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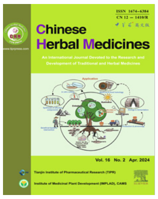

Review

Advances in research and utilization of botanical pesticides for agricultural pest management in Inner Mongolia, China

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ABSTRACT

Traditional Chinese herbal medicines not only cure human diseases, but also play an important role as insecticides. Compared with conventional chemical agents, traditional Chinese herbal medicines are characterized by low toxicity, low residues, and being eco-friendly, and they have become a research hotspot. Traditional Chinese herbal medicines have tremendous flexibility and indefinite potential. Therefore, this paper reviewed the types of insecticides belonging to traditional Chinese herbal medicines in Inner Mongolia, China, including their traditional uses, secondary metabolites, biological activities, action mechanisms, application methods, and development status. In addition, the most relevant issues involved in the development of traditional Chinese herbal medicines was discussed. We believe that traditional Chinese herbal medicines can be better implemented and developed; such that its other advantages, such as an insect repellent, can be promoted. Moreover, this study lays a solid foundation for further research on traditional Chinese herbal medicines in Inner Mongolia, China.

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1. Introduction

Traditional agriculture will seriously harm the diversity of species, and the abuse of chemical fertilizers and pesticides makes traditional agriculture even more unsuitable for the green and health concept of today's society. Compared with traditional agriculture, organic agriculture follows the principle of dynamic balance and interaction between crops and soil, microorganisms, environment and ecosystem, effectively protecting biodiversity, reducing human intervention as much as possible, and restoring natural ecosystems (Azadi et al., 2011; Mondelaers, Aertsens, & Van Huylenbroeck, 2009; Muller et al., 2017; Rembiałkowska, 2007). The concept of organic agricultural production system has been on a constant rise, ever since Sir Albert Howard proposed it in his book *An Agricultural Testament* (1940) (Howard, 1943). In recent years, organic agriculture has grown rapidly, and according to the Ecology and Agriculture Foundation, organic farming is practiced in more than 100 countries including Australia, Argentina, and China (Li, Wang, & Guo, 2013). According to statistics, by the end of 2021, there are 17.3 million hectares of agricultural land in the world. China's agricultural land area is nearly 1.504 million hectares, accounting for nearly 11.5% of the world's total. However, a large number of crop production will inevitably be accompanied by the threat of pests. However, in order to pursue the rapid insecticidal effect, chemical pesticides are frequently used on a large scale, which has caused irreversible harm to human beings and the environment. Nowadays, the development of environment-friendly organic agriculture such as botanical pesticides has gradually entered people's field of vision and has been highly respected. With the development of organic agriculture in China, Certification and Accreditation Administration of the People's Republic of China issued the "China Organic Standard GB19630.1–4-2005" (https://www.ekowarehouse.com/certification/China-organic-cnca, https://www.cnca.gov.cn) in 2005. This standard has been implemented nationwide via the China National Organic Products Certification Program. As a practical approach and an important part of sustainable development, organic agriculture is not only a substitute for long-term traditional agricultural production practices, but also a new approach for environmental protection, rational resource use, and sustainable agricultural ecosystem development.

The use of plant-based biological products as botanical pesticides is a promising approach for achieving high yields in organic agriculture (Isman, 2020). The botanical pesticides are active ingredients derived from plants with no pesticide residue; they decompose easily, have high efficacy, and are eco-friendly. They are a new type of botanical pesticide that can replace chemical pesticides and promote the development of organic agriculture, and thus, relieve the pressure of synthetic pesticides on the environment to a certain extent (Zhang, Ma, Feng, Wu, & Han, 2015; Zheng, Yan, & Wang, 2016). The active ingredients are usually not single compounds, but some or even most organic substances in plant organisms. Plant-derived pesticides have the characteristics of being environment-friendly, not easy to produce resistance, specific modes of action, promoting crop growth and improving disease resistance. Due to its advantages, botanical pesticides are made into various forms of application for plant protection, especially in the organic sector and for low-input food production, such as botanical insecticides, fungicides, bactericides, and herbicides. For example, *Sophora flavescens* Alt. and *Stellera chamaejasme* L. are used in melons, fruits, vegetables, and special crops including tea, mulberry, Chinese herbal medicines, and flowers (Al-Samarrai, Singh, & Syarhabil, 2012; Dar, Nisar, Mudasir, & Mudasir, 2014; Marutescu, Popa, Saviuc, Lazar, & Chifiriuc, 2017).

Nowadays, we are facing the critical moment of moving from traditional agriculture to organic agriculture and eventually developing into ecological agriculture. It is urgent to understand the biological activity and mechanism of action of plant-derived pesticides. And Inner Mongolia, China, is rich in vegetation, which contains a large number of plant source pesticides for development. Therefore, we summarized the types of plants used as sources of organic compounds with pesticide activity in Inner Mongolia, China; the main highlights of the historical development of plant pesticides; pesticidal secondary metabolites screened out and their biological activity, their mechanisms of action, and their mode of application. The insecticidal and bacteriostatic mechanisms of secondary metabolites such as alkaloids, volatile oils, organic acids, flavones, terpenes, and sterols, among others, were specifically considered, as well as insecticides and bacteriostatic compounds with different modes of action. Finally, we discussed the possible directions of future development of botanical pesticides. In doing so, we try to provide novel insights for further research of botanical pesticides that might help to construct a new perspective for the development of plant-derived pesticides for a greener and more sustainable organic agriculture in Inner Mongolia, China.

2. Sources of botanical pesticides

Botanical insecticides contain active ingredients from plants with insecticidal effects. Such plant extracts have broad-spectrum applications along with low toxicity and are efficient and easy-to-degrade. They possess no residual insecticide and do not cause resistance to insecticide. Botanical insecticides are effective against most plant pests but do not harm or accumulate in humans, livestock, or the surrounding environment. The effective components, industrial production method, mechanism and mode of action, among others, of botanical insecticides are different from chemical ones. Plant insecticides can be integrated in pest management strategies in the future (Freeman et al., 2021). The practice of using botanical pesticides or plant derivatives in agriculture can be traced back to the ancient cultures of China, Egypt, India, and Greece (Thacker, 2002). Despite the rich resource base of medicinal plants in China and the long history of using botanical pesticides, the research on this subject began in the 1930s and progressed slowly. With the development of science and technology in the 19th century, the research on and application of botanical pesticides gradually evolved from empirical methods into scientific experiments. With constant interaction and co-evolution with insects, plants formed a physical defense mechanism within their morphological structure and consumed significant amounts of material and energy to produce secondary metabolites that inhibit life activities, such as volatile essential oils, alkaloids, etc. Although most such secondary metabolites have protective effects on plants, they are not directly involved in maintaining plant growth, development, and reproduction processes and can affect the food choice of insects in the surrounding environment. Thus, plants can actively resist pests, resulting in lesser damage to the population in general. Botanical pesticides are environmentally friendly, generally have low toxicity, and do not easily cause resistance to diseases and pests (Freeman et al., 2021).

Since 1949, botanical pesticides have been developed and applied along with chemical pesticides, for example, the mass movement for native pesticides in 1958 and the upsurge of botanical pesticide development in the 1970s. However, due to the relatively low level of technology at that time, coupled with the subsequent rise of efficient pesticides such as pyrethrum, the use of botanical pesticides ebbed (Isman & Grieneisen, 2014). The use of toxic plants, minerals, oils, sprays, and boiling water, has been commonly implemented in practice. For example, *Pyrethrum cinerariifolium* Trev., *Nicotiana tabacum* L., and *Derris trifoliata* Lour., have been used to develop products widely used in pest management (Miresmailli & Isman, 2013). Two major monographs have been published in China so far. The first one, *Zhong Guo Tu Nong Yao Zhi* (*Folk Pesticides in China* in English), contained the description of 220 species of botanical pesticides categorized into 86 families. The second, *Poisonous Plants in China* (Chen & Zheng, 1987), lists more than 1300 species of poisonous plants, of which most had been used as botanical pesticides. Simultaneously, the research and application of chemical pesticides intensified, but due to the negative effects on non-target species and the environmental risks resulting from their massive use, the interest turned to scientific plant materials with pesticidal properties.

In recent years, with the rapid development of modern technology and focus of general public on environmental quality, plant pesticides have been paid increasing attention. Using plant resources to develop new pesticides has become an important modern pesticide development path (Isman & Grieneisen, 2014). The vast land of Inner Mongolia has rich terrain diversity, resulting in an abundance of plant resources distributed in grassland, desert, forest, and other ecosystems. Indeed, up to 2176 wild plants were reported at *the Fourth National Survey of Traditional Chinese Medicines* from Inner Mongolia (Li, He, Xu, Wang, & Huang, 2019). As many traditional Mongolian medicines have insecticidal effects, they may be potential botanical-pesticide sources. Such a strategy can lay a solid theoretical foundation for the development of botanical pesticides in Inner Mongolia.

