



Review

# Progress in Agricultural Unmanned Aerial Vehicles (UAVs) Applied in China and Prospects for Poland

Linlin Wang <sup>1,2</sup>, Xinrong Huang <sup>2,3</sup> , Wanjian Li <sup>2,3</sup>, Kangting Yan <sup>1,2</sup>, Yifang Han <sup>1,2</sup>, Yali Zhang <sup>2,3</sup> ,  
Lucjan Pawlowski <sup>4,\*</sup> and Yubin Lan <sup>1,2,\*</sup>

- <sup>1</sup> College of Electronic Engineering, South China Agricultural University, Guangzhou 510642, China; wlinlin@stu.scau.edu.cn (L.W.); ktyan@stu.scau.edu.cn (K.Y.); hanyifangfangfang@stu.scau.edu.cn (Y.H.)  
<sup>2</sup> National Center for International Collaboration Research on Precision Agricultural Aviation Pesticides Spraying Technology, Wushan Road, Guangzhou 510642, China; xrhuan@stu.scau.edu.cn (X.H.); 19981002@stu.scau.edu.cn (W.L.); ylzhang@scau.edu.cn (Y.Z.)  
<sup>3</sup> College of Engineering, South China Agricultural University, Guangzhou 510642, China  
<sup>4</sup> Environmental Engineering Faculty, Lublin University of Technology, 20-618 Lublin, Poland  
\* Correspondence: l.pawlowski@pollub.pl (L.P.); ylan@scau.edu.cn (Y.L.)

**Abstract:** With the acceleration of the Belt and Road Initiative, Poland–China agricultural trade has increasingly strengthened, but there is little exchange or cooperation in agricultural machinery. China’s agricultural UAV industry has flourished over the past 7 years. In China, by using typical food crops and economic crops to control diseases and pests, agricultural drones can reduce the use of fertilizer, pesticides, and water, improve operational efficiency, open up new markets through the ‘sale + services’ mode, and reduce production costs and labor shortages. The spraying of agricultural UAVs and related pest-disease-defense services applied in China are also suitable for Poland’s decentralized, small-scale production modes. By learning from China’s development progress of precision-agriculture aviation, Poland can develop 5th-generation (5G) unmanned intelligent organic farms from traditional organic agriculture, use agricultural UAVs in the spraying of Plant Protection Products (PPPs), and carry out special protection or loss management on typical fruits. Furthermore, by building its own spraying system, aviation industry, and service team, Poland can realize resource optimization, technological empowerment, application expansion, and industrial innovation. Therefore, this paper focuses on the development experience of Chinese agricultural UAVs and discusses its enlightenment to the precision-agriculture aviation application of Poland.

**Keywords:** China; Poland; agricultural UAV; Belt and Road Initiative; agricultural development



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## 1. Introduction

The year 2021 marks the eighth year of the Belt and Road Initiative. As the host of the first China–CEEC (Central and Eastern European Countries) Summit, Poland has always been an active responder of the ‘16+1’ mechanism and the Belt and Road Initiative. (In April 2019, Greece joined the ‘16 + 1’ cooperation as a full member; thus, the mechanism has been upgraded to the ‘17 + 1’ cooperation mechanism). Since its accession to the European Union (EU) in 2004, Poland’s status in the EU has continuously improved. It not only has a relatively strong regional economic influence, but also has the ambition and comprehensive national strategy to become a regional power [1]. In 2012, leaders of China and the CEEC met formally in Warsaw, Poland. For the first time, China put forward a twelve-point proposal to promote cooperation between the two sides, which also created institutionalized cooperation between China and the CEEC. In 2013, the ‘16 + 1’ mechanism was formally established. In 2015, China became Poland’s second-largest source of imports and the largest trading partner in Asia. In 2016, the heads of state of China and Poland reached an important consensus on elevating bilateral relations to a comprehensive strategic partnership, opening a new chapter in the history of China–Poland

relations. As of 2020, the two countries have held eight leaders' meetings and issued eight action plans, which provide an institutional foundation and guarantee the implementation of the "Belt and Road" policy goals in Europe, and make the CEEC pioneers in advancing the construction of the Belt and Road Initiative.

At present, cooperation between China and Poland continues to deepen, and Poland has been China's largest trading partner among the CEEC for 14 consecutive years. According to the statistics of Eurostat, the import and export volume of goods between Poland and China was USD 12.40 billion, with an increase of 10.7% in the first half of 2019. Among them, Poland's exports to China reached USD 1.38 billion, up 24.4%, accounting for 1.0% of Poland's total exports, up 0.2 percentage points. Poland imported USD 11.02 billion from China, up 9.2%, accounting for 8.4% of Poland's total imports, an increase of 0.9 percentage points [2]. At the 8th China–CEECE Summit held in Dubrovnik on 12 April 2019, Premier Li Keqiang of the State Council of China pointed out that China and Poland should deepen cooperation in agriculture and other infrastructure-construction fields. Polish Prime Minister Morawiecki said Poland–China relations have been developing rapidly and cooperation areas are extensive, and they look forward to more progress in cooperation with China in agricultural products, mechanical and electrical products, and other fields.

In recent years, the operation of agricultural UAV in China has attracted attention. Since 2014, with the promotion of China's policies, plant-protection UAV has witnessed a booming development trend. From a past technology follower to a present industry leader [3], DJI agricultural UAVs [4] and XAG agricultural UAVs [5] made in China have been exported to Europe. In agricultural aviation, Poland's aviation industry developed earlier, beginning in the early 20th century, from the agricultural aircraft PZL-101 Gawron, designed for increasing useful loads in the 1950s; to the agricultural aircraft PZL-106 series, developed and designed for the member states of the Council for Mutual Economic Assistance in Eastern Europe in the 1970s (the aircrafts are shown in Figure 1). Poland now has rich experience in the development, design, and maintenance of a wide range of aircraft, and has a huge potential market for agricultural UAV applications. China and Poland can find opportunities to deepen agricultural cooperation between the joint construction of the Belt and Road Initiative and the "responsible development plan" of the Polish government, so as to promote the steady improvement of bilateral relations. Guided by agricultural demand and with China–Poland exchanges as the carrier, this paper summarizes the application and development experience of agricultural UAV in China's rural areas in recent years, as well as reference to significance and enlightenment for Poland, so as to promote the future healthy development of China–Poland agriculture, and even China–EU relations.



(a)



(b)

**Figure 1.** Agricultural aircraft PZL series [6]. (a) PZL-101 Gawron [7]; (b) PZL-106. Copyright source: (a) reproduced from ([https://en.wikipedia.org/wiki/PZL-101\\_Gawron](https://en.wikipedia.org/wiki/PZL-101_Gawron) (accessed on 22 July 2021)), with permission from Łukasz Golowanow, Maciej Hypś, 2008. (b) reproduced from ([https://en.wikipedia.org/wiki/PZL-106\\_Kruk](https://en.wikipedia.org/wiki/PZL-106_Kruk) (accessed on 4 October 2021)), with permission from Stefan Krause, 2021.

The contributions of this work are as follows:

- The development history of China's agricultural UAVs in the past 20 years is introduced in detail and is sorted into a timeline for the first time. It is easy for readers to see how China promotes the cooperation of industry–university–research institutions, then makes itself enter the golden period of agricultural-drone industry, and finds the emerging 'sale + services' mode to solve the bottleneck of selling machines and the reorganization of surplus labor.
- By comparing the agricultural similarities between China and Poland, several fields where agricultural drones can be applied in Poland have been put forward, such as developing 5G unmanned intelligent organic farms, the spraying of PPPs, and applications in Poland's typical crops.
- The analysis shows that there is huge market space for unmanned agricultural production in Poland. Poland can firmly grasp the opportunity of the 'Belt and Road Initiative' and use its aviation advantages to develop its own RS-aviation ground-spraying system, domestic aviation industry, and service team, and realize its technological innovation and application expansion.

## 2. China–Poland Cooperation and Opportunities

### 2.1. Transportation Hub in Europe

Convenient transportation promotes agricultural trade and provides a transportation basis for bilateral agricultural-drone cooperation. As shown in Figure 2, Poland is located at the junction of Eastern and Western Europe, with many international highways running through it. It is a shortcut and transportation hub to other countries in Central and Eastern Europe, which can radiate the entire European continent. On the route from China to Europe, the first stop into the EU member states is Poland, which is also the first stop into the European Economic Area. According to the Polish Ministry of Infrastructure and Development, the Belt and Road Initiative, including the development of a direct land-transport network between China and the EU, is the most interesting entry point for Poland.



**Figure 2.** China–Europe Railway Express Routes [8]. Copyright source: reproduced from (<https://news.cgtn.com/news/3d3d514e776b544f33457a6333566d54/index.html> (accessed on 5 March 2021)), with permission from Zhang Huimin, 2021.

Poland is the meeting point of the Amber Road and the Silk Road. Nearly 90% of China–Europe freight trains, such as 'Chongqing–Xinjiang–Europe', 'Zhengzhou–Europe' and 'Xi'an–Europe', shown in Figure 3, pass through Poland or make their European

terminus in Poland. The Polish freight company “PKP Freight”, which runs freight trains from Poland to Beijing, sends 20 freight trains between Poland and China every week. Each trip takes 11 to 14 days, which is two times faster than sea freight and cheaper than air freight [9]. In particular, the number of China–Europe freight trains has increased since last year despite COVID-19. By June 2021, the total number of China–Europe freight trains has exceeded 41,000, with a cumulative value of more than USD 200 billion and more than 50,000 types of goods. The annual transport value has increased by nearly 7 times in five years.



