.jp/eng/news_release/release/en2025_06_16.pdf) (Accessed 18 Aug., 2025)
  - 190) Technical Bulletin. [https://www.corteva.com/content/dam/dpagco/corteva/global/corporate/general/files/active-ingredients/DF\\_Arylex-TechBulletin\\_1-29-19.pdf](https://www.corteva.com/content/dam/dpagco/corteva/global/corporate/general/files/active-ingredients/DF_Arylex-TechBulletin_1-29-19.pdf) (Accessed 20 Aug., 2025)
  - 191) Broadleaf Weed Control in Multiple Crops/Arylex Active. <https://www.corteva.com/products-and-services/arylex.html> (Accessed 20 Aug., 2025)
  - 192) R. Herrera, M. R. Weimer, M. Morell, P. L. Havens, G. Meregalli, S. Papineni, L. A. Laughlin and G. Shan: Rinskor active herbicide-A new environment-friendly tool for weed management in rice and aquatic environments. In “Recent Highlights in the Discovery and Optimization of Crop Protection Products,” ed. by P. Maienfisch and S. Mangelinckx, Academic Press, pp. 511–523, 2021.
  - 193) V. V. Zakharychev and A. M. Martsynkevich: Development of novel pyridine-based agrochemicals: A review. *Adv. Agrochem.* **4**, 30–48 (2025).
  - 194) <https://www.corteva.com/resources/media-center/corteva-announces-bexoveld-active-as-global-brand-for-newest-active-ingredient.html> (Accessed 20 Aug., 2025)
  - 195) Fluchloraminopyr-tefuryl-KingAgroot. <https://www.kingagroot.com/en/assets/pdf/Fluchloraminopyr-tefuryl.pdf> (Accessed 20 Aug., 2025)
  - 196) <https://news.agropages.com/News/NewsDetail---45926.htm> (Accessed August 20, 2025)

- 197) Isoflex™ Active Overview/FMC Crop. <https://www.fmc.com/en/isoflexactive> (Accessed 21 Aug., 2025)
- 198) Broclozone-KingAgroot. <https://www.kingagroot.com/en/assets/pdf/Broclozone.pdf> (Accessed 21 Aug., 2025)
- 199) J. Leipner and N. Ruta: Discovery of anisiflupurin, an inhibitor of cytokinin dehydrogenase that mitigates heat-induced yield reduction in rice. *Pest Manag. Sci.* **81**, 2662–2670 (2025).
- 200) <https://news.agropages.com/News/NewsDetail---48009.htm> (Accessed 21 Aug., 2025)
- 201) J. N. Scutt, N. J. Willetts, B. F. Campos, S. Oliver, A. Hennessy, P. M. Joyce, S.-J. Hutchings, G. le Goupil, W. L. Colombo and S. S. Kaundun: Metproxybicyclone, a novel carbocyclic aryl-dione acetyl-CoA carboxylase-inhibiting herbicide for the management of sensitive and resistant grass weeds. *J. Agric. Food Chem.* **72**, 21380–21392 (2024).
- 202) Major breakthrough in fight against resistant grass weeds. <https://www.syngenta.com/media/media-releases/2025/major-breakthrough-fight-against-resistant-grass-weeds> (Accessed 24 Aug., 2025)
- 203) CYNDA's innovative herbicide Fepoxydim officially obtained the ISO general name, is expected to be launched in 2024. <https://www.echemi.com/cms/1877498.html> (Accessed 24 Aug., 2025)
- 204) K.-B. Haaf, O. Peters, B. Laber, G. Lange, E. Gatzweiler, S. Geibel, D. Passon, A. Endler, S. Lange, S. Kahlau, T. Eroschenko, P. Waldraff and P. Lümmer: The novel herbicide icafolin-methyl is a plant-specific inhibitor of tubulin polymerization. *Pest Manag. Sci.* **81**, 2652–2661 (2024).
- 205) <https://www.bayer.com/media/en-us/bayer-submits-registration-applications-for-novel-herbicide-in-four-major-markets/> (Accessed 24 Aug., 2025)
- 206) R. Campe, E. Hollenbach, L. Kämmerer, J. Hendriks, H. W. Höffken, H. Kraus, J. Lerchl, T. Mietzner, S. Tresch, M. Witschel and J. Hutzler: A new herbicidal site of action: Cinmethylin binds to acyl-ACP thioesterase and inhibits plant fatty acid biosynthesis. *Pestic. Biochem. Physiol.* **148**, 116–125 (2018).