3. Plant secondary metabolites

3.1. Alkaloids

Alkaloids are secondary plant metabolites with physiological activities found in various botanical families, including Ranunculaceae, Leguminosae, and Compositae. As the oldest alkaloid used in agriculture, nicotine is one of the earliest molecules used as a pesticide (Ntalli & Menkissoglu-Spiroudi, 2011). However, the use of nicotine alone as a pesticide in agriculture has declined because it is highly toxic to mammals, and even the human skin absorbs it very quickly (Murray, 2006). To overcome this disadvantage, nicotine was mixed with other pesticides. Some experiments showed that the pest control rate reached 86% when using 1.2 nicotine-matrine cream and 1.5% matrine solution at 1200 and 1500 dilution. At the same time, it was surprising that the natural enemies of forest pests were not harmed when different concentrations of pesticide sprays were used in an experiment in the forest (Huang, 2019). Many botanical pesticides containing alkaloids are also used in Inner Mongolia, China. For example, *Sophora alopecuroides* L. (**A**) contains aloperine and quinoline biphenyls, such as aloperine (**1**), andcytisine (**2**), which has a significant nematicidal effect. Matrine (**3**), which is extracted from *S. flavescens* (**B**), has been officially registered since 1993. Matrine is very suitable for compounding with other pesticide ingredients, and the combination of matrine and nicotine can also play a significant role in killing insects. The toxicity of 1.2% nicotine matrine cream and 1.5% matrine solution to *Artona funeralis* Butler were 0.596 mg/L and 0.612 mg/L, respectively. Harmaline (**4**), which is extracted from *Peganum harmala* L. (**C**) exerts stomach toxicity (Bournine, et al., 2017), whereas coniine (**5**), extracted from *Cicuta virosa* L. (**D**), has paralytic effects on insects (Liu, Hua, Zhang, & Xuan, 2010). Veratrine (**6**), a major component of *Veratrum nigrum* L. (**E**), is a mixture of alkaloids mainly used to control three-year-old *Mythimna separata* Walker, *Aphis* spp., and *Tetranychus urticae* C. L. Koch (Liu, 2017; Kang, 2017). The alkaloids in *Aconitum coreanum* (H. Lév.) Rapaics exhibit biological activity against flies, lice, mosquitoes, and aphids. For example, aconitine (**7**), hypaconitine (**8**) and mesaconitine (**9**) extracted from *Aconitum kusnezoffii* Reichb. (**F**) act as stomach toxins, antifeedants, and growth inhibitors of *M. separata* and as a prominent contact poison of *Dendrolimus punctatus* Walker, *Myzus persicae* Sulzer, *Pieris rapae* L. (Liu, Yu, Li, Li, & Ji, 2013) (Figs. 1–3). Fig. 2 provides a good representation of the geographical distribution of key plant-derived pesticides in Inner Mongolia, China as shown in Fig. 1. Besides favorable insecticidal action, the alkaloids from the genus Aconitum also have antifungal activity. Thus, the total alkaloid solution of *Aconitum leucostomum* Vorosch. at a concentration of 20 mg/mL shows a remarkable inhibitory effect on *Fusarium solani* (Mart.) Sacc. and *Phytophtora drechsleri* Tucker (inhibition rate of 100%) (Liu, Wu, & Li, 2009).

The alkaloids produced by plants in Inner Mongolia, China, include diterpenoid alkaloids, quinolizidine alkaloids, and other alkaloids, which belong to plant secondary metabolites and have notable insecticidal activity. The use effect of alkaloid pesticides is compared with that of existing pesticides, and the results show that the total drug investment per hectare is reduced by 30%−40%. From an economic point of view, alkaloid pesticides have the characteristics of low cost, can prevent a variety of diseases, and reduce labor costs; moreover, they do not easily produce drug resistance (Chen, Wang, Yuan, Chen, & Wang, 2012). Notwithstanding, alkaloid pesticides also have limitations in their industries; for example, their raw materials cannot be standardized, their modern production industry processes have not matured, and plants producing alkaloids in different regions will be affected by local soil and temperature, resulting in a large difference in alkaloid content (Goolsby, Maestas, Saelao, & Lohmeyer, 2022). In summary, although alkaloids have a suitable control effect on all kinds of pests, several problems remain unsolved: 1) Alkaloids used in determining insecticidal activity are still very limited, which should be promoted. The government should increase its corresponding support; for example, policies that have been introduced to reduce farmers' taxes and increase farmers' corresponding welfare will better promote the friendly development of green agriculture. 2) As there are few types of insects that are sufficiently studied, limiting research to the activity of a few insects, more attention should be paid to insect diversity. 3) As the effective component content of natural products is not ideal, it is best to optimize the chemical structures of natural products through technical means.

3.2. Volatile oils

Volatile oils, also known as essential oils, are found in some plant families. For example, Compositae, Umbelliferae, Magnoliaceae, and

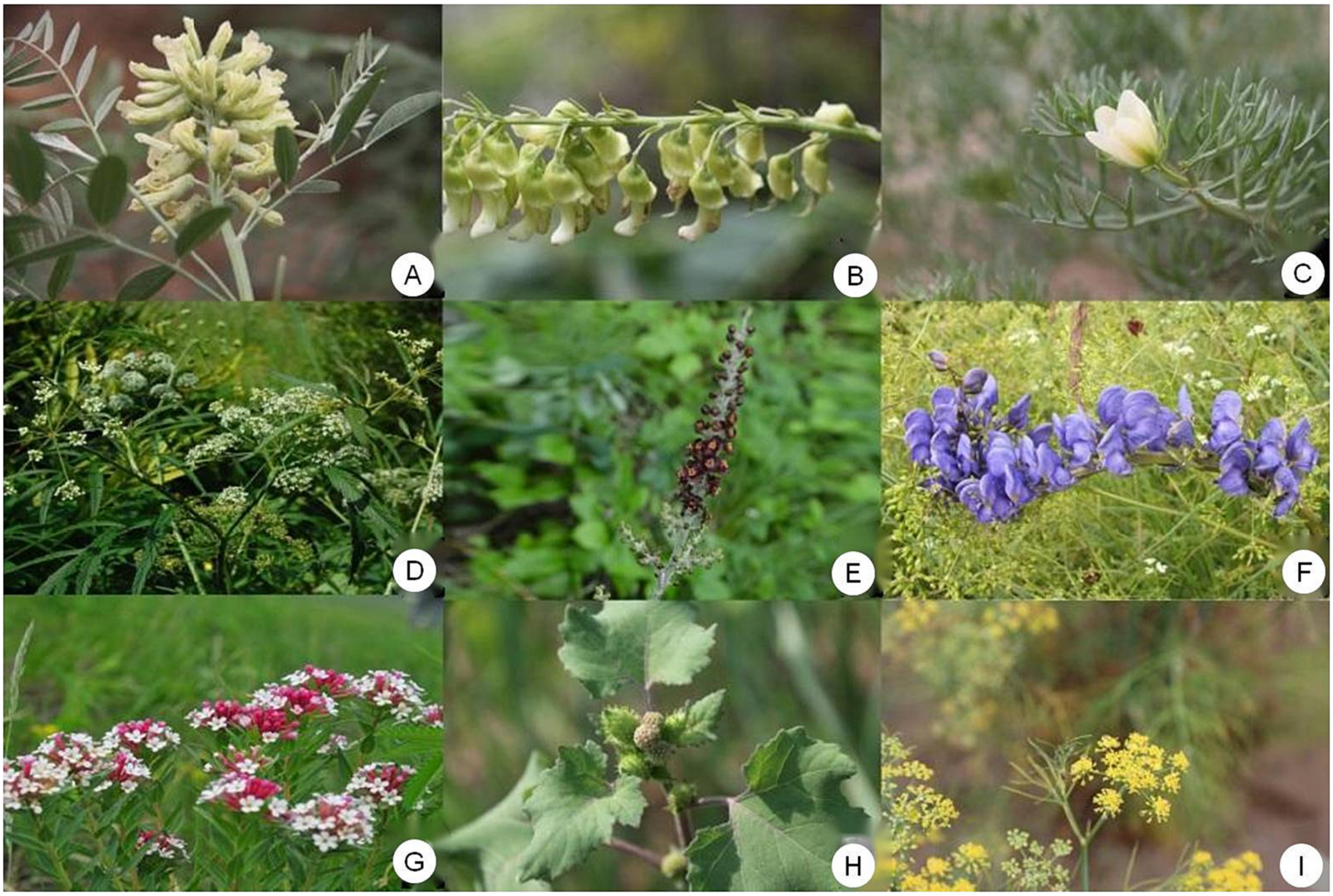


Fig. 1. Representative plants of botanical pesticides in Inner Mongolia, China. A: *Sophora alopecuroides* L.; B: *Sophora flavescens* Aiton*;* C: *Peganum harmala* L.; D: *Cicuta virosa* L.; E: *Veratrum nigrum* L.; F: *Aconitum kusnezoffii* Rchb.; G: *Stellera chamaejasme* L.; H: *Xanthium sibiricum* Patrin ex Widder; I: *Foeniculum vulgare* Mill.

Ericaceae have natural volatile complex compounds characterized by a strong odor. Usually, volatile oils can be distilled with steam and consist of terpenes, terpenoids, and other aromatic and aliphatic constituents. Volatile oils are widely used as plant pesticides due to their volatile characteristics (Bassolé & Juliani, 2012).