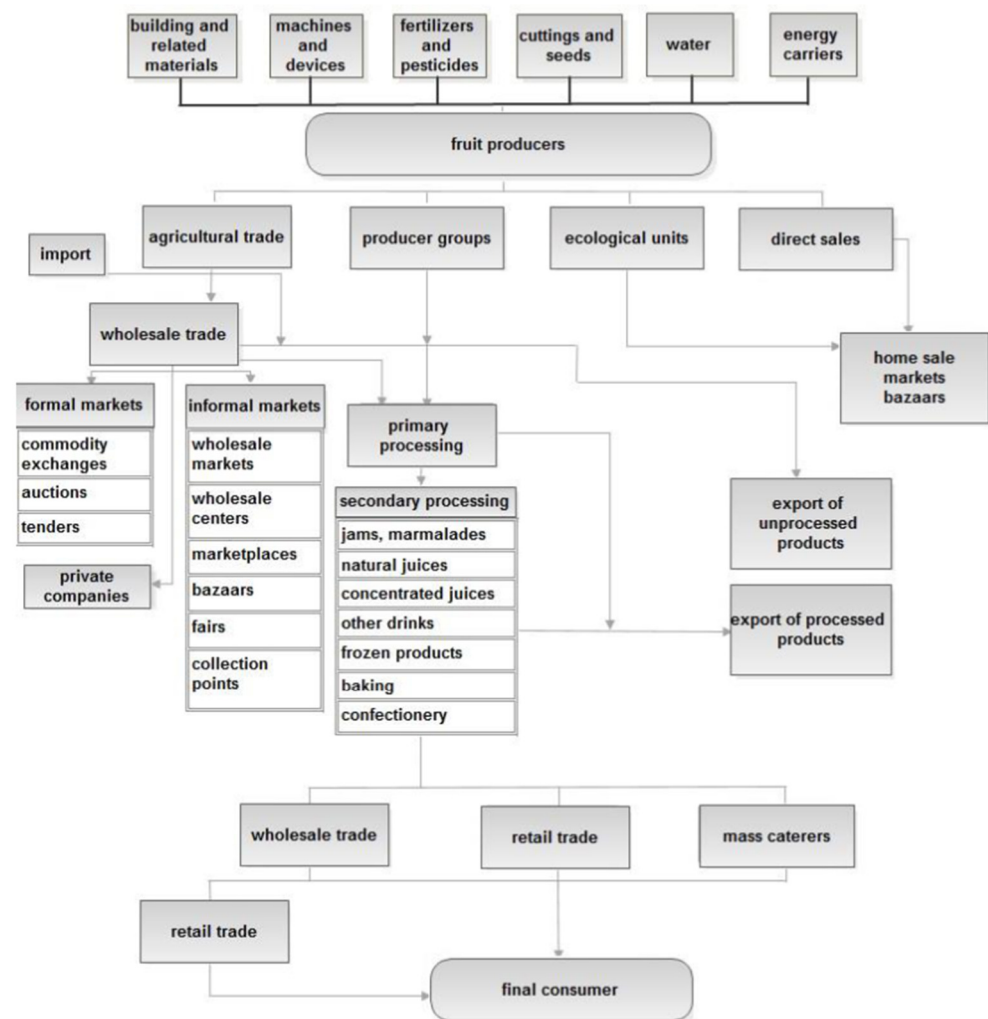
**Figure 3.** China–Europe freight train Chang’an Train (Xi’an, China–Slawków Poland) [10]. Copyright source: reproduced from (<http://itl.xa.gov.cn/zmq/xwzx/mtbd/5e6c33cffd85086744819381.html> (accessed on 11 November 2021)), with permission from Xi’an Daily, 2019.

In addition to land transportation, Gdansk Port in northern Poland is the distribution center of COSCO SHIPPING in the Baltic Sea. Every week, 20,000 TEU freighter ships travel between Poland and the Far East [11]. Since the implementation of the “Belt and Road” initiative, the two countries have opened a direct route from Warsaw to Beijing, and COSCO SHIPPING has opened a regular route from Shanghai to Gdansk [12]. Therefore, both land and water transportation between China and Poland are very convenient, which is conducive to the transportation of agricultural UAVs and related parts. The China–Europe freight train will provide a sustained impetus to promote bilateral agriculture and trade cooperation.

## 2.2. Mature Fruit and Its Product-Supply Chain

Convenient transportation has promoted the rapid development of agriculture and the trade of agricultural products. Agriculture is an important economic industry in Poland. Fruit tree and shrub industries are important parts of agriculture. Poland is one of the largest fruit producers in the temperate zone in Europe, and has rich experience, scientific production, and learning and research systems in agricultural storage and processing, nondestructive drying detection, maturity-picking technology, cold-chain transportation, plant protection, and other horticultural production. Its fruit supply chains are shown in Figure 4; it is very mature and the division of work in each link is clear.





**Figure 4.** Poland's main processes of fruit supply chains and their links [13]. Copyright source: reproduced from [Organization of supply chains in the fruit sector in Poland] *Annals of the Polish Association of Agricultural and Agrobusiness Economists* 2019, 21, 191–199, with permission from Bogdan Klepacki, 2021.

In 2019, the total cultivated area of fruit trees in Poland was 430,000 hm<sup>2</sup>, with a total output of 3.93327 million tons. Due to spring frost, soil-water shortages and high temperature, the output was reduced by 22.5% compared with 2018, which caused the price of most fruits to rise. The highest yield of apple was about 78.3% of the total fruit in Poland. Cherry is the second-largest fruit, followed by blackcurrant, plum, pear and strawberry, raspberry, chokeberry, highbush blueberry, and other small berries [14]. Poland's fruit harvest plays an important role in the agroprocessing industry. Take the blackcurrant, for example, which is widely used in the production of fruit juices and jams. According to the Polish National Agricultural Support Center, Poland was the second-largest producer of blackcurrant in the world in 2019. Blackcurrant is mainly grown in Lublin province in southwestern Poland, accounting for about 45% of all plantations in Poland. In recent years, the annual harvest of blackcurrant in Poland has reached 100,000–125,000 tons. About 38% of the fruits are exported in frozen form to Belarus, Germany, and the UK [15].

Polish President Andrzej Duda said that China and Poland have a huge investment space in the agriculture and food industry. Poland is one of the largest apple-producing and exporting countries in the world, and China is the next key market of the Polish apple industry [16]. Poland's apple market has been hit hard since the Ukraine crisis. Therefore, Poland is particularly eager to open up new customers in the agricultural and

food industries, and strives to relieve the pressure on Polish domestic export companies. On 20 June 2016, China and Poland signed a trade agreement to export Polish apples to China. On November 10, Polish apples were officially approved for export to the Chinese market, which not only solved the problem of overcapacity of Polish apples, but also enriched the trade structure between China and Poland. In 2017, China–Poland trade exceeded USD 21.3 billion, a year-on-year increase of 20%. Among them, imports from Poland amounted to USD 3.34 billion, an increase of 32.4% [17]. In 2018, the trade volume between the two countries exceeded USD 24.524 billion, with a year-on-year growth of 15.5%, reaching a record high. All this shows that more and more Polish farmers benefit from the increase in trade between China and Poland.

It is worth noting that under the background of the rapid promotion of the Belt and Road Initiative, bilateral trade between China and Poland is more convenient. Chinese mechanical and electrical products and transport equipment have entered the Polish market on the China–Europe freight train, and Polish dairy products, frozen fruits, and concentrated juice have also entered the Chinese market in increasing numbers. On 15 October 2020, a China–Europe freight train from Malasević, Poland arrived in Central China’s Wuhan, with 50 containers loaded with 16,770 cartons of pure liquid milk and milk powder weighing more than 1100 tons. This freight-train shipment of dairy products was not only the first of its kind from Poland, but also the first from the EU. It provides a brand-new international logistics solution for dairy-product exports to China that shortens transportation time and thus extends the products’ sale period. In addition to dairy products, the sale of fruits from Poland to China, such as apples and blueberries, has grown significantly in 2020 [18]. The industrial structure between China and Poland has a strong complementarity [19,20].

In the future, China and Poland can continue to strengthen bilateral trade in food and agricultural products, agricultural science and technology cooperation, and other fields; make full use of the advantages of their products; improve the bilateral trade structure; solve the problem of excessive single-trade structure between these two countries; and achieve mutual benefit and win-win results.

According to data from the National Support Centre for Agriculture (KOWR), Polish agricultural exports in 2019 amounted to EUR 31.4 billion. Although this amount is a record, the growth rate has reduced to less than 6%, a 4% decrease from previous years. The representative of the Polish Institute of agriculture and Food Economics said that the decrease in export growth was mainly restricted by relevant international laws and regulations. At the same time, the increase in Polish production costs and the decline in food competitiveness were also two reasons [21]. In order to further enhance the export competitiveness of Polish agricultural products and reduce production costs, encouraging farmers to join cooperatives is one of the more effective solutions.

### 2.3. Agricultural Trade Contacts

In the past decade, in order to promote exchanges with China, Poland has implemented some publicity projects and plans, of which the main focus was agriculture. The first one was the “GO CHINA” plan, put forward on 12 March 2012. Subsequently, three of Poland’s domestic publicity projects were hosted by the Polish Ministry of Agriculture, mainly involving fresh apples, dairy products, and beef, with the aim of introducing Polish agricultural products to China. This series of plans has played an obvious role in promoting the development of Chinese multinational companies and the recovery of the Polish economy, and increasing the income of Polish farmers.

After the resumption of the Polish Poultry Export Agreement between China and Poland in July 2018, Poland will focus on the further development of the Chinese market in agricultural products and has great expectations in agricultural food exports to China. At the first China International Import Expo (CIIE) held in Shanghai in November 2018, the Polish government sent a government delegation to look for cooperation opportunities and established the largest pavilion among EU member states, as shown in Figure 5. According

to statistics, nearly 1/3 of the exhibitors are enterprises in the food industry [22]. Poland's dairy-product exports to China surged 70 percent year-on-year during the first half of 2020 despite the COVID-19 pandemic, which drove a dairy-product sales boom in China [18].



**Figure 5.** Polish pavilion in 1st CIIE [23]. Copyright source: reproduced from [<https://www.ciie.org/zbh/2019syz/20190223/10952.html>] (accessed on 11 November 2021)], with permission from China International Import Expo, 2018.

Agricultural products are one of the important product groups traded between China and Poland [24]. As seen from Table 1, the total trade value between China and Poland has increased between the years 2010 to 2020 on the whole, and reached a peak in 2020. In agricultural trade, the share of agricultural products in total products was still small; however, the trade deficit decreased year by year and reached its lowest point in the past ten years in 2020. The export share of agricultural products in total products also dropped to 1.17% in 2020, the import share of which was 5.66%. This means there are still great substantial trade opportunities and competition for Polish agricultural products in the Chinese market. In the future, Poland can carry out more economic and trade cooperation with China on agricultural products, and strengthen exchanges between agricultural experts from both sides.