- 207) <https://www.basf.com/hk/en/media/news-releases/anz/2019/11/BASF-introduces-Luximax-to-Australian-farmers.html> (Accessed 25 Aug., 2025)
- 208) <https://www.echemi.com/cms/1245590.html> (Accessed 24 Aug., 2025)
- 209) <https://www.basf.com/global/en/media/news-releases/2020/06/p-20-168.html> (Accessed 25 Aug., 2025)
- 210) PoaCure/Product Information. <https://www.sdsbio.co.jp/products/turf/23809.html> (in Japanese) (Accessed 25 Aug., 2025)
- 211) C. Brabham, P. Johnen, J. Hendriks, M. Betz, A. Zimmermann, J. Gollihue, W. Serson, C. Kempinski and M. Barrett: Herbicide symptomology and the mechanism of action of methiozolin. *Weed Sci.* **69**, 18–30 (2021).
- 212) Cinflubrolin—KingAgroot. <https://www.kingagroot.com/en/assets/pdf/Cinflubrolin.pdf> (Accessed 25 Aug., 2025)
- 213) S. Kahlau, F. Schröder, J. Freigang, B. Laber, G. Lange, D. Passon, S. Kleeßen, M. Lohse, A. Schulz, P. von Koskull-Döring, S. Klie and S. Gill: Aclonifen targets solanesyl diphosphate synthase, representing a novel mode of action for herbicides. *Pest Manag. Sci.* **76**, 3377–3388 (2020).
- 214) I. H. Kang, C. Brabham, J. Lee, L. Wu, Q. Lu, M. Yan, P.-S. Lai, D. F. Rhoades, D. Nesnow, S. Jeffrey, B. McGonigle, S.-I. Kim, J. L. Andreassi, S. O. Pember, S. Gutteridge and R. P. Emptage: Dual mode of action herbicide rimisoxafen targets both phytoene desaturase and solanesyl diphosphate synthase. *Pest Manag. Sci.* **81**, 6330–6339 (2025).
- 215) S. Tresch, J. Schmotz and K. Grossmann: Probing mode of action in plant cell cycle by the herbicide endothall, a protein phosphatase inhibitor. *Pestic. Biochem. Physiol.* **99**, 86–95 (2011).
- 216) M. Shino, T. Hamada, Y. Shigematsu, K. Hirase and S. Banba: Action mechanism of bleaching herbicide cyclopyrimorate, a novel homogenisate solanesyltransferase inhibitor. *J. Pestic. Sci.* **43**, 233–239 (2018).
- 217) M. Shino, T. Hamada, Y. Shigematsu, K. Hirase, S. Banba, Y. Tsukamoto and J. Kadotani: Discovery and mode of action of cyclopyrimorate: A new paddy rice herbicide. In “Recent Highlights in the Discovery and Optimization of Crop Protection Products,” ed. by P. Maienfisch and S. Mangelinckx, Academic Press, pp. 451–457, 2021.
- 218) R. Sadre, M. Frentzen, M. Saeed and T. Hawkes: Catalytic reactions of the homogenisate prenyl transferase involved in plastoquinone-9 biosynthesis. *J. Biol. Chem.* **285**, 18191–18198 (2010).
- 219) Dodhylex™ active/FMC Corp. <https://www.fmc.com/en/dodhylexactive> (Accessed 27 Aug., 2025)
- 220) I. H. Kang, R. P. Emptage, S. I. Kim and S. Gutteridge: A novel mechanism of herbicide action through disruption of pyrimidine biosynthesis. *Proc. Natl. Acad. Sci. U.S.A.* **120**, e2313197120 (2023).
- 221) <https://www.syngenta.com/media/media-releases/2023/syngenta-and-fmc-commercialize-breakthrough-technology-transforms-grass> (Accessed 27 Aug., 2025)
- 222) New pesticides for BCPC's global database. <https://www.bcpc.org/latest-news/new-actives-and-new-fields-for-bcpcs-global-database-2> (Accessed 27 Aug., 2025)
- 223) Ledprona: EPA Greenlights Innovative Biopesticide for Potato Crops. <https://www.useforesight.io/news/ledprona-epa-greenlights-innovative-biopesticide-for-potato-crops> (Accessed 7 Sep., 2025)