Pests containing volatile oil components can exert toxicity via contact, feeding deterrence, fumigation, and fungicidal actions. For example, a volatile oil derived from *Schisandra chinensis* (Turcz.) Baill. is a contact toxin to *Meloidogyne incongnita* (Kofold & White) Chitwood and *Sitophilus zeamais* Motschulsky. It is also used as a fumigant, with an apparent dose–effect relationship. The LC_{50} value of *M. incongnita* is 122.941 μg/mL. Furthermore, the volatile oil has a contact-killing effect and a relatively good effect on *M. incognita*, with suitable lethality. A study has demonstrated that the use of *Schisandra* volatile oils as a fumigant can meet insecticidal needs (Zhou, 2016). In addition, studies have examined the effects of different essential oils and compound essential oils to repel mosquitoes *Aedes albopictus* Skuse and *Culex pipiens pallens* Coquillet through mosquito-repellent experiments. Among them, pennyroyal and pine oils have shown a suitable repellent effect on these two mosquitoes, and the combination of different essential oils coupled with slow-release technology is more conducive for the mosquito-repellent effect of these essential oils (Wang et al., 2016). Another study proved that the oil extracted from *Artemisia annua* L., diluted 2–4 times, can exert strong direct contact toxicity against *Lasioderma serricorne* Fabricius larvae and adults. Furthermore, it exerts high insect-repellent toxicity at different concentrations. However, the fumigation effect of this essential oil is relatively weak. Therefore, *A. annua* is considered one of the important sources of botanical pesticides (Wang, Ren, & Wang, 2011).

Plant essential oils with the reputation of being "liquid gold" also have a unique advantage in the field of pesticides; the unique smell can drive out and trap some pests, and the chemical composition can also have a contact effect on pests (Sharma, Rao, Kumar, Mahant, & Khatkar, 2019). Those substances are a kind of suitable insecticide without toxic and harm to humans and with an effective killing effect on pests. Due to the broad variety of essential oil actions on pests (stomach toxicity, growth inhibition, fumigation, antifeedant, etc.), it is difficult for pests to develop drug resistance. However, essential oil pesticides have the disadvantages of harsh preservation conditions and high preparation costs. The preparation of plant essential oils cannot be synthesized by chemical means and can only be extracted when the plant is fresh. If the plant is old, it is difficult to extract essential oils. The preservation mode and preservation life of the isolated essential oils also determine the maintenance time of the essential oil activity. Under normal circumstances, the activity of pure essential oils can be maintained for two years; even if the smell remains unchanged after two years, its biological activity may have disappeared.

3.3. Flavonoids

Flavonoids are widely distributed in plants and belong to the secondary plant metabolites exhibiting attractant properties (Wu, 2009). The active ingredients of *S. chamaejasme* (**G**) include neochamaejasmin A (**10**)**,** which acts as a contact stomach toxin in insects. It has been reported that after three days of 1.6%

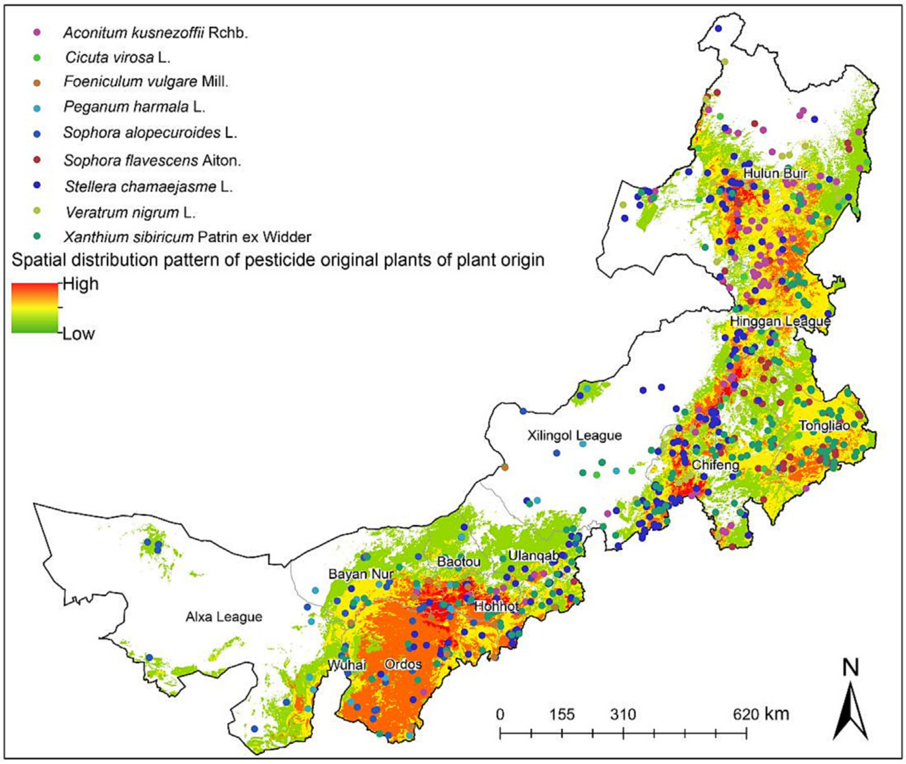


Fig. 2. Geographical distribution of botanical pesticides in Inner Mongolia, China.

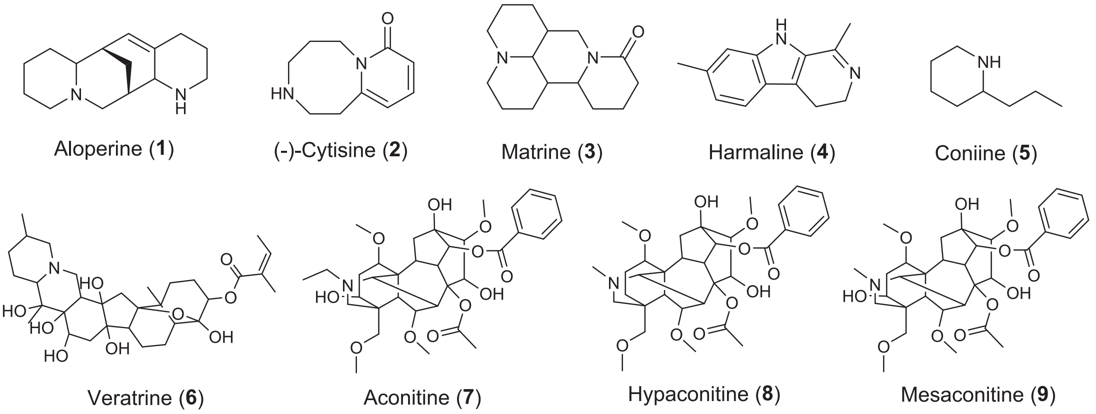

Aloperine (**1**)
(-)-Cytisine (**2**)
Matrine (**3**)
Harmaline (**4**)
Coniine (**5**)
Veratrine (**6**)
Aconitine (**7**)
Hypaconitine (**8**)
Mesaconitine (**9**)

Fig. 3. Chemical structures of alkaloids from botanical pesticides.

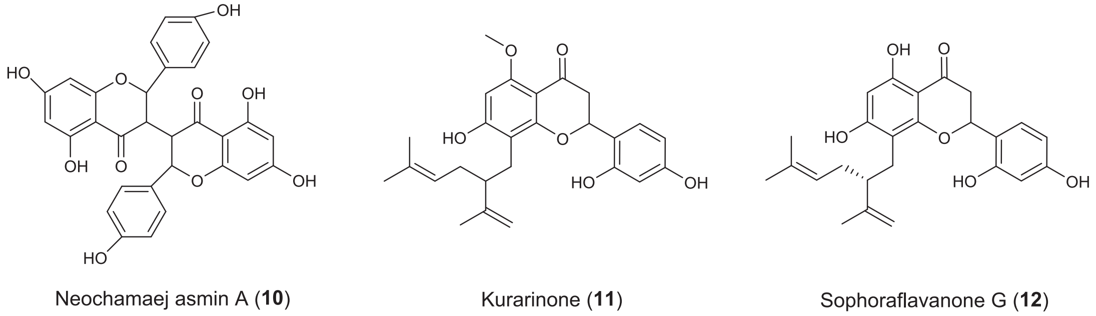

Neochamaej asmin A (**10**)
Kurarinone (**11**)
Sophoraflavanone G (**12**)

Fig. 4. Chemical structures of flavonoids from botanical pesticides.

neochamaejasmin A administration, the insecticidal control effect reached above 70%. After 7 and 10 d, the control effect reached above 80%. These preliminary results indicated that as a botanical insecticide, neochamaejasmin A has a quick and long-lasting effect (Wei, 2017). The insecticidal activity of flavonoid extract of *Platycladus orientalis* (L.) Franco against *Aphis sophoricola* Macchiati has also been reported. In a control experiment conducted in the field, treatment with the extract at 30 mg/mL concentration for 24 h achieved an 85.19% control effect, which was not significantly different from the effect of imidacloprid. The extensive and effective insecticidal effect of *P. orientalis* can be ascribed to its development as a plant-derived pesticide in Inner Mongolia (Wang & Wang, 2013). Kurarinone (**11**) and *Sophora* flavanone G (**12**), both extracted from *S. flavescens*, have insecticidal and antibacterial effects on mosquitoes, fungi, and bacteria. (Zheng, Yao, & Shao, 1999). Additionally, the crude extracts of flavonoids of *Urtica cannabina* L. and *Urtica laetevirens* Maxim. act as antifeedants of five-year-old *P. rapae* (Yang, Cai, & Tang, 2008) (Figs. 1 and 2, Fig. 4).