Under the current economic downturn, China–Poland agricultural cooperation is also seeking new breakthroughs. With the diversification of international shopping platforms, Chinese residents' online consumption demand has been continuously released. Therefore, overseas cross-border e-commerce plays a positive role in enriching the supply of domestic agricultural products, promoting the development of new industries and new models, and better meeting the needs of residents. Demand drives production, the continued willingness of bilateral agricultural trade contacts can promote further agricultural machinery cooperation. With the support of emerging cross-border trade modes, the “Belt and Road” Initiative will provide opportunities for China and Poland to expand agricultural-drone cooperation. As we know, the fruit industry is an important part of Polish agriculture and there is a huge market space in China. Fruit protection and management can be the first pilot file of the follow-up development of agricultural UAVs.

**Table 1.** Foreign trade between China and Poland in 2010–2020.

| Specification  | 2010   | 2011     | 2012     | 2013     | 2014     | 2015     | 2016     | 2017     | 2018     | 2019     | 2020     |
|--|--------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| million USD  |        |          |          |          |          |          |          |          |          |          |          |
| Trade in total products                              |        |          |          |          |          |          |          |          |          |          |          |
| Import   | 1696.6 | 2047.9   | 1997.7   | 2231.7   | 2934.7   | 2741.9   | 2537.7   | 3353.5   | 3646.2   | 3943.8   | 4319.9   |
| Export   | 9438.3 | 10,939.5 | 12,386.7 | 12,574.9 | 14,256.8 | 14,344.9 | 15,094.1 | 17,873.1 | 20,944.3 | 23,906.1 | 26,735.8 |
| Balance  | 7741.7 | 8891.6   | 10,389.0 | 10,343.2 | 11,322.1 | 11,603.0 | 12,556.4 | 14,519.6 | 17,298.1 | 19,962.3 | 22,415.9 |
| Trade in agricultural products                       |        |          |          |          |          |          |          |          |          |          |          |
| Import   | 38.8   | 51.8     | 75.8     | 207.7    | 240.9    | 170.0    | 131.4    | 118.3    | 199.0    | 267.4    | 244.5    |
| Export   | 296.7  | 341.6    | 308.5    | 327.5    | 320.7    | 319.0    | 299.3    | 355.7    | 374.8    | 369.2    | 311.6    |
| Balance  | 257.9  | 289.8    | 232.7    | 119.8    | 79.8     | 149.0    | 167.9    | 237.4    | 175.8    | 101.8    | 67.1     |
| Share of agricultural products in total products (%) |        |          |          |          |          |          |          |          |          |          |          |
| Import   | 2.29   | 2.53     | 3.79     | 9.31     | 8.21     | 6.20     | 5.18     | 3.53     | 5.46     | 6.78     | 5.66     |
| Export   | 3.14   | 3.12     | 2.49     | 2.60     | 2.25     | 2.22     | 1.98     | 1.99     | 1.79     | 1.54     | 1.17     |

Data source: According to the UN Comtrade database.

#### 2.4. Agricultural Policy

In agricultural products and food management, in addition to the implementation of the relevant laws and regulations on agricultural product safety of the EU, the Food Hygiene and Nutrition Law is the main law in agricultural products and food in Poland. The Polish National Bureau of Metrology is responsible for formulating product quality and identification standards for domestic agricultural products and food [25]. On 1 January 2017, Poland began to implement two farm bills the ‘Simplified Agricultural Products Direct Selling Law’ and the ‘Polish Product Marking Law’ to reduce taxes and fees for farmers and encourage agricultural development. The relevant agreements between China and Poland on the import and export of agricultural products can be traced back to June 1988. In September 1994, China and Poland began to carry out import and export inspections and quarantine agreements. To date, more than 10 agreements have been signed on pork, dairy products, poultry meat, breeding eggs, and aquatic products exported to China [26].

UAVs have been widely used in geodesy, agriculture, etc. Agricultural UAVs are becoming a new force in precision-agricultural aviation in China. This is a commercial and economic opportunity to open up the market for the use of UAV, but it is necessary to ensure the sustainable development of the UAV industry while maintaining the maximum level of security [27]. According to the regulations of the Polish Civil Aviation Authority on flights other than recreational or sports flights beyond visual line of sight (BVLOS), different BVLOS flight types must meet different requirements. Ground survey activities and research and testing related to agriculture and forestry belong to professional flight, and agricultural aviation activities belong to automatic flight [28].

In the past decade, China has shown great concern and support for the management policy and technological development of plant-protection UAV, especially the national key research and development program of “high-efficiency technology and intelligent equipment for aerial–ground application” with a project fund of CNY 96 million in 2016. In response to serious domestic pesticide overapplication, backward plant-protection equipment and application technology, and weak independent research and development ability, it aimed to develop high-efficiency and intelligent precision equipment, strengthen technological integration and innovation, and achieve pesticide-application reduction and efficiency enhancement; the program [29] carried out EIGHT research directions, including aviation plant-protection spraying-technology parameters and intelligent equipment-control factors and performance indicators, research and development of key components of agricultural aviation plant-protection intelligent equipment, and research on low-altitude and low-volume spray technology for agricultural aviation, which has played a positive role in promoting the development of chemical fertilizer and pesticide-reduction technology in China. China is developing rapidly in plant protection UAV, and the relevant policies and subsidies are increasingly perfect. The new development direction of Polish agricultural



aviation can learn from Chinese research directions and formulate the development policy of plant-protection aircraft and the Agriculture 4.0 R&D (Research and Development) plan in line with Poland's national conditions.

### *2.5. Funding and Investment*

In 2016, Poland implemented the “Responsible Development Plan”, which made electric vehicles, UAVs, big-data analysis, and R&D innovation as the focus of attracting investment [12]. The key areas for attracting foreign investment in Poland mainly include energy, infrastructure, food processing, the service industry, electronic products, automobile manufacturing, biotechnology, aviation manufacturing, R&D, etc. [30].

The investment and cooperation between China and Poland are very close. Bilateral trade reached USD 27.8 billion in 2019, an increase of 13.4% year-on-year. The two countries have established 37 pairs of friendly provinces and cities, and have hosted many China–Poland local cooperation forums. The two sides are also committed to deepening cooperation in energy, transportation, logistics, infrastructure, and other areas to enhance the value of cooperation [31]. At present, the number of Chinese companies in Poland has increased to more than 70, and the total direct and indirect investment in Poland has exceeded USD 3 billion. From January to June 2020, the bilateral trade volume of China and Poland rose against the trend, reaching USD 13.28 billion, an increase of 3.2% year-on-year. Despite the overall decline in China's total imports, imports from Poland have maintained positive growth [11].

High-level visits between the Ministries of Agriculture (MOA) of China and Poland are frequent, the agricultural cooperation mechanism is sound, the “China–Poland Agricultural Science and Technology Cooperation Center” has achieved fruitful results, and agricultural cooperation has developed steadily in agricultural technology and agronomy. In August 2019, Shandong Institute of Pomology and the Polish Horticultural Research Institute signed a cooperation agreement on the “Framework Agreement on Establishment of Horticulture Sci-Tech Park”, which includes the establishment of a Horticultural Science and Technology Park in China and Poland, the introduction and demonstration of each other's characteristic resources and new technologies, the development of scientific cooperation and research, undertaking various research projects between the two countries, and establishing a joint laboratory to reach scientific and technological cooperation [32]. The two countries plan to establish a Chinese horticultural science and technology park in Poland and introduce Chinese fruit-tree resources and excellent new technologies.

Agricultural UAVs are the organic combination and progression of the previous cooperation between China and Poland. With the support of relevant investment policies and a research cooperation basis, China–Poland agricultural cooperation can continue to further strengthen in-depth exchanges on agriculture, especially in agricultural UAVs. Poland has a large number of high-quality talents, solid basic research, and a business environment conducive to innovation in aviation [30]. Poland can use its comprehensive advantages and learn from China's own development process to open up a new agricultural drone market, such as application in characteristic crops, promotion of emerging technologies, and training of new agricultural talents.

## **3. The Development of China's Precision Agriculture Aviation**

### *3.1. Transformation and Breakthrough*

In plant protection, Chinese farmers used to use manual knapsack sprayers or tractors in large-area pesticide spraying. This often leads to excessive use of pesticides and fertilizers, which not only exposes farmers to health risks, but also pollutes the surrounding soil and water sources. Moreover, due to the scattered land and the complex terrain, scattered farmers in China are unable to adopt large-scale ground agricultural machines, but can only rely on human labor to manage the farmland, so the workload is very heavy.

At present, Chinese rural land transfer is accelerating, and numbers of family farms, new agricultural economic entities, and large farmers have emerged. This promotes the

rapid development of agricultural aviation plant-protection machinery with specialization, wide applicability, and increasing efficiency by reducing spraying. As a new type of plant-protection operation in China, agricultural UAVs can replace manual labor to complete complex and dangerous agricultural activities efficiently such as sowing, spreading fertilizers, and spraying pesticides, thus helping farmers improve agricultural production efficiency and reduce operating costs. Fully autonomously flying agricultural UAVs can easily take off from high-stalk crops, paddy fields, and hilly and mountainous areas, when manual and ground-based mechanical operations cannot solve the launch problem. It can also alleviate the pressure of rural labor shortage and aging population caused by the development of urbanization. It is an effective way to prevent and control sudden diseases and insect pests in large areas and reduce the damage of pesticides to operators. The application of low-altitude and low-volume aerial application technology of UAV meet the current requirements of China's small-scale agricultural development.