In recent decades, remarkable achievements have been made in the insecticidal research of flavonoid pesticides at home and abroad. However, to apply flavonoids to pesticides and popularize agricultural production, the development of this kind of botanical pesticide still has a long way to go. At present, the problems of flavonoid pesticides are mainly manifested in the exploration of active components, action mechanisms, chemical structures, etc. In addition, the R&D return ratio of this kind of pesticide is not high, and its economic effect is limited (Goolsby, Maestas, Saelao, & Lohmeyer, 2022). In addition, the active components of flavonoids also have their disadvantages in the field of pesticides; as the content of these active components is not high, the effect is not noticeable, the effective time is short, and the insecticidal species is limited, making the control over the population weak. These limitations have seriously affected its use in the field of pesticides. As society's concept of green environmental protection has gradually improved, flavonoid pesticides have gradually come into the eyes of farmers and scholars, and the unique environmental protection characteristics of flavonoid pesticides have also attracted the attention of many researchers. As such, we believe that with scientific progress, these problems will no longer exist, and flavonoid pesticides will have a bright future in agricultural production.

3.4. Terpenoids

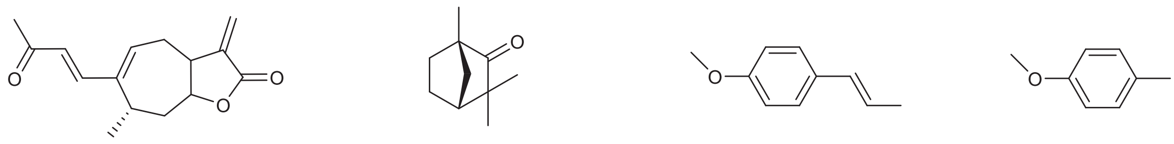
Terpenoids are a class of naturally derived substances widely present in plants. They are often classified according to the number of isoprene units in the molecular structure (monoterpenoids, diterpenoids, sesquiterpenoids, etc.) (Wu, 2009). Pentacyclic triterpenes, the active ingredients of *Hypecoum leptocarpum* Hook. f. & Thomson, show contact toxicity and antifeedant action on *M. separata* (Yang, 2009). Triterpenoid saponins extracted from *Pulsatilla chinensis* (Bunge) Regel display contact toxicity on *Lymantria dispar* L., and *Aphis* spp. (Liu, 2005; Xue, 2013), whereas xanthatin (**13**), which is extracted from *Xanthium sibiricum* Patrin ex Widder (**H**) (Figs. 1 and 2, Fig. 5), belongs to sesquiterpene lactones and has a tendency to induce stomach toxicity (Li, Gao, Gao, Zhao, & Sun, 2008). A study on the antifungal mechanism of the leaf oil of *Eupatorium adenophorum* Spreng, comprising 10H-α-9-oxo-agerophorone (37.73%), and 9-oxo-10,11-dehydro-agerophorone (23.41%), showed that it could damage the plasma membrane and intimal system of *Phytophthora capsici* Leonian and *Pythium myriotylum* Drechsler, causing cell rupture, cytoplasm leakage, and organelle degradation. In *P. myriotylum*, the oil decreased superoxide dismutase, catalase, peroxidase, and succinate dehydrogenase activities and increased malate dehydrogenase activity, bacteria malondialdehyde content, and soluble sugar content, which increased after an initial decrease. These changes indicate that the oil functions by removing reactive oxygen radicals, destroying the energy metabolism pathway, affecting intracellular biosynthesis, and ultimately inducing cell apoptosis (Liu, Chen, Zhang, Wang, & Feng, 2017). Although terpenoid botanical pesticides are abundant, more studies are required to optimize their performance. Moreover, although the development of botanical pesticides against insects is our primary goal, our fundamental goal is to develop products that are beneficial to people's lives. Therefore, it is necessary to implement toxicity tests for terpenoid botanical pesticides, which will be directly related to the health and safety of non-target animals.

The active components of Celastraceae and neem are the most widely studied terpene pesticides (Goolsby, Maestas, Saelao, & Lohmeyer, 2022). As the largest natural terpene production source in the world, turpentine is mainly exudated by pine plants and composed of monoterpenes, which can synthesize many kinds of insecticidal compounds, such as terpene alcohols, terpene amides, etc. Additionally, they have high development prospects and broad application potential. Currently, although much research has focused on polyterpenes, there are relatively few studies on monoterpenes and sesquiterpenes, and there is still room for research on the pesticides of the latter two components (Goolsby, Maestas, Saelao, & Lohmeyer, 2022). The secondary metabolites isolated from neem plants are mainly composed of triterpenes, which currently have a suitable application effect. These have the unique advantages of killing more than 200 kinds of pests, albeit with some disadvantages. These include a complex molecular structure that contains more hydroxyl groups, easy degradation, poor stability, and low solubility.

It is generally significant to study the botanical pesticides of terpenoids. In the process of crop production, the grain quality will be affected by pathogens or bacteria, and the yield and safety of grain will be significantly reduced because of plant viruses. However, as chemical pesticides cannot ensure food security due to residues and other problems, it is necessary to develop terpenoid antimicrobial agents with high efficiency and low toxicity in agricultural production. A large number of studies have shown that a plant's essential oil produced by terpenoids has many advantages, with remarkable antiviral activity, its residue is non-toxic, and it does not easily produce side effects, making it an important research resource in agriculture (Goolsby, Maestas, Saelao, & Lohmeyer, 2022).

3.5. Sterols

Sterols, among the most widely distributed ingredients of natural substances, are a class of natural or synthetic organic



Xanthatin (**13**) Monoterpene (+)-fenchone (**14**) (*E*)-anethole (**15**) Estragole (**16**)

Fig. 5. Chemical structures of terpenoids and others from botanical pesticides.

compounds characterized by a molecular structure of 17 carbon atoms distributed in four rings. To develop a pesticide, some scholars have recently begun to research the use of sterols in pest control. Thus, it has been reported that sterols from plants growing in Inner Mongolia, China could control arthropods in agricultural fields. Sterols extracted from *Xanthoceras sorbifolia* Bunge have been evaluated for their antibacterial activity. Results have shown that they can exert a potent antibacterial effect on *Escherichia coli* and *Bacillus subtilis*, with a better effect and lower minimum inhibitory concentration than the commonly used sodium benzoate (Cao, Li, Deng, Han, & Tian, 2010). Furthermore, *Corydalis bungeana* Turcz. exerted contact toxicity against *M. persicae* (Zhang, Zhao, Hen, Qin, & Liu, 2010). Sterols crude extracted from *Cuscuta chinensis* Lam. act as contact toxins against houseflies and is used as an insecticide in Inner Mongolia (Zhou, Huang, Xu, & An, 2006). Sterol pesticides are an important branch of pesticides in which the sterol pesticide processing industry is a precision chemical specialty derived from the synthesis of raw pesticide drugs. The birth of super-efficient pesticides and the increased understanding of environmental protection demand more stringent requirements for the processing of sterol pesticides (Ugwu, 2021).

After special preparation processing, the application performance and economic value of sterol pesticides can be significantly improved. However, it has been difficult to develop a new type of pesticides in recent years, and the long development time and a significant amount of manpower, material, and financial resources invested in the development process affect the development of the pesticide synthesis industry. As such, some enterprises are focusing on the research and development (R&D) of sterol pesticide processing, thus promoting the development of the pesticide preparation processing industry. In recent years, countries have also increased the R&D of environment-friendly preparations and dosage forms, and the industrialization of sterol pesticides has developed rapidly. However, based on this rapid development, technicians have not paid sufficient attention to the basic theory of preparation development. In R&D, as the key points of the related preparation structure, auxiliary research, and development are ignored, there is still much room for progress in controlling the quality of R&D preparations.

3.6. Organic acids

Organic acids are organic compounds that contain a carboxyl group in their molecular structure and have acidic properties. Organic acids are present in many Chinese medicinal herbs and produced in many plants of Inner Mongolia, China. For example, a study on the effects of ethyl palmitate against *Tetranychus cinnabarinus* Boisduval revealed that the activity of antioxidant enzymes increased, including superoxide dismutase, catalase, and peroxidase, whereas the activity of Ca^{2+}-ATPase decreased, indicating that ethyl palmitate may lead to the death of mites by stimulating the oxidation mechanism *in vivo* and inhibiting nerve conduction. Furthermore, the study also reported that the severe destruction of cellular substructure will directly affect the normal function of cells, leading to the death of mites (Bu et al., 2012). Organic acids extracted from *H. leptocarpum* have anthelmintic properties as they inhibit the growth and development of *M. separata* (Yang, 2009). Organic acids are among the active ingredients of *Viola philippica* Cav. exhibiting antifeedant action on three-year-old *P. rapae* (Wang, Zhou, & Yi, 2010). And organic acids are one of the active ingredients of *Saposhnikovia divaricata* (Turcz.) Schischk. extracts with antifeedant action on *Rhizoctonia cerealis* Vander Hoeven (Hu, Lv, Zhou, & Li, 2012; Liu, Chen, Zhang, Wang, & Feng, 2017).

Organic acid pesticides also have some disadvantages; most natural compounds are too complex to be artificially synthesized or too expensive to prepare, the active ingredients are easy to dissolve, and the drug ingredients are complex and cannot be standardized. Additionally, the impact of botanical pesticides is slow, some farmers think that the pesticides they use lack efficacy (Wuryantini, Endarto, Wicaksono, & Yudistira, 2021). However, organic acid pesticides also have advantages that cannot be ignored, namely that the effective components of organic acid pesticides are natural substances, not synthetic chemicals, which will naturally degrade and will not pollute the environment after use. Secondly, organic pesticides have many kinds of effective components, and the mixed-use of organic acid pesticides can achieve the purpose of multiple resistance, making their efficacy unique; moreover, the pests do not easily become drug-resistant. Finally, these pesticides have high efficacy for plant bacteria and viruses, cause low harm to humans and livestock, and have low costs (Ravindra, Mukesh, & Chetan, 2021). Thus, organic acids combined with other antibacterial plant source additives such as essential oils are an ideal chemical substitute for pesticide products.

3.7. Other secondary metabolites

In addition to the above-mentioned products, there are many other secondary metabolites with pest control properties produced by plants growing in Inner Mongolia. For example, osthol, which is extracted from *Cnidium monnieri* (L.) Cuss., is a phenylpropanoid with contact toxic action on *Oryzaephilus surinamensis* Linnaeus and *Plodia interpunctella* Hübner (Wang & Xu, 2013). Phenylpropenes monoterpene (+)-fenchone (**14**), (*E*)-anethole (**15**) and estragole (**16**), which are extracted from *Foeniculum vulgare* Mill (**I**) (Figs. 1 and 2, Fig. 5). show insecticidal activity. The components of *F. vulgare* fruits can be used as a pesticide against *Sitophilus oryzae* Linnaeus, *Callosobruchus chinensis* Linnaeus, and *L. serricorne* by fumigation and direct contact methods (D.H. Kim & Ahn, 2001; S.I. Kim, Chan, Ohh, Cho, & Ahn, 2003). Rotenone is a compoun that is extracted from *Amorpha fruticosa* L. It has been confirmed that 4% rotenone has a good insecticidal effect on the larvae of the light bamboo moth, and its main insecticidal mechanism involves gastric toxicity and contact killing. Therefore, rotenone can be used as an effective chemical component to control the larvae of moth causing poison blight. The insecticidal effect of *A. fruticosa* should be studied further (Cao, Lu, & Bai, 2005; Mao, 2018).

In order to protect themselves and survive the fierce competition against pathogens and pests, plants have developed a range of secondary metabolites over their long evolutionary process. The diversity of plant secondary metabolites and their different functions have gradually evolved as long-term plant adaptive responses to biotic stress. This constant effort by plants to adapt to their environment involves a variety of secondary metabolites that may have a strong potential as active ingredients for botanical pesticides (Lin, 2009). Current research focuses mainly on the insecticidal effects of alkaloids and volatile oils but there are many more secondary metabolites with insecticidal effects to be studied. Especially, the mixed-use of secondary metabolites warrants further research, as a mixture of various secondary metabolites makes it more difficult for insects to develop resistance, which indicates the great potential of such mixtures for biological pest control (Cheng, Kang, Shi, & Gao, 2015).

4. Different modes of application

4.1. Botanical insecticides

The research on the mechanisms of action of bioactive products is essential to the improvement of their quality and sustainable application. It is necessary to elucidate the target system of pests in order to understand how pesticides work (their mode of action). Botanical pesticides can be grouped according to the type of damage inflicted to target pests or pest control. For example, one insecticide may influence the insect's digestive system, while another may affect its nervous system. A survey of the existing literature identified numerous botanicals in plants growing in Inner Mongolia possessing a variety of possible types of action against insects (Tables 1 and 2). The different modes of action on insects are described below.

4.1.1. Antifeedant and repellents

Botanical pesticides interfere with the insect's taste receptors, adversely affecting the search for food or its perception as unpleasant and leading to insect's death. The common mechanism of action of antifeedant is associated with their effect on chemical receptors and the central nervous system of the pests. Antifeedants have the advantage of indirect insecticidal activity; their specificity makes them efficient and non-toxic, and it is difficult for pests to develop resistance to them (Han, Xiao, & Jiang, 2014). For example, acetone extracts from the aerial parts of *V. philippica* had an obvious antifeedant effect on *P. rapae* (0.05 g/mL), with an antifeedant rate of 53.27% and 60.82% within 24 h and 48 h, respectively (Wang, Zhou, & Yi, 2010). The antifeedant rates of acetone extracts from whole plants of *U. cannabina* (1 g/mL) and *U. laetevirens* (1 g/mL) against five-year-old *P. rapae* were 73.7% and 52.8%, respectively (Yang, Cai, & Tang, 2008). *Euphorbia fischeriana* Steud. roots were also found to possess significant feeding deterrent activity against two stored-product insects (*Tribolium castaneum* Herbst and *S. zeamais*). Four feeding deterrents were isolated from ethanol extracts of *E. fischeriana* roots by bioassay-guided fractionation. Jolkinolide B and 17-hydroxyjolkinolide B possessed strong antifeeding activities against *S. zeamais* (effective concentration that inhibited the activity by 50% [EC_{50}] = 342.1 and 543.9 mg/L, respectively) and adults of *T. castaneum* (EC_{50} = 361.4 and 551.5 mg/L, respectively). Furthermore, 17-hydroxyjolkinolide A and 12-deoxyphorbol 13-(9*Z*)-octadecenoate 20-acetate A also deterred feeding in the two grain storage insects with EC_{50} values of 631.9 and 884.3 mg/L for *S. zeamais* and 656.5 and 1,058.4 mg/L *T. castaneum* adults, respectively (Geng et al., 2011). Researchers have studied the active ingredients in methanol extracts of 32 plants, including *Ipomoea nil* (Linnaeus) Roth (55.84%), *Ampelopsis japonica* (Thunb.) Makino (50.00%), *Hyoscyamus niger* L. (41.18%), *Ephedra equisetina* Bunge (26.32%), and *Oxytropis fetissovii* Bunge (9.90%). The plants showed antifeedant activity against the third instar larvae of *Plutella xylostella* Larvae (Tian, Fang, & Dai, 2018). In the future pest control, we suggest that more attempts should be made to use antifeedants in combination with other control agents to kill pests, although some pests have been tested, however, greater efforts should be made to continue to encourage people to make breakthroughs in this direction.

There are several types of mosquitoes, and the three common types are *Anopheles*, *Culex*, and *Aedes*. With the widespread use of chemical insecticides, the phenomenon of mosquito resistance has emerged. Research on the mosquito-repellent effect of botanical pesticides has shown the great potential of new-generation mosquitoes and insect repellents. The action of botanical pesticides involves the volatile oil components (Zhao et al., 2016). Gas molecules that are obtained by volatilization of chemical substances can stimulate the olfactory organs of insects, eliciting their escape. Seeds crude extracts (ethanol, ethyl acetate, acetone, chloroform, petroleum ether extract) of *Trigonella foenum-graecum* L. at a concentration of 1.6 $\mu g/cm^2$ repelled 80% of adults of *Tribolium confusum* Jacquelin du Val (Tang et al., 2009). Researchers used a Y-tube olfactometer to determine the repellent activity of plant essential oils against *A. albopictus* female adults. The essential oils, nepeta and peppermint oils, were extracted from plants distributed in Inner Mongolia. The results showed that nepeta oil's deworming rate was as high as 98%, and the essential oils of other plants, such as peppermint oil also showed high potential as mosquito repellents (Liu, Yan, & Li, 2015).

4.1.2. Contact and stomach toxicity

Direct or indirect contact can be realized between botanical pesticides and insect pests through the epidermis or the sensory organs of the latter, resulting in insect death. The mechanism of action is associated with the detrimental effect of the active plant component on the nerve or respiratory center of the insect. Seeds methanol extracts (1%) of *C. chinensis* exert a remarkable toxic activity on houseflies, with mortality reaching 100% at 48 h (Guo, Wang, & Zhang, 2005). Studies have shown that matrine, rotenone, and osthole are chemical compounds that can be extracted from plants in Inner Mongolia. They can kill *Coptotermes formosanus* Shirak through contact killing and have excellent effects. The strength of their contact-killing effect was as follows: rotenone > osthole $\geq$ matrine (Zeng, Chen, & Wang, 2019). A contact toxic effect of the petroleum ether extracts of *C. bungeana* (whole plants) was reported for *M. persicae* in an earlier study. Reportedly, after treatments with the petroleum ether extracts (100 g/L), the mortality of *M. persicae* reached 80%, 96.67%, and 98.3% at 12, 24, and 48 h, respectively (Zhang, Zhao, Hen, Qin, & Liu, 2010). Aqueous extracts of the areal parts of *P. harmala* (6 g/L) and *Ammopiptanthus mongolicus* Kom. (1 g/L) acted as contact toxins against *Bursaphelenchus xylophilus* Steineret Buhrer. The nematocidal activity of *A. mongolicus* was much better than that of *P. harmala* (Gao, Zhu, & Liu, 2009).