The development of Chinese large-scale manned agricultural aviation began in 1951. At present, China has 1400 fixed-wing aircrafts and more than 60 helicopters for agriculture and forestry. The area using fixed-wing aircrafts and helicopters to control diseases, pests, and weeds and spray fertilizer is over 2 million  $\text{hm}^2$ . However, the number of agricultural aircraft in China only accounts for about 0.13% of the total number of agricultural aircraft in the world, and the agricultural aviation operation area only accounts for 1.70% of the cultivated land area [33,34]. Since 2005, Chinese agricultural-related research institutions have begun to propose to the MOA and the Ministry of Science and Technology (MOST) to establish projects for the development of plant-protection UAV. In 2008, with the funding of the '863' National Program of the MOST, domestic research institutions began to develop single-rotor unmanned pesticide applicators. It marked that Chinese research institutions officially began to explore the aviation pesticide-application technology of plant-protection UAV. In 2009, China Agricultural University (CAU) cooperated with enterprises to develop the first multi-rotor plant-protection UAV at home and abroad. Since 2010, UAV aerial plant-protection operations have gradually emerged and developed rapidly in China, and Chinese plant-protection UAV has also started the first step in commercialization. The "3CD-10" single-rotor oil-powered plant-protection UAV produced by Hanhe made its debut at the National Agricultural Machinery Expo. In 2012, CAU cooperated with enterprises to develop the first electric single-rotor plant-protection UAV in China. In April 2012, the first "on-site observation and seminar on low-altitude aerial pesticide-spraying technology" was held in Beijing. Taking this as a starting point, research on low-altitude and low-volume aerial pesticide-spraying technology has gradually become a hot spot. In 2012, the Department of International Cooperation of the MOA of China initiated and organized a two-year international cooperation research project on plant protection UAV among China, Japan, and South Korea, named "Research on Aerial Spraying Application Technology of Rice by Plant Protection UAV". In January 2013, commissioned by the MOA, CAU conducted a test and evaluation on 13 domestic plant-protection UAVs in the rice-growing area of Hainan Province. The test results showed that all domestic UAVs had obvious control effects on rice diseases and insect pests. Based on the results, the MOA began to promote UAV aviation plant-protection technology nationwide in 2013. Subsequently, the local governments of Henan, Fujian, Jiangsu, Guangdong, Shandong, and other provinces began to include agricultural aircraft in the category of agricultural machinery subsidies for the first time [35,36]. In 2014, the No. 1 Central Document clearly put forward the requirements for strengthening the construction of agricultural aviation. Immediately afterwards, Chinese industry experts jointly participated in the discussion and drafted a report on promoting the development of plant-protection UAV and agricultural aviation, which was submitted to the State Council and the MOST. In 2015, Hunan and Henan provinces started pilot subsidies for plant-protection UAV. In the same year, all kinds of social capital entered the field of agricultural UAV in China. DJI, XAG and other enterprises accelerated the layout of the agricultural aviation market. Since then, the promotion and application of plant-protection UAV in China has stepped into a fast lane. The No. 1 Central

Document of 2015 and 2016 continued to focus on innovation-driven smart agriculture and put forward the demand for vigorously developing agricultural aviation applications. In the Joint Circular of the General Offices of the Ministry of Agriculture and Rural Affairs (MOARA), the Ministry of Finance (MOF) and the Civil Aviation Administration of China on Launching Pilot Programs of Farm Machinery Purchase Subsidy for Standard Operation of Plant Protection Drone was released in 2017, which could guide the development and standardized application of agricultural UAV technology. Since then, plant-protection UAV has been officially included in the catalog of national agricultural-machinery subsidies. In March 2018, the General Office of the MOARA and the General Office of MOF issued the ‘Notice on the Pilot Program of Subsidies for the Purchase of New Agricultural Machinery Products from 2018 to 2020’. It aimed to support and promote technological innovation, R&D, and production of agricultural machinery products, as well as speed up the testing, identification, and promotion of new products. It particularly indicated that it would continue to support subsidies for plant-protection UAV. The major events mentioned above are shown concisely in Table 2.

**Table 2.** The development brief of China’s agricultural drones.

| Time | Major Event  |
|------|--|
| 1951 | China’s large-scale manned agricultural aviation began to develop.   |
| 2005 | Proposal to establish projects for the development of plant-protection UAV.  |
| 2008 | Domestic research institutions began to develop single-rotor unmanned pesticide applicators and explore the aviation pesticide-application technology of plant-protection UAV officially.                      |
| 2009 | The first multi-rotor plant-protection UAV was developed.  |
| 2010 | Plant-protection UAV was developed rapidly in China and started commercialization.   |
| 2012 | The first electric single-rotor plant-protection UAV in China was developed. Research on Aerial Spraying Application Technology of Rice by Plant Protection UAV was organized by China, Japan, and South Korea |
| 2013 | The MOA began to promote UAV aviation plant-protection technology nationwide.  |
| 2014 | The No. 1 Central Document clearly put forward the requirements for strengthening the construction of agricultural aviation  |
| 2015 | Social capital entered agricultural UAV and accelerated the layout of the agricultural aviation market.  |
| 2017 | Plant-protection UAV was officially included in the catalog of national agricultural-machinery subsidies   |

Since the implementation of the “13th Five-Year Plan” in 2015, China has also given strong support to the development of plant-protection UAV. Including the first batch of the 2016 national key research and development program ‘high-efficiency technology and intelligent equipment for aerial–ground application’, the special project of the MOST ‘R&D of Agricultural Aviation Operation Key Technology and Equipment’ in 2017, and in the key project of the 2018 National Natural Science Foundation of China ‘Plant Protection UAV Pesticide Atomized Deposition and Efficient Utilization’, key support was given to plant-protection UAV, key working components, and pesticide-application technology [37–39]. Since 2018, local governments have accelerated the modernization of agriculture, purchased plant-protection UAV for unified prevention services, increased the areas of unified prevention and spraying operations, and increased the subsidy standards for drones, which has accelerated the development of plant-protection UAV. With the strong support of the government, the market for plant-protection UAV developed rapidly, accounting for 41.5% of the industrial UAV market in 2018.

According to the “2019 China Civil UAV Development Report” issued by the General Aviation Branch of the China Air Transport Association in April 2020, agricultural plant protection is a popular application field for civilian UAVs. As of the end of 2019, Chinese total

production of various kinds of plant-protection UAV consisted of more than 170 varieties, with more than 55,000 in possession, and the operating area exceeded 56.67 million  $\text{hm}^2$ .

### 3.2. Applications

The vertical take-off and landing method of plant-protection UAVs can improve work efficiency. Particularly when there are many ditches and river channels in the farmland, the problem of the ground plant-protection machinery being unable to enter is overcome. Moreover, manual knapsack electric sprayers have low control benefits. For example, *Xanthomonas oryzae pv. oryzicola* invades from rice mobile cells and wounds and is spread by rain. Artificial field operations will increase the chance of human transmission of germs [40]. Therefore, in recent years, plant-protection drones in China have been put into use in the prevention and control of crop diseases and pests, such as using in cotton, citrus, rice, and forest.

#### 3.2.1. Cotton

Xinjiang is China's largest cotton-production area and one of the cotton areas with the most applications of agricultural UAVs in China. According to statistics from the Xinjiang Agriculture and Animal Husbandry Machinery Administration, as of July 2020, Xinjiang has more than 5000 agricultural UAVs based on the Beidou navigation system, with an operating area far exceeding 1.33 million  $\text{hm}^2$ . However, with the adjustment of planting structure and changes in climatic conditions in Xinjiang in recent years, pests in cotton fields have entered a period of recurrence and frequent occurrence. *Aphis gossypii* Glover is a worldwide and explosive cotton pest. A large-scale outbreak will seriously restrict the quality and efficient production of cotton. Studies show that adding appropriate additives to pesticides can improve the adhesion of liquid, promote plant absorption, and obviously improve the control effect of pesticides [41].

The intensive agriculture-development mode of Xinjiang is very suitable for the field spraying of plant-protection UAVs. The working status of agricultural machinery in cotton field is shown in Figure 6; they are spraying pesticides through UAV's nozzles or boom sprayer. Wang et al. [41] studied the control effect of spraying different pesticides and additives on cotton aphids with DJI agricultural UAV MG-1S and analyzed related economic benefits. The results show that the use of MG-1S to control cotton aphids gives priority to 22% sulfoxaflor SC, which is mixed with the additive Maifei, which can achieve an ideal control effect. Compared with 'mechanical + manual' spraying, UAV has a lower control effect on cotton aphids after 1 day of application. There was no difference between the two methods at 3 days and 5 days after application, but the operation efficiency of UAV was increased threefold, the amount of application liquid was reduced by one-third, and the mechanical operation cost was reduced by 60 CNY/ $\text{hm}^2$ . In addition, it is inconvenient to work in the farmland with mechanical or manual sprayers, causing mechanical damage to the cotton during the operation. The spraying of UAV can avoid cotton damage, so it can meet the needs of modern agriculture for high efficiency, pesticide saving and cost reduction.





**Figure 6.** Working status of plant-protection UAVs (a) and ground machinery (b). Copyright source: own work.

UAVs are often used to collect canopy visible light and multispectral image for identification of cotton pests and yield estimation. Cotton root rot (CRR) is a persistent soilborne fungal disease that is devastating to cotton in the southwestern U.S. and Mexico. Research has shown that CRR can be prevented or at least mitigated by applying a fungicide at planting, but the fungicide should be applied precisely to minimize the quantity of product used and the treatment cost. Previous studies have shown that remote sensing (RS) from manned aircraft is an effective means of delineating CRR-infested field areas. Wang et al. [42] used an UAV to collect high-resolution RS images in three Texas fields known to be infested with CRR; two new automated classification methods that take advantage of the high resolution inherent in UAV RS images were also evaluated. The results indicated that the new automated methods were up to 8.89% better than conventional classification methods in overall accuracy. One of these new methods, an automated method combining k-means segmentation and morphological opening and closing provided the best results, with overall accuracy of 88.5% and the lowest errors of omission (11.44%) and commission (16.13%) of all methods considered. Single-boll weight is the main factor of cotton yield and a key index used to evaluate the quality of cotton. The percentage of boll opening in the area and VDVI at the flowering and boll-setting stages were highly correlated with upper single-boll weight. Xu et al. [43] proposed a method based on high-resolution UAV visible-light RS images to estimate the upper single-boll weight in north Xinjiang. The prediction model was established by performing least-squares linear regression, BP neural networks and K-fold cross-validation. The model demonstrated that the single-boll weight of a cotton boll was highly correlated with the density of the cotton boll in the region ( $R^2 = 0.2498$ ) and the vegetation index ( $R^2 = 0.7752$ ) in the flowering and boll-setting stages. By considering both these parameters in the model, a higher correlation coefficient ( $R^2 = 0.8162$ ) could be obtained. This study can realize large-scale prediction of single-boll weight and provides a new idea for breeding screening.