Botanical pesticides can be absorbed along with the food into the digestive tract of insects, where they disrupt the normal physiological function of the digestive system and cause insect poisoning. Meng et al. (2010) studied the gastric toxicity of matrine *P. xylostella*. After 72 h of feeding *P. xylostella* larvae with leaves treated with 2 mg/mL matrine, the adjusted mortality rate reached 95.83%. In addition, the Glutathione-s-transferase (GST) and acetylcholinesterase (ACHE) activities in diamondback moth larvae were significantly decreased after matrine treatment at different mass concentrations. This indicates that matrine has a toxic effect in the body of the insect, activating the defense system in the body of the insect and increasing the activity of GSTs, and thus accelerating the metabolism of toxin (Meng et al., 2010). Harmaline, which is extracted *P. harmala* reduced the bodyweight of larvae of *P. interpunctella* by reducing the protein content and inhibiting the activity of α-amylase. Additionally, harmaline was cytotoxic to epithelial cells of the midgut in *P. interpunctella* (250–500 mg/L). The damage in the plasma membrane of the epithelial cells caused the cytoplasm to flow into the midgut, hindering further development of the larvae and leading to mass mortality (Rharrabe, Bakrim, Ghailani, & Sayah, 2007).

4.1.3. Inhibition of insect growth

Many botanical pesticides can interfere with the growth and development of pests. At present, active ingredients in plants are considered to interfere with the endocrine system of insects, leading to abnormal growth and development. Liu, Wang, Chen, & Zhang, 2018 studied the effect of active substances of botanical pesticides (matrine and turpentine) on *Frankliniella intonsa* Trybom. growth and explored the underling mechanisms. After treatment with turpentine and matrine, the chitin content in *F. intonsa* increased significantly, whereas the water-soluble protein and total protein content decreased. The results showed that matrine and turpentine interfered with the normal regulation mechanism of protein synthesis and relative content, and inhibited the growth and development of insects, thus achieving the function of inhibiting insects (Liu, Wang, Chen, & Zhang, 2018). *P. orientalis* extract

Table 1
General introduction of common botanical pesticides in Inner Mongolia, China.

Botanical family	Botanical taxa	Part(s) used	Effective components	Control objects	Mechanisms of action	References
Cupressaceae Bartling	*Sabina vulgaris* Antoine.	Stems, leaves	Volatile oils, Lignans	3-year-old *M. separata*, *P. xylostella*, *H. armigera*, *S. zeamais*, 5-year-old *P. rapae*	Stomach toxicity, antifeedant activity	Li, 2006; Shan, Ma, & Zhang, 2011
Convolvulaceae	*C. chinensis*	Seeds	Flavonoids, sterols, terpenoids, lignans	Housefly	Contact toxicity action	Guo, Wang, & Zhang, 2005; Zhou, Huang, Xu, & An, 2006
Ericaceae	*Rhododendron dauricum* L.	Leaves	Flavonoids, phenolic acids, volatile oils	*L. dispar*	Contact toxicity action	Hui, 2012; Xie, 2014
Equisetaceae	*Equisetum arvense* L.	Whole plants	Alkaloids, organic acids, flavonoids, glycosides	3-year-old *P. rapae*	Contact toxicity action, stomach toxicity	Li & Yang, 2005; Yang, Li, & Zhang, 2003
Euphorbiaceae	*Euphorbia esula* L.	Whole plants	Diterpenes, triterpenes, sterols	*Aphis* spp, *P. rapae*	Contact toxicity action, antifeedant action	Liu, Wang, Zhang, Zhang, & Zhou, 2014; Xie, 2007; Lu, 2008
	Euphorbia humifusa Willd.	Whole plants	Triterpenes, flavonoids	*M. incongnita*, *S. zeamais*	Inhibition of breeding	Li & Yang, 2002; Lu, 2008
	Euphorbia pekinensis Rupr.	Roots, leaves	Diterpenes, triterpenes, flavonoids, tannins	*T. castaneum*, *P. xylostella*, *P. rapae*, *M. separata*, *H. armigera*	Contact toxicity action, antifeedant action, inhibiting the growth	Ju, Xu, & Zhou, 2005; L. Wang, Jiang, & Han, 2016; X. Wang, Yang, Cui, & Zhang, 1996
	Leptopus chinensis (Bunge) Pojark.	Roots	Alkaloids	*P. xylostella*	Antifeedant action, stomach toxicity, inhibiting growth	Cui, Sun, Han, & Liu, 2006; Xue, 2013
	Ricinus communis L.	Seeds	Alkaloids, ricinine, toxoprotein	*Aphis* spp, *P. rapae*	Contact toxicity action, antifeedant action	Wen, Feng, & Zheng, 2008; Zhao, Zhang, She, & Wu, 2001
Leguminosae	*Ammopiptanthus mongolicus* (Kom.) S.H.Cheng	Stems, leaves	Volatile oils	*B. xylophilus*	Contact toxicity action	Gao, Zhu, & Liu, 2009
	Trigonella foenum-graecum L.	Seeds	Pyridine alkaloids: trigonelline	*R. dominica*, *T. confusum*, bean weevils	Contact toxicity action, repellent action	Pemonge, Jesus, & Regnault-Roger, 1997; Tang et al., 2009
	Thermopsis lanceolata R. Br.	Whole plants	Quinolizidine alkaloids	*B. xylophilus*, *M. separata*, *Aphis* spp, *Thrips* spp, *D. vitifoliae*	Contact toxicity action	Li, Shen, & Zhang, 2009; Wang, Nan, Zhou, & Zhang, 2013; Wei & Zhao, 2000
Liliaceae	*V. nigrum*	Whole plants	Alkaloids: veratridine, Ryanardine	3-year-old *M. separata*, *Aphis* spp	Contact toxicity action, antifeedant action	Lv, Zeng, Wang, Xie, & Wang, 2004; Shi, Wang, Li, & Tian, 2007
Magnoliaceae	*S. chinensis*	Fruits	Volatile oils	*M. incongnita*, *S. zeamais*	Contact toxicity action	Zhou, 2016
Papaveraceae	*C. bungeana*	Whole plants	Alkaloids, sterols, phenolic compounds	*M. persicae*	Contact toxicity action	Zhang, Zhao, Hen, Qin, & Liu, 2010
	H. leptocarpum	Whole plants	Pentacyclic triterpenes, organic acids	*M. separata*, *T. urticae*	Contact toxicity action, inhibiting growth, antifeedant action	Yang, 2009; Zhang, 2014
Ranunculaceae	*A. coreanum*	Roots	Alkaloids, diterpenoid alkaloids	*T. truncatus*	Contact toxicity action	Liu, 2005; Liu, Yu, Li, Li, & Ji, 2013
	Aconitum kusnezoffii Rchb.	Whole plants	Diester alkaloids: aconitine, mesaconitine, hypaconitine.	Flies, lice, mosquitoes, *L. erysimi*	Contact toxicity action, repellent action, antifeedant action, inhibiting growth	Luo, Mu, & Li, 1997; Shen, Zhai, Lin, & Xie, 2002
	P. chinensis	Whole plants	Triterpenoids: triterpenoid saponin	*D. superans*, *L. d. dispar*, *Aphis* spp	Contact toxicity action	Liu, 2005; Wang, 2006
Thymelaeaceae	*S.chamaejasme*	Roots	Alkaloids, flavonoids: neochamaejasmin A	*P. rapae*, *O. furnacalis*, *M. persicae*	Contact toxicity action	Wei, 2017; Zhang, Wang, Xu, & Zhao, 2000
Umbelliferae	*C. monnieri*	Fruits	Phenylpropanoids: osthole	*R. dominica*, *S. zeamais*, *O. surinamensis* *P. interpunctella*	Contact toxicity action, inhibiting growth	Wang & Xu, 2013
	C. virosa	Roots	Alkaloids: coniine	*T. truncatus*	Contact toxicity action	Liu, 2005
Urticaceae	*U. laetevirens*	Whole plants	Alkaloids, flavonoids, terpenoids	5-year-old *P. rapae*	Antifeedant action	Yang, Cai, & Tang, 2008
Violaceae	*V. philippica*	Stems, leaves, flowers	Flavonoids, organic acids, coumarin	3-year-old *P. rapae*	Antifeedant action	Li et al., 2013; Wang, Zhou, & Yi, 2010

was sprayed on hives of *G. mellonella* and *A. grisella* larvae breeding. The results showed that *P. orientalis* extract had a weak larvicidal effect for 7 d, and the chrysalis and the mature of *G. mellonella* and *A. grisella* are maiming or death. This may be because the volatile oils such as anisone, camphor, camphor acetate, terpinol. contained in the leaves of *P. orientalis* may change the arrangement of the waxy layer of the epidermis of the pest (Chen, Wang, Yuan, Chen, & Wang, 2012).

4.2. Botanical fungicides

Over the years, plant pathogenic fungi have caused destructive losses in agriculture worth millions of dollars. Chemical fungicides are usually effective in controlling plant pathogenic fungi. However, in the past few decades, their excessive and repeated use has led to negative effects, including the destruction of natural biological systems and the development of fungal resistance. The application of botanical fungicides, which are active ingredients extracted from plant parts or plants and processed into products that can be used to control plant diseases, effectively prevents the above problems caused by synthetic fungicides.

In recent years, many scientists worldwide have focused their research on the development of botanical fungicides. The antifungal activity and action mechanisms of the volatile oil, including damage to the cell membrane of the spores, and *F. vulgare* on *Alternaria tenuissima* (Kunze: Fr.) Wiltshire were evaluated *in vitro* and *in vivo*. The results showed that it can inhibit the biomass, spore germination, and mycelium growth of the pathogen, and the negative effects were concentration dependent. In addition, the volatile acid severely damaged the cell membrane of *A. tenuissima*, and thus, achieved the fungistatic effect (Ma & Zeng, 2016). In order to clarify the antifungal activity and mechanism of thymol on *Fusarium* causing watermelon wilt, the mycelial growth and cell membrane permeability of this fungus were studied. After treatment with thymol, the mycelial growth was decreased, branching was reduced, and cell membrane conductivity was reduced. Furthermore, it was found that this substance could reduce the protein and DNA content in the pathogen compared with the normal levels. The antifungal effect can be attributed to changes in mycelial permeability of *Fusarium* and inhibition of the biosynthesis of some proteins and DNA in the fungus (Zhang, Chen, Xue, & Shi, 2013). Among the plant resources available in Inner Mongolia (Tables 2 and 3), antifungal effects have been reported for ethanol extracts from roots of *A. leucostomum*. This extract inhibits mycelial growth in *Magnaporthe grisea* (T. T. Hebert) M.E. Barr (100 mg/mL), *Penicillium italicum* Wehmer (100 mg/mL), *P. drechsleri* (100 mg/mL), *Fusarium oxysporum* f. sp. *niveum* (E. F. Smith) Snyder et Hansen (100 mg/mL), and *F. solani* (100 mg/mL) by 70.18%, 69.68%, 87.72%, 61.35%, and 54.30%, respectively, within 7 d of its application. It also inhibits spore germination of *F. oxysporum* f. sp. *niveum* (20 mg/mL), *F. solani* (20 mg/mL), by 74.60%, 100%, respectively, within 8 h of its application (Liu, Wu, & Li, 2009). Physcione, extracted from *Rheum franzenbachii* Münter, is a quinone compound with a good inhibitory activity on *Botrytis cinerea* Pers. and *Pyricularia grisea* Sacc. (EC_{50} = 3.74 and 1.14 mg/L, respectively), and particularly on *Blumeria graminis* (DC.) Speer and *Sphaerotheca fuliginea* (Schltdl.) Pollacci (EC_{50} = 0.68 and 0.33 mg/L, respectively) (Zhang, Li, Dong, & Chen, 2016).

Botanical pesticides are the earliest and more widely used pesticides in China. Currently, most registered botanical pesticides in China are insecticides. Although there are many botanical insecticides that have obtained registration qualifications, there are few actual manufacturers (Shao, Liu, Sun, & Hu, 2017). Concomitantly, the mechanism of action of many compounds extracted from plant tissues and identified as showing insecticidal activity warrants further investigation. Despite their great potential for development, the research history of botanical fungicides is relatively short. Researchers have screened more than 200 plant species in the northwestern region of China and made the corresponding assessment of their fungicidal activity. These studies have led to the conclusion that Asteraceae and Leguminosae are the most promising plant families for the development prospects in plant fungicide research (Feng et al., 2002). Numerous plant species in these two families are widely distributed in Inner Mongolia, which confirms the potential for further development of botanical pesticides in the region.

Although in-depth research and application models of botanical pesticides still show limitations, compared with the high risks of environmental pollution of traditional chemical pesticides, botanical pesticides show great advantages in the richness of their sources, their low residual power and thereby low pollution hazard, and their great potential for sustainable application. Thus, botanical pesticides currently attract increasing attention among researchers. The comparative advantages and limitations of traditional chemical pesticides and botanical pesticides are summarized to provide a more comprehensive overview (Table 4).

5. Challenges and prospect of botanical pesticides

Crop diseases and pests can be disastrous to agriculture, as they can severely restrict agricultural productivity and hence seriously threaten food security. For example, the east African locusts could have devastating effects on agriculture in East Africa and beyond (Devi, 2020). Botanical pesticides are an important tool in integrated pest management and the implementation of botanical pesticides is expected to increase in the next decade of development and expansion of organic agriculture. However, despite extensive research on botanical pesticides, our knowledge is still very incomplete. Therefore, future studies should address the following:

First, basic research is lacking. In Inner Mongolia, only a few potential botanical pesticide sources have been developed and used in actual pesticide production. Most active ingredients present in registered botanical pesticides, and their mechanisms of action against pests, remain unclear (Na et al., 2017). Current research methods mainly refer to the methods used in chemical-pesticide research and take insect death rate within a certain period as the indicator of effective control (Garnham, 1947). However, pesticides tend to regulate the growth of individual pests and the reproduction of populations (Zhang, Ma, Feng, Wu, & Han, 2015). We should promote a variety of suitable effect indicators, while

Table 2
General introduction of botanical fungicides and insecticides in Inner Mongolia, China.

Botanical family	Botanical taxa	Part (s) used	Effective components	Control objects	References
Polygonaceae	*Rheum rhabarbarum* L.	Stems, leaves	Physcion	*B. cinerea, P. grisea, B. graminis, S. fuliginea*	Zhang, Li, Dong, & Chen, 2016
Sapindaceae	*Xanthoceras sorbifolium* Bunge	Seeds	Sterols	*B. subtilis*	Cao, Li, Deng, Han, & Tian, 2010
Umbelliferae	*S. divaricata*	Roots	Volatile oils, chromones, coumarins, organic acids	*R. Cerealis*	Hu, Lv, Zhou, & Li, 2012; Liu et al., 2017b
	Heracleum moellendorffii Hance	Roots	Volatile oils	*R. cerealis, S. sclerotiorum, P. capsici*	Zhang, 2007

Table 3
General introduction of both antibacterial and insecticidal plants in Inner Mongolia.

Botanical family	Botanical taxa	Part(s) used	Effective components	Control objects	Mechanisms of action	References
Asclepiadaceae	*Cynanchum mongolicum* (Maxim.) Kom.	Whole plants	Alkaloids, volatile oils	*Aphis* spp, *A. alternata*, *B. sorokiniana*, *S. turcica.*	Contact toxicity action, inhibiting growth	Zhang, Bai, Tian, & Wu, 2004; Zhang & Wu, 2004
Compositae	*X. sibiricum*	Whole plants	Sesquiterpene lactone compounds: xanthatin	*H. armigera*, *P. nodorum*, *G. zeae*, *P. rapae P. xylostella*, *M. persicae*, *L. erysimi*	Contact toxicity action, inhibiting growth, antifeedant, stomach toxicity, repellent action	Li, Gao, Gao, Zhao, & Sun, 2008; Zhou, Wei, Ou, Zhong, & Wang, 2009
Euphorbiaceae	*E. fischeriana*	Roots	Diterpenes, tannins	*B. brassicae*, *M. persicae*, grubs, *C. bowringi*, *P. brassicae*, *P. rapae*, *Aphis* spp, *P. striiformis* var. *striiformis*	Contact toxicity action, inhibiting growth	Ju, Xu, & Zhou, 2005; Wang, 2011
	Euphorbia helioscopia L.	Seeds, stems, leaves	Triterpenes, flavonoids	*T. urticae*, *A. gossypii*, *S. sclerotiorum*, *V. dahliae*	Inhibiting growth	Ju, Xu, & Zhou, 2005; Lu, 2008
Leguminosae	*Oxytropis glabra* DC.	Stems, leaves	Alkaloids, toxoprotein	*A. gossypii*, *H. armigera*, *S. aureus*, *S. pyogene*, *B. subtilis*	Contact toxicity action, antifeedant activity	Meng, Wang, Xu, & Zhang, 2000; Wang, Li, Ma, Zhang, & Ma, 2012; Zhou, Huang, Xu, & An, 2006
	S. alopecuroides	Stems, leaves, seeds	Quinolizidine alkaloids: aloperine, cytisine	Root-knot nematodes (*Meloidogyne* spp), *A. gossypii*, *T. urticae*, *R. solani*, *B. cinerea*, *S. sclerotiorum*, *G. zeae*	Contact toxicity action, antifeedant activity, inhibiting growth, stomach toxicity	Jiang, Zhao, & Xue, 1998; Qin, Ma, & Yuan, 2002; Su, Huang, Zhang, Luo, & Han, 2016
	S. flavescens	Roots, seeds	Quinolizidine alkaloids: matrine, cytisine Flavonoids: kurarinone, sophoraflavanone G	*A. gossypii*, *P. rapae*, *S. aureus*, *A. niger*, *F. verticillioides*, *Rhizoctonia* spp.	Contact toxicity action	Han & Han, 2016; Su, Huang, Zhang, Luo, & Han, 2016; Zheng, Yao, & Shao, 1999
Papaveraceae	*Chelidonium majus* L.	Whole plants	Alkaloids: chelidonine	*P. rapae*, *B. maydis*, *S. microspora*, *F. o.* f. sp. *lycopersici*	Contact toxicity action	Wang, 2016; Wei, 2013
Ranunculaceae	*Aconitum barbatum* var. *puberulum* Ledeb.	Roots	Alkaloids: diterpenoid alkaloid	*S. exigua*, *B. subtilis*	Antifeedant action, inhibiting growth	Feng, 2010; Sun, 2008; Zhang, 2007
	A. leucostomum	Roots	Alkaloids	*A. gossypii*, *M. grisea*, *P. italicum*, *F. bulbigenum*, *F. solani*, *F. o.* f.sp. *niveum*	Contact toxicity action, antifeedant action	Liu, Wu, & Li, 2009
Solanaceae	*Datura stramonium* L.	Whole plants, seeds	Alkaloids	*P. rapae*, *T. urticae*, *M. separata*, *A. gossypii*, *B. subtilis*	Contact toxicity action, antifeedant action, stomach toxicity action	Li, Gao, Gao, Zhao, & Sun, 2008; Zhang et al., 2004
Umbelliferae	*Angelica dahurica* (Hoffm.) Benth. & Hook. f. ex Franch. & Sav.	Roots	Coumarins, volatile oils	*P. rapae*, *A. glycines*, *P. graminis*, *R. solani*, *R. cerealis*	Inhibiting growth	Hu, Lv, Zhou, & Li, 2012
	F. vulgare	Seeds	Volatile oils	*L. serricorne*, *M. separata*, *C. cladosporioides*, *B. subtilis*, *C. fulvum*, *U. virens*	Contact toxicity action, inhibiting growth	Ju, Xu, & Zhou, 2005; D.H. Kim & Ahn, 2001; S.I. Kim, Chan, Ohh, Cho, & Ahn, 2003; Ma, He, Wang, Wang, & Gao, 2007; Wu, Zhang, & Zhou, 2015
Urticaceae	*U. cannabina*	Whole plants, seeds	Flavonoids, lignans, organic acids	5-year-old *P. rapae*, *B. subtitles*	Inhibiting growth, antifeedant action	Ao et al., 2015; Cheng, Li, & Qi, 2005
Zygophyllaceae	*P. harmala*	Stems, leaves	Alkaloids: harmine	*Aphis* spp, *P. rapae*, *S litura*, *S gregaria*, *F. bulbigenum*, *F. o.* f. sp. *niveum*, *P. capsici*, *N. ditissima*	Antifeedant action, inhibiting growth	Liu, Jiang, & Zhao, 2010; Ma et al., 2003; Zhang, Wang, Gong, Zhang, & Zhang, 2006
	Tribulus terrestris L.	Fruits	Sterols, saponins, alkaloids, flavonoids	*H. armigera*, *S. nodorum*, *F. culmorum*	Contact toxicity action, inhibiting growth	Lv, 2007; Ma, Wang, Li, & Guo, 2014