### 3.2.2. Huanglongbing (HLB) of Citrus

Citrus has a long planting history in China with a complete variety, and its output and planting area have been ranked first in the world for a long time. According to the statistics of the National Bureau of Statistics of China, citrus production in 2019 was 45.8454 million tons [44]. As a devastating citrus disease, HLB is caused by *Candidatus Liberibacter* spp., and there are no pesticides to prevent it. Diseased plants usually turn yellow at the top of the canopy when the disease first appears, and then spread to other plants through field

transmission of *Diaphorina citri* after the onset. The key to HLB is prevention. Finding the diseased plants in the orchard in time and removing them immediately reduces the loss to the minimum. The traditional prevention and control methods mainly rely on manual identification, which is highly subjective and inefficient.

In recent years, the UAV low-altitude RS technology can be used to monitor a large area of orchards and improve work efficiency; as shown in Figure 7, the RS UAVs collect hyperspectral or multispectral images to detect HLB. Lan et al. [45] obtained hyperspectral images of citrus orchards by UAV, and established a discriminant model to identify HLB in the test orchards. They respectively extracted the average spectra of the region of interest (ROI) from the canopies of healthy and diseased citrus trees. After removing the abnormal data, they used the Savitzky–Golay smoothing algorithm to smooth the reflectivity spectrum, performed spectral transformation on the smoothed original spectrum to obtain the additional antilog spectrum and first-order differential spectrum. They then added the original spectrum and took the first three principal component variables of each spectrum and the full-band spectral variables as modeling variables and compared them. Combined with the KNN model and SVM model, the classification accuracy rate reached 94.7%. For the Shatangju mandarin cultivar, Deng et al. [46] proposed a nondestructive citrus HLB field-detection method based on hyperspectral reflectance in this study. A characteristic band-extraction method based on entropy distance and sequential backward selection is explored. Several machine-learning algorithms (logistic regression, decision tree, SVM, KNN, linear discriminant analysis, and ensemble learning) were used to discriminate between disease groups: healthy, symptomatic HLB-infected, and asymptomatic HLB-infected, based on leaf reflectance. The comparison of different traditional machine learners revealed that SVM performed the best in terms of high classification accuracy and low complexity. The SVM learner achieved 90.8% accuracy, while in two-group classification (healthy vs. symptomatic HLB leaves), the accuracy reached 96%. The ensemble method also achieved high accuracy but with relatively high complexity. The results also show that using only a few bands is insufficient for classification. In this study, 13 characteristic bands extracted by the proposed method provided the best performance. This provided a lot of data and theoretical support for the follow-up detection of citrus HLB. Lan et al. [47] used a commercial multispectral camera (ADClite) mounted on DJI M100 UAV to collect green, red, and near-infrared multispectral images of a large-area citrus orchard and preprocess them. Several machine-learning algorithms, such as SVM, KNN, logistic regression, naïve Bayes, and ensemble learning, were compared to model the healthy and HLB-infected samples after parameter optimization. The results showed that the ensemble-learning and neural-network approaches had strong robustness and the best classification results (100% in AdaBoost and 97.28% in neural network) using the threshold strategy. The above studies have verified the feasibility of using UAVs instead of manpower to efficiently obtain the monitoring information of a large-scale orchard and accurately detect the HLB.

### 3.2.3. Rice

China is a large rice producer, and its rice output ranks first in the world. Rice has also been one of the most widely planted and most edible food crops in China since ancient times. As shown in Figure 8, agricultural UAVs are often used on rice to spray precisely. Yu et al. [48] combined UAV RS diagnosis with precision operation of agricultural UAV, and used UAV-hyperspectral technology to establish the prescription maps of fertilization amount in the rice-tillering stage. Combined with the operation parameters of agricultural UAV, the grid division of fertilizing plots was carried out to determine the amount of precise fertilization, and precision fertilization was carried out by agricultural UAV. The rice yield of UAV-variable topdressing was essentially the same as that of traditional topdressing, but the amount of pure nitrogen decreased by 27.34%. The study results can provide data and model the basis for the precision-variable topdressing of agricultural UAV in the tillering stage of rice in cold regions.



**Figure 7.** RS UAVs obtain hyperspectral images and monitor HLB of citrus orchards. Copyright source: own work.



**Figure 8.** Agricultural UAV sprays pesticides on rice. Copyright source: own work.

Plant-protection UAVs are not only used for aerial spraying and information collection, but also for research on rice fertilization, sowing, and auxiliary pollination. Li et al. [49] designed a centrifugal rice spreader with a ring. This spreader is light and compact (1.50 kg) and can be installed in a drone for rice seeding. The spreader uses centrifugal force to spread rice seeds, and rice seeds will hit the ring and rebound, so that the rice seeds are non-hollow and axisymmetric fan-blade shape-distributed. We optimized the key parameter of the spreader and installed it in a drone for a field trial; the results showed that drone rice direct-seeding can reach 9295.65 kg/hm<sup>2</sup>. In order to realize UAV low-altitude and high-velocity sowing operations and ensure the uniformity of the sowing, Song et al. [50]



designed a pneumatic UAV sowing device, making use of the airflow to blow the seeds out in different directions. The results showed that, in the range of 1–2.8 m, it is unnecessary to consider the effect of working height fluctuation on the sowing width and uniformity when sowing by this device. Taking the sowing width and uniformity coefficient of variation and energy consumption and other factors into account, the optimal sowing height of UAV was 2 m. Li et al. [51] found that cover width of wind field, wind speed in three directions, and distribution of wind field will directly affect the agricultural UAV's field effect. The distribution of wind field formed by the uniaxial single-rotor electric unmanned helicopter and round multi-axis multi-rotor electric unmanned helicopter is different [52,53]. Li et al. also explored the distribution law of rice pollen in the wind field of small UAV. The flight speed of 4.53 m/s contributes to the maximum pollen-distribution width and area ratio of more than five pollen grains, which is the most favorable speed to pollination. Liu et al. [54,55] used single-rotor agricultural UAV for the supplementary pollination during seed production of 10 hybrid combinations with large parental row ratios in the hybrid rice-seed-production bases of Hunan, Hainan, and Guangdong Province from 2012 to 2015, which was under the conditions of different natural wind speeds. The results showed that under the parental row ratio of 6:(40–60), the seed setting rate and yields of the supplementary pollination by single-rotor agricultural UAV could reach even higher than those of artificial pollination, indicating the single-rotor agricultural UAV could be used in supplementary pollination for hybrid-rice-seed production.

In November 2020, DJI released a new agricultural UAV T20, and launched seed-sowing system 2.0 [56]. The new system has a capacity of 20 L, a sowing rate of 15 kg/min, and a sowing span of 7 m. It can be reinstalled on T20 within 3 min and supports a variety of operating scenarios, such as rice direct seeding, rapeseed seeding, grassland supplementary seeding, solid-fertilizer seeding, shrimp paddy-field feed seeding, etc. Take rice direct seeding as an example; the operating efficiency is about 70 times higher than manual spraying. The system currently sells for CNY 5000 in China. Because ground machinery and manned aircraft are difficult to operate in the hilly areas of southwest China, plant-protection UAV sowing technology is a new idea to solve the mechanical direct seeding of rice in scattered plots of hilly and mountainous areas.

#### 3.2.4. Forest

Agricultural UAVs can also be used for the prevention and control of diseases and pests in forest areas [57]. For example, the forest area of Heilongjiang in China is large and the spread of *Dioryctria sylvestrella* is fast; aerial spraying can quickly control the spread of pests. As shown in Figure 9, although the helicopter has a large load and a long flight time, it has a large drift and high professional requirements. Therefore, it has poor practicability for contractors who contract to operate small-scale Korean pine forests. At the same time, the helicopter spraying needs a special pilot, and it needs to be approved by the air-traffic-control department before taking off. It is feasible and effective to control *Diaphorina citri* in a large area by helicopter spraying. However, the spraying requires the continuous scale of orchards, and there will be blind spots if there are high-voltage poles or buildings in the garden. In addition, a fixed-wing aircraft requires a runway of a certain specification for take-off and landing, which is not easy to achieve in high mountains and dense forests.

Compared with fixed-wing aircraft and helicopters, the advantages of UAV spraying are its small size, high flexibility, easy handling and control, and its suitability for grass-roots forest farmers. Using UAVs to spray pesticides for pest prevention and control, droplets directly attach to the treetops and pinecones, which can improve the efficacy of pesticides and solve the problem that the red pine tree cannot be manually sprayed, as well as reduce direct contact with pesticides and the risk of poisoning. The plant-protection UAV is not restricted by the landform or the time, and it can plan its route intelligently to avoid leakage or repeated spraying and reduce health risks. In the vigorous orchard, the control effect of the middle and lower part of the tree is not good when flying directly, so



pruning work should be carried out in advance to ensure that the tree has better ventilation and light transmittance; it can not only reduce the occurrence of pests and diseases, but also reduce the control cost and ensure the effect of spraying control. In the southern citrus orchard, the agricultural UAV can use the rain-stop gap to complete spraying during the rainy season. New shoots, especially summer shoots, mostly occur at the top of the tree. When the tree is taller, it is difficult to spray the top manually. Plant-protection UAVs are more convenient and effective to spray for shoot control and prevention of new shoot diseases and pests [58].



(a)



(b)

**Figure 9.** Agricultural helicopters spray in pine forests, Lushan, Jiangxi Province. (a) Helicopter's spraying nozzles; (b) helicopters over the forest. Copyright source: own work.

To sum up, this section lists the mature application of agricultural UAVs to four representative crops in China, as well as conventional application cases. The major applications of categories mentioned above are shown concisely in Table 3.

**Table 3.** The applications of China's agricultural drones in representative categories.

| Representative Categories | Application Cases  | Technology Used   |
|---------------------------|--|---|
| cotton                    | Control cotton aphids, detect cotton root rot, and yield estimation [41–43]  | Spraying pesticides with additives and collecting high-resolution RS images [41–43]   |
| citrus                    | Nondestructive rapid detection of citrus HLB in large orchard [45–47]  | Collecting hyperspectral and multispectral images [45–47]   |
| rice                      | Precision operation, information collection, sowing, and auxiliary pollination [48–55]   | Combined UAV RS diagnosis with precision spraying, sowing-device design, distribution law of rice pollen in the wind field, and supplementary pollination flight parameters selection [48–55] |
| forest                    | Control the spread of pests, substitute workers to complete tree-top spraying, and spraying in rain-stop gap during rainy season [57,58] | Flexible spraying and prevention [57,58]  |

### 3.3. Cost Savings

At present, in the main citrus production areas, citrus diseases and pest control and summer shoot control are still based on chemical agents. Spraying methods are still mainly carried out by sprayers and high-pressure sprays, which require a lot of labor and have low efficiency. With the increasing shortage of rural labor, it is often difficult to seize a favorable opportunity to complete the spraying operation with high quality. In May 2019, Wang et al. [58] compared the effects and costs of artificial stretcher spray and plant-protection UAV to control citrus diseases and pests (mainly citrus canker) and control summer shoots in a 3-year-old citrus orchard in Dingdang Town, Guangxi Province. As

shown in Table 4, the diseased-leaf rates of citrus canker by UAV control and artificial spraying were 2.20% and 2.51%, and the disease index was 0.24 and 0.28, respectively. Plant-protection drone spray control summer shoots can increase the efficiency by 20.3%. The rent of using agricultural drones for pesticide spraying is 225 CNY/hm<sup>2</sup> (including mechanical use and labor costs), and the average pesticide cost is 606.75 CNY/hm<sup>2</sup>. The labor cost of stretcher sprayer per time was 450.00 CNY/hm<sup>2</sup> (three people prevent 0.8 hm<sup>2</sup> per day and the daily service cost per person was CNY 120.00). The average drug cost per time was 2220.00 CNY/hm<sup>2</sup>. Compared with the stretcher sprayer, plant-protection UAV can save an average of 1613.25 CNY/hm<sup>2</sup> per time for drug costs and 225 CNY/hm<sup>2</sup> for labor costs, which saves an average cost of 1838.25 CNY/hm<sup>2</sup> each time.

**Table 4.** Details of spraying-operation costs.

| Spraying Methods           | Diseased-Leaf Rates of Citrus Canker (%) | Disease Index | Cost of Pesticide Spraying * (CNY/hm <sup>2</sup> ) | Average Drug Cost per Time (CNY/hm <sup>2</sup> ) |
|----------------------------|--|---------------|---|---|
| Artificial stretcher spray | 2.20                                     | 0.24          | 450   | 2220.00   |
| Plant-protection UAV       | 2.51                                     | 0.28          | 225   | 606.75  |

\* includes mechanical use and labor costs.

Li et al. [49] also analyzed the production benefits of the three planting methods of rice planting (mechanical transplanting, mechanical sowing, and UAV sowing). Rice is calculated by the current market price of RMB 2.60 CNY/kg, the labor cost is calculated as RMB 100 CNY/day, and the agricultural materials are calculated according to the actual purchase price. Among the three cultivation methods in Table 5, the labor cost for mechanical transplanting is the highest at RMB 960 CNY/mu, followed by mechanical sowing at RMB 610 CNY/mu, and the drone sowing cost is the lowest at RMB 550 CNY/mu. Because it is easy to transfer in the field, the UAV sowing is less high than the mechanical transplanting and mechanical sowing in the field, and the use cost is lower, and it is more labor-saving than mechanical sowing in farming. In the economic benefit analysis of the three cultivation methods, the output value of mechanical transplanting was RMB 1690 CNY/mu, and the production input was RMB 1195 CNY/mu, thus the output-to-input ratio was 1.41. The output value of mechanical sowing was RMB 1560 CNY/mu, and the production input was RMB 878 CNY/mu, the output-to-input ratio was 1.78. The UAV sowing production value was RMB 1335.80 CNY/mu, the production investment is 828 CNY/mu, and the output-to-input ratio was 1.61. Among the three cultivation methods, UAV sowing is the most labor-saving and the least production input. In terms of output-to-input ratio, the ratio of mechanical sowing was the highest, followed by UAV sowing and mechanical transplanting. With the increasing labor cost, the labor cost in production input will gradually increase, and the economy of UAV sowing will become more and more obvious.

**Table 5.** Details of operation costs and income in rice planting.

| Planting Methods         | Sowing Cost (CNY/mu) | Production Input (CNY/mu) | Output Value (CNY/mu) | Output-to-Input Ratio |
|--------------------------|----------------------|---------------------------|-----------------------|-----------------------|
| Mechanical transplanting | 960                  | 1195                      | 1690                  | 1.41                  |
| Mechanical sowing        | 610                  | 878                       | 1560                  | 1.78                  |
| UAV sowing               | 550                  | 828                       | 1335.8                | 1.61                  |

According to XAG official public account's existing data, as of 31 August 2020, XAG's smart agricultural products and technology have served about 8.72 million farmers, and more than 50,000 agricultural automatic machines have carried out unmanned operations in 42 countries and regions. In the past two years, XAG has reduced its greenhouse gas emissions by 368,063 tons to meet the challenge of climate change by using environmentally

friendly electricity instead of tractor diesel. Based on the advanced UAV precision-spraying technology, XAG has saved 5.09 million tons of agricultural water, and has reduced the use of 22.1 thousand tons of pesticides and fertilizers and created new employment opportunities for rural youths, such as UAV trainers and operators.

By the end of October 2020, data from DJI's official public account showed that the total operation area of DJI agricultural UAVs in Xinjiang had exceeded 60 million  $\text{hm}^2$ , trained more than 65 thousand pilots, and saved more than 15 million tons of water. The comprehensive economic benefits in cost saving and efficiency increasing of aviation pesticide spraying, operation labor costs, secondary disaster compensation, rework caused by wrong spraying/missing spraying, or unfavorable losses of pest control, etc. are more than CNY 20 per mu. Take Xinjiang Province as an example: in the 44-day cotton-defoliation season starting from September 2020, more than 6400 pilots controlled 7130 DJI plant-protection UAVs and completed more than 40 million mu of cotton-defoliation operations. Because the UAV can avoid ground mechanical-seedling compression, it is expected to bring about 684 thousand tons of cotton production and generate CNY 3.8 billion for cotton farmers in Xinjiang. In 2020, the DJI Plant Protection Machine conducted plant protection for 5.5 million mu of fruits in Xinjiang, involving Korla fragrant-pear pollination, Hami melon pest control, and red-date pollination and pest control. According to statistics, the agricultural UAV operation area of Xinjiang Province in 2020 exceeded 115 million mu, an increase of 166% over 2019. Because UAV can save 90% of water compared with manual operation, it saved 3.45 million tons of water in water-starved Xinjiang.

### 3.4. Service and Promotion

At present, one of the most common modes adopted by agricultural UAV manufacturers is the 'sale + services' mode. The UAV manufacturers themselves organize and set up professional pest-prevention organizations or plant-protection service companies to undertake plant-protection operations directly in order to make profits. In plant-protection services, the cross-region operation is of great significance. It can provide big data support and deployment management services for the users of plant-protection UAV, supervise the quality of the operation throughout the whole process, and standardize the operation process and parameters.

Taking the cross-region operation track of XAG plant-protection UAV in 2018 as an example, weeding operations of wheat were carried out in central China from February to March, and operations of 'one-spray-three-prevention' of wheat were carried out in Central and East China from March to June. Rice-weeding operations were carried out in Northeast China, rice insecticides were carried out in Northeast China from July to August, and cotton-defoliation operations were carried out in Xinjiang from September to October. The realization of the cross-region UAV prevention operation in China can solve the operation needs of farmers to the greatest extent, allocate resources to maximize the utilization and benefits of spare UAVs, increase the penetration rate of spraying operations, and solve the problem of seasonal and regional shortage of rural labor force.

China attaches great importance to scientific and technological innovation in leading the high-quality development of modern agriculture, encourages interdisciplinary integration, and accelerates the application of advanced industrial technologies in the agricultural field. In aviation plant protection, the National Aviation Plant Protection Technology Innovation Alliance (the Alliance) was established in May 2016, led by Anyang Quanfeng Aviation Plant Protection Technology Co., Ltd. supported by the MOARA. At present, the Alliance has attracted the participation of many enterprises and scientific research institutions to jointly research agricultural aircraft-manufacturing technology and equipment, special formulation-creation technology, aviation-spraying technical standards, development of autonomous flight-control systems, and high-efficiency and lightweight aviation key-spraying equipment, etc. and accelerating the promotion of demonstration applications. In 2019, the Alliance united with the National Agro-Tech Extension and Service center, South CAU, the Institute of Plant Protection (IPP) of the Chinese Academy of Agricultural

Sciences (CAAS) and other units to carry out the demonstration work of agricultural drones to control crop diseases and pests in Inner Mongolia, Jilin, Heilongjiang, Jiangsu, Jiangxi, Henan, Guangdong, Yunnan, and other provinces; one of these joint test and related operations in Xinfeng are shown in Figure 10. Moreover, they achieved a series of technological breakthroughs, and issued one group standard and two operation guidelines.



**Figure 10.** The joint rice test of the Alliance members is conducted in Xinfeng, Jiangxi, in mid-August, 2019. (a) A technician and two operators discuss spraying plan; (b) Operator controls UAV to spray pesticide as planned. Copyright source: own work.

Take Guangdong Province, where the author's unit is located, as an example; on January 2020, the People's Government of Guangdong Province announced the "Implementation Opinions on Accelerating the Promotion of Agricultural Mechanization and the Transformation and Upgrading of Agricultural Machinery Equipment Industry" [59], which proposed to incubate a group of high-tech agricultural-machinery enterprises with high technical level and great development potential, and support the development of enterprises in the direction of "specialized, refined, special, and new", and create an agricultural UAV industry highland in the Guangdong-Hong Kong-Macao Greater Bay Area. This would give full play to the advantages of Guangdong's UAV industry; actively develop agricultural aviation; standardize and promote the popularization and application of agricultural UAVs; guide enterprises to carry out research on agricultural UAVs, agricultural robots, agricultural machinery operation monitoring, etc.; and accelerate the application of information technologies such as the Internet of Things, big data, mobile Internet, intelligent control, and satellite positioning in agricultural machinery equipment and operations.

#### 4. Application and Promotion of China–Poland Agricultural Aviation

Agricultural cooperation between China and Poland began in the 1950s. The two countries have carried out effective cooperation in wheat, soybeans, fruit trees, vegetables, sugar beets, beekeeping, and animal husbandry. In the 1980s, China also imported 400 T042 agricultural trailers with a payload of 8 tons and 20 tons of sugar beet seeds from Poland. In 1988, using the opportunity for the Polish government to repay the loan to Chinese government, Heilongjiang agricultural reclamation general aviation companies bought five Polish M18A agricultural aircraft (shown in Figure 11) for agricultural aviation operations such as weeding, disease prevention, pest control, fertilization and spraying plant-growth agent of wheat, soybean, corn, and rice, as well as forest aviation operations such as forest pest control, patrol, and firefighting [60].





**Figure 11.** Polish agricultural aircraft M18A [61]. Copyright source: reproduced from (<https://www.planespotters.net/photo/314478/d-fsbc-fsb-air-service-germany-pzl-mielec-m-18a-dromader> (accessed on 11 November 2021)), with permission from Marlin Lehmann, 2012.

In 2016, the Polish Strategy for Responsible Development proposed five pillars to promote development, including the *żwirko i Wigura* project in reindustrialization. The government focused its resources on the design and manufacture of UAVs, striving to achieve a strong position in the field of UAVs and promote the rapid development of Aviation Valley. The regional specialization project in Eastern Poland, which promotes social and regional development, establishes basic infrastructure such as the further development of the Aviation Valley in Rzeszów, attracts small innovative enterprises and establishes cooperatives, and develops aviation IT as an aviation software hub, especially for UAVs [12].

Therefore, it is entirely feasible to strengthen the exchanges between China and Poland in agricultural aviation and deepen the cooperation between the industry–university–research think tank of agricultural UAV, which is conducive to the complementary advantages of the two countries in scientific R&D and application of agricultural aviation, and of great significance to actively serve the plant-protection operations in Asia and Europe and even the world.

#### 4.1. Transformation and Development of Small Farms

There are three ownership types in the Polish agricultural economic structure: state ownership (state farms), collective ownership (agricultural production cooperatives and agricultural groups), and individual ownership. However, individual ownership is dominant in the agricultural economy. In 2019, more than 1.4 million farms used 14.7 million  $\text{hm}^2$  of land and maintained 10 million  $\text{hm}^2$  of Livestock Unit (LSU) (an increase of 1.2% over the previous year), and most of the farms were privately owned [14]. The income of the farm depends on the economic size and the type of agriculture. In the Polish farm structure, more than half (53.5%) are the smallest farms, that is, Utilised Agricultural Area (UAA) with no more than 5  $\text{hm}^2$ , which is mainly characterized by low economic potential and low-efficiency production mode. However, in the current society where industrial scale and production efficiency are generally pursued, small and medium-sized family farms are also unique advantages of Polish agriculture. The percentage of the largest farm with an area of 50  $\text{hm}^2$  and a larger UAA is only 2.4%. The average area of agricultural land for the farm is 10.4  $\text{hm}^2$ . The sown area of grain occupies the dominant position, accounting for 72.4% of the total planting area. The harvesting of basic crops in Poland's state farms and

agricultural cooperatives has all been mechanized. In addition, Polish agriculture has a high degree of water conservancy and chemistry, and rural electrification is fast. However, during the harvest period, Poland has a shortage of domestic labor and needs to bring in seasonal foreign workers. For example, in 2018, Poland issued 328,800 work permits for foreigners, an increase of 40% year-on-year.

#### 4.1.1. Organic Agriculture and Farms in Poland

Organic Agriculture is a substitute for traditional agricultural methods [62]. Poland started a large-scale organic agriculture movement in the early 1980s. In 2001, Poland promulgated the first organic agriculture decree, which clearly stipulated the national standards for organic agricultural production.

The development of organic agriculture has accelerated the birth of organic farms. In recent years, due to the climate, soil conditions, and local traditions, Polish agricultural production has developed towards modernization, intensification, specialization, and regionalization, as shown in Figure 12. Farms in Poland are mostly family-run, and chemical fertilizers are rarely used in the farming process, thus keeping the soil healthy. At the beginning of the 21st century, the Polish government took the development of organic agriculture as an important measure to promote sustainable economic and social development. According to the person in charge of the National Institute of Plant Protection in Poznan, Poland's 1.4 million family farms generally have a size of 10–12 hm<sup>2</sup>. Compared with most other EU countries, their crops use fewer pesticides, which is about the size of the former 20%. The implementation of small-scale farms and scientific crop rotation provides a good foundation for effectively reducing pests and promoting ecological agriculture [63].



**Figure 12.** Organic farms in Ochoza, Poland [64]. Copyright source: reproduced from (<https://www.winterwood.co.uk/our-farms/poland/> (accessed on 12 November 2021)), with permission from Winterwood Farms, 2018.

With Poland's accession to the EU and the implementation of the Agricultural Environment Program, organic agriculture in Poland has been booming. The number of organically certified organic farms and the area of farmland, as well as organic food-processing enterprises have grown rapidly. Before 2013, the area of ecological agricultural land increased more than seven times, but it has been declining since 2014. In 2018, the number of organic

farms was 19,907, and the area of ecological agriculture was about 485,000 hm<sup>2</sup>, accounting for 3.3% of the total land area. More than 88% of the organic farms only grew plants, and 72.1% of the organic areas received special support from CPA, and more than 20,000 production personnel worked in the ecological agricultural land [65]. Poland's use of the EU's unified organic label helps consumers distinguish between organic and non-organic food in the market, and also encourages more processing companies and merchants to engage in organic food processing and trade [66].

Compared with 2018, farm income has improved. The income of Polish family farms in 2019 was PLN 43,745, an increase of nearly 15% over 2018, and the output value increased by 30.7%, but the total cost also increased by 32.4% [14]. At the same time, the retail prices of agricultural production materials have generally increased, with plant-protection products (PPPs) rising by 1.9% and agricultural machinery services rising by 3.1%. Among them, mineral or chemical fertilizers and lime wastes rose the fastest; phosphate fertilizer rose by 7.4% and nitrogen fertilizer rose by 8.7%. In the process of agricultural intensification and concentration, the increase in the consumption of production materials (fertilizers, pesticides, fuels, energy), fertilizer management, agricultural technology treatment, and the incineration of crop residues caused the emission of greenhouse gases and other polluting gases, of which 21% of ammonia gas emissions are related to the consumption of nitrogen fertilizer. Due to the large-scale drought in Poland and the 'Agricultural Nitrate Pollution of Water Quality and Further Prevention of Pollution' production regulations introduced in July 2018, the total consumption of nitrogen fertilizer was 67.7 kg/ha, a decrease of 15.8%, but per hectare UAA applied 23.4 kg of phosphate fertilizer and 38.7 kg of potash fertilizer, an increase of 1.3% and 1.6%, respectively, over the previous year.

In Poland, the consumption of PPPs for each crop varies greatly. As the area of arable land increases, the use of nitrogen, phosphorus, potassium, and calcium fertilizers is also increasing. To sum up, the increase in production cost and the adverse agricultural conditions, such as increasing pollution emissions, decreasing soil fertility, poor water resource and labor shortage, will not only affect farmers' income and production enthusiasm, but also influence the sustainable development of organic farms and agriculture in Poland. Therefore, learning from China's application cases of plant-protection drones is a good idea for Poland to use agricultural UAVs in organic farms and develop related UAV fertilizer and pesticide; it can reduce fertilizer dosage, increase spraying efficiency, save water and costs, and will be an important measure to ensure Poland's ecological environmental security and alleviate the shortage of resources and labor.

#### 4.1.2. China's Smart Agriculture and 5G Unmanned Farms

Smart agriculture is based on the most efficient use of various agricultural resources, and minimizes agricultural energy consumption and costs, minimizes damage to the agricultural ecological environment, and achieves the overall optimization of the agricultural system. It is aimed at the entire agricultural chain, the entire industry, and the entire agricultural system. The ubiquity of process intelligence is characterized by comprehensive perception, reliable transmission and intelligent processing, and other Internet-of-Things technologies as support and means, with automated production, optimized control, intelligent management, systematic logistics, and electronic transactions as the main production. It is a modern agricultural development model and form of high yield, high efficiency, low consumption, high quality, ecology, and safety [67]. Due to the serious aging of China's agricultural population and the increase in labor costs, labor productivity, agricultural production efficiency, and resource utilization are in urgent need of improvement. The new round of "Agriculture 4.0" layout has also gradually shifted China's traditional production methods to precision, smart agriculture, and the direction of 5G unmanned farms [68].

Yubin Lan's team put forward the idea of an ecological unmanned farm in May 2017. It took two years to build the first 5G ecological unmanned farm in Zhutai Town, Shandong Province, and is planned to be completed in 2023 (shown in Figure 13). Ecological unmanned farms make it possible for machines to replace humans through the integra-



tion of modern agronomy and agricultural machinery equipment, green plant-protection technology, UAVs, robots, 5G networks, artificial intelligence, Internet of Things, big data, cloud computing, 3S, and other emerging technologies. The farm uses the RS-aviation-ground integrated information-monitoring system to obtain agricultural information of different growth stages of crops, and uses collaborative operations such as aviation-ground intelligent agricultural robots and agricultural equipment to realize intelligent perception, analysis, and decision making of the agricultural production environment. With early warning and online guidance by experts, the new model of unmanned farms with precision planting, visual management and intelligent control of green ecological agricultural production is achieved, and unmanned production operations in all-weather, whole-process, and full-space farms are completed.



**Figure 13.** 5G ecological unmanned farm in Zhutai Town, Shandong Province. Copyright source: own work.

In 2020, South China Agricultural University carried out an unmanned farm promotion demonstration. In early May, the unmanned rotary-tillage machine completed land cultivation, and the unmanned rice direct-sowing machine completed rice direct seeding. In the following months, the unmanned highland gap sprayer was used to spray pesticides on rice, and the drones carried out necessary field management operations such as pesticide spraying and variable fertilization. At the end of August, the harvester and the unmanned grain truck cooperated to complete the harvest operation. The intelligent unmanned farm relied on biotechnology, intelligent agricultural machinery, and information technology to enable the unmanned farm to achieve full coverage of the cultivation, management, and harvesting production links, and accurate operations such as full automatic and automatic obstacle avoidance of agricultural machinery-transfer operations, real-time monitoring of the crop-production process, and unmanned intelligent decision making throughout the process, etc., to achieve a safe, reliable, environmentally friendly, and energy-saving farm operation mode, actively promoting the development of China's smart agriculture.

At present, as a key network support in Chinese 'new infrastructure' plan, 5G mobile communication technology can better serve the development of agriculture. Target and environmental identification (crop monitoring on farms, forest resources in forest farms, monitoring of pests and diseases, etc.) and information collection and services (agricultural production management, water quality monitoring) are the main applications of 5G in agriculture. The 5G Smart Farm in Wuzhen International Interconnection Agriculture Expo Park in Zhejiang Province, China is exploring the application of new technologies such as 5G automatic picking and 5G RS UAV platforms. In Chongqing, the first UAV based on



the 5G network has been put into use, with an operating efficiency of 20.00~26.67 hm<sup>2</sup>/d, which is 20 times that of manual operation [69].

5G technology can realize real-time interconnection and extremely low latency of IoT equipment in the farmland. By deploying various sensors in the field, crop-related, soil, environmental, disease, and pest data are collected and transmitted to the data center for analysis and establishment of the crop-data model. The technical experts can guide the daily management of farmers remotely through the decision-making system. China–Poland telecommunications cooperation has a history of 16 years, and China’s 5G technology field has obvious advantages in product quality, service efficiency, and price [16].

#### 4.1.3. Developing Poland’s 5G Unmanned Intelligent Organic Farms

The Polish government provides complete infrastructure for rural areas, and farmers enjoy better social and public services. Only with good farmland infrastructure such as water networks, road networks, power grids, and communication signals, can we develop and promote unmanned farms on a large scale. Therefore, Poland can learn from the development model of China’s 5G unmanned farms and combine China’s unmanned smart farms with its own organic farms to develop 5G unmanned intelligent organic farms, as shown in Figure 14. Small-scale family farms should be effectively integrated and managed to reduce agricultural labor costs, improve agricultural management efficiency, and improve the yield and quality of agricultural products. As the two countries have a broad space for cooperation in unmanned agriculture and precision unmanned operations, China and Poland should strengthen scientific and technological cooperation in smart agriculture, and jointly grasp the huge development opportunities brought by Agriculture 4.0 represented by agricultural informatization; this will have a positive impact on the agricultural models of both countries and bring breakthrough changes in economic development and daily life.



**Figure 14.** Unmanned 5G harvesters operate on the Wanhe organic farm in Chongming District, Shanghai, China [70]. Copyright source: reproduced from (<http://www.medianet.com.au/releases/181655>(accessed on 19 November 2019)), with permission from Xinhua-Asia Net. 2019.

#### 4.2. Spraying of PPPs

Poland's PPPs are mainly imported, the sales of which calculated by product weight were 65,300 tons in 2018. However, only 17,000 tons came from domestic production. 67.6% of domestically produced PPPs are herbicides; the remaining 24.1% are fungicides, 4.8% are insecticides and acaricides, and 3.5% are production regulators. At the same time, the PPPs imported from abroad are mainly herbicides (54.1%). The remaining imported products accounted for fungicides (32.3%), insecticides (9.5%), and growth regulators (4.1%) [14]. In 2019, the overall sales of PPPs were still large, but they were down by about 8.5% compared to the previous year. For example, herbicides decreased by 16.6% during the year, while sales of fungicides increased by 13.3%. The weather in Poland in March 2019 is conducive to improving field drought and soil temperature, and is also conducive to winter crops and green vegetation of permanent grassland. Therefore, mineral fertilizers and herbicides were used earlier than in 2018.

##### 4.2.1. Herbicides

Weeds will not only fight for water, sunlight, and nutrients with crops, but also form biological competition with crops, and even spread pests and diseases that affect the final crop quality and yield, causing huge economic losses every year. As of 2018, there have been 22 cases of resistant weed species reported in Poland. The current mainstream weeding method is chemical weeding, which means spraying herbicides indiscriminately on fields. Although the weeding effect is more significant, it also brings many problems, such as obvious waste, serious pesticide residues, damage to the ecological environment, higher weed resistance, applicator health threats, and high labor intensity. At the same time, the physical characteristics of weeds and crops are very close, so it is increasingly important to accurately identify weeds in crop fields and perform precise weeding. The spraying mode of the herbicide is an important factor affecting the weeding effect. Compared with traditional methods, agricultural UAV has the characteristics of high efficiency, low cost and low environmental pollution for the prevention and control of farmland diseases, pests, and weeds, which is particularly suitable for the prevention and control of outbreaks, epidemics, and regional diseases, pests, and weeds. Therefore, in recent years, many scholars have carried out related research work on herbicide-spraying methods of different crops.

Rapeseed is an important economic crop in China and Poland. Poland grows winter rapeseed, and it consumed 1.739 kg of active substances per hectare in 2018, of which herbicides accounted for 53%, with an average consumption of 0.922 kg. In the actual process of rapeseed production and planting, it is inevitable that weeds with different growth scales will grow together with rapeseed, which will affect the quality and yield of rapeseed.

Accurate and automatic identification of rapeseed fields is of great significance for guiding precise spraying and weeding. Wang et al. [71] took rapeseed named Zheshuang 758 and four common weeds in rapeseed fields as research objects, and used RGB SLR cameras and ADC multispectral cameras mounted on simulated drone platforms to obtain low-altitude RS images of rapeseed and weed canopies, then studied the influence of different motion speed and shooting height on the performance of the analytical model. The accuracy test showed that the prediction accuracy of the classification model based on full-band and characteristic-band reflectivity was 100%. With the extension of the timeline, the classification accuracy of rapeseed and weeds decreased first and then increased. For the rapid detection of pesticide-spraying effects and utilization, Ju et al. [72] calculated the number of *Miscanthus* pixels before and after spraying glyphosate to evaluate the weeding effect of drone spraying. The results showed that there was no significant difference between the weed control rate in the drifting area and the uniform spraying area, but the drift phenomenon will cause the waste of pesticides and may also cause uneven spraying in some areas. To avoid this problem, it is necessary to use UAVs to spray pesticides under low-wind conditions or implement targeted remedial measures after drone RS aerial mapping. The difference between the normalized over-red and over-green vegetation index

(EXG-EXR) can be used to effectively detect the weeding effect of spraying. This method can provide technical support for improving the herbicide-spraying effects in farmland.

There are many types of weeds in farmland, and the herbicide-spraying effects on different crops by agricultural UAVs still require a large number of experiments for comparison and verification. Precise weeding is closely related to the accuracy of weed identification. As a platform, UAV provides the user with the ability to collect the needed images at any time along with the ability to cover the agriculture fields faster than the terrestrial platform [73]. Therefore, such UAV-imagery systems are capable to fit the gap between aerial and terrestrial RS and showed great potential in the weed management and weed detection steps. Agricultural UAVs have been used to collect imagery for crop and pest monitoring. Joseph E Hunter et al. [74] found that the UAV-integrated system (UAV-IS) was 0.3- to 3-fold more efficient than ground-based broadcast applications at identifying and treating target weedy areas, while minimizing treatment on non-weedy areas. The UAV-IS can be used for the detection and mapping of weed escaping to direct UAV sprayers, to control them before seed production occurs to eliminate any potential herbicide-resistant individuals. Huang et al. [75] hold that UAV RS offers an efficient and effective platform to monitor weeds for its high spatial resolution and proposed a semantic labeling approach for accurate weed mapping of high-resolution UAV imagery, which can provide decision-support information for herbicide treatment. Meanwhile, the agricultural UAVs can also provide technical support in the evaluation of herbicide efficacy quality, which makes the calculation of the weeding rate more accurate.

#### 4.2.2. Fungicides

Wheat powdery mildew caused by the biotrophic fungi *Blumeria graminis* (DC) Speer f. sp. *tritici* Emend. E.J. Marshcl, is one of the most important wheat diseases worldwide. Particularly during the wheat-heading stage, ground machines can be hardly used effectively, or the crop will be seriously damaged because of machine rolling. Qin et al. [76] studied the impact of UAV (UAV N-3)-spraying parameters (different working height and spraying concentrations) on the deposition of droplets on the wheat canopy and the prevention of powdery mildew, and figured that when UAV spraying was chosen to prevent wheat powdery mildew under a serious disease situation, an auxiliary agent for spraying could be added to prolong the retention of pesticide on the plant surface to extend the pesticide effect. Kong et al. [77] selected DJI agricultural UAV MG-1S and the knapsack electric sprayer to spray propiconazole and kresoxim-methyl, using Allure Red as the spray tracer, and studied the droplet-deposition distribution under two different spray conditions, and investigated and calculated the effect of its control on wheat powdery mildew. The concentration of the spraying liquid of the electric sprayer was 0.17 g/L. The laboratory test shows that the spraying of propiconazole and kresoxim-methyl only needs 100~150 cm<sup>2</sup> droplets to achieve a 90% control effect. Although the control effect of the electric sprayer is better than that of MG-1S after seven days of application, the droplets density on the wheat flag leaf and the inverted two leaves is more than 200 cm<sup>2</sup>, and the droplets almost completely cover the entire leaf, which not only wastes water resources, but also consume too much pesticide and polluted the environment. The field experiment showed that the droplet density of the flag leaf and inverted two leaf was only 29.7 cm<sup>2</sup> and 9.5 cm<sup>2</sup>, but the control effect on wheat powdery mildew could reach 85%~90% after seven days, which proved the feasibility of UAVs' spray method with high concentration and low volume. Wheat is the main grain in Poland, and the use of the downforce wind field in agricultural UAV is helpful for pesticide penetration, covering the front and back of crop leaves and roots, and effectively improving the pesticide utilization rate [78].

#### 4.3. Application of Typical Crops

##### 4.3.1. Apple

Poland has a wide variety of two-color apples which are well-known at home and abroad. Poland is one of the largest apple producers and exporters in the world, and

apple production accounts for about 78.3% of Poland's total fruits [9,14]. It is completely different from China's storage and preservation. Polish apples use a full cold-chain storage facility. The sorting, storage, transportation, and packaging are strictly controlled by professionals, which can ensure the full tracking of the fruit from harvest to packaging and retail. All packaging is made of environmentally friendly materials, which is conducive to the breathing of the apple without losing moisture.

In 2019, Poland's apple output ranked second in the world (behind China), about 3.08 million tons, a decrease of about 23% compared to 2018. The main reason is that spring frost has a greater impact on fruit trees during flowering and fruit setting, and hail occurs occasionally in summer. The lack of water in the soil has caused serious reductions in fruit tree production. In 2018, the PPPs used per hectare of apple trees reached 10.464 kg, of which fungicides accounted for 94.6%, herbicides and insecticides accounted for only 2.9% and 2.4%, respectively [14]. The tree shape is mainly high