Table 4
Advantages and limitations of traditional chemical and botanical pesticides.

Category	Several typical	Advantages	Limitations	References
Traditional chemical pesticides	Bifenthrin, benzoylate insecticide, dichlorodiphenyltrichloroethane	1. Strong contact killing can quickly stop pests and diseases. 2. Broad-spectrum insecticide can kill multiple pests at the same time. 3. Farmers can use traditional chemical pesticides by using sprayers and other equipment: the effect is good, the price is low, and the operation is simple.	1. Derived from chemical products and difficultly degraded. 2. Large residues in agricultural products and soil environment. 3. Pests are prone to drug resistance, and pesticide residues will increase after increasing the dose. 4. Strong lethality will cause great damage to human health, animals and natural enemies of pests.	Alavanja, Ross, & Bonner, 2013; Bardin et al., 2015; Geiger et al., 2010; Isman, 2008, 2015; Mitra, Chatterjee, & Mandal, 2011; Nicolopoulou, Maipas, Kotampasi, Stamatis, & Hens, 2016; Pant, Dubey, & Patanjali, 2016; Suriani, 2016; Wang, Zhang, & Wu, 2019; Xu et al., 2017; Zhang, Gao, Mu, Zhou, & Li, 2014; Liu et al., 2013.
Botanical pesticides	Pyrethrum, matrine, nicotine.	1. Derived from nature and can be degraded into simple natural compounds in the environment without polluting the environment. 2. Complex active ingredients are difficult to induce drug resistance in pests. 3. Low residues and low toxicity to humans, animals and natural pests. 4. Derived from plants, rich in sources, easy to collect, and low in cost.	1. The effective components in plants are only a small part, and requiring the use of a large amount of plant raw materials. 2. Most botanical pesticides work slowly. 3. The active ingredients are easily broken down and difficult to store. 4. Unstable efficacy and inconsistent effectiveness. 5. Originating from plants will make their processing more affected by regional and seasonal factors. 6. Intellectual property protection of natural plants will limit commercial development of botanical pesticides.	Cao, Lu, & Bai, 2005; Han, Xiao, & Jiang, 2014; Liu, Yan, & Li, 2015; Mao, 2018; Tian, Fang, & Dai, 2018; L. Wang, Jiang, & Han, 2016; Q.Z. Wang & Wang, 2013; X.F. Wang, Ren, & Wang, 2011; Y. Wang, Zhang, & Wu, 2019; Weng, 2013; Zeng, Chen, & Wang, 2019; Zhao et al., 2016; Sun et al., 2012

in-depth research on the mechanism of pesticide action from different plant sources lays the theoretical foundation for scientific development of pesticides (Cui et al., 2020; Rotundo et al., 2019; Yalpani et al., 2017). Simultaneously, improper selection of plants will inevitably involve the scope of protection of plant-related patents and form a competitive relationship with other Chinese medicine industries (Isman, 2008). This will increase the cost of botanical pesticide production and application, making it difficult for farmers and manufacturers to accept. Therefore, we need to further review ancient books, strengthen research, and screen out plants that are rich in resources, low in development costs, and easy for farmers and industry to use.

Second, a rational use of plant resources is currently weak. Developing plants as pesticides for organic agriculture can make full use of abundant wild resources or enhance their cultivation (Zhang et al., 2019b). However, we must face other issues as well. Blind mining will cause the loss of wild plant resources (Wang, Zhou, & Yi, 2010). When underground plant parts are used as a raw material, especially when the roots of wild plants are collected on a large scale, their reproduction and the soil environment will be negatively affected (Wang & Xiao, 2015). This is inconsistent with the concept of sustainable use of resources. In the selection of plants, we recommend choosing the aerial plant body for raw materials to effectively control costs, while concomitantly protecting wild resources (Zhang et al., 2019a). In the case of those wild species whose underground parts are the source of pesticidal agents, we should try to collect plants after flowering and pollination have occurred to ensure sustainable use of the resource (Dai, Zhang, & Liu, 2015). After extraction of secondary metabolites, a large amount of plant residues may cause pollution. It is necessary to solve the problem of recycling residues and reduce plant production costs through comprehensive utilization, such as the development of fertilizers. For example, plant residues can be turned into biological fertilizers for the enhancement of plant growth (Mehta, Palni, Franke-Whittle, & Sharma, 2014).

Third, we generally assume that botanical pesticides have low toxicity and are harmless to non-target organisms, as in most laboratory experiments. However, studies generally focus on the effects on target species, while the effects on non-target species are ignored, and important information on potential sublethal effects elicited by botanical pesticides in non-target species is scarce (Guedes, Smagghe, Stark, & Desneux, 2016; Papanastasiou et al., 2017). Research showed that the body masses of honey bees (*Apis mellifera* L.) decreased for the adults that emerged from larvae fed on a diet exposed to andiroba oil, citronella oil, garlic extract, neem oil and rotenone (Xavier et al., 2015). Research on some plant-derived pesticides such as cinnamon essential oil has shown that the sublethal exposure to target species will cause the transgenerational effects, which can promote the generation of offspring with greater weight. This will negatively affect the control effectiveness of such products. (Haddi, Oliveira, Faroni, Guedes, & Miranda, 2015; Silva, Haddi, Viteri, & Oliveira, 2017). Therefore, more in-depth and comprehensive research is needed on botanical pesticides and the practical application of plant-derived pesticides still needs to establish a systematic evaluation mechanism and different safety detection indicators from those used in the evaluation of traditional chemical pesticides.

Inner Mongolia is a traditional agricultural and pastoral land but, to date, no large-scale botanical-pesticide production enterprises have been established widely spread plant resources, such as *Cynanchum hancockianum* (Maxim.) Al. Iljinski, *Oxytropis glabra* (Lam.) DC., and *S. chamaejasme* are abundant, providing a broad market space and resource reserve for the expansion of botanical pesticides. With the current trend in world economy development and an increasing demand for clean crops and healthy foods, botanical pesticides for food safe production attract increasing attention (Kestel et al., 2022). The situation demands that researchers focus a serious effort on solving the problems mentioned herein, associated with the development of plant-derived pesticides, and make full use of their advantages to ensure the sustainable development of resources. This will not only give an opportunity for complete utilization of the advantages of plant resource diversity in Inner Mongolia but, more importantly, it will provide new opportunities for the sustainable development of global organic agriculture.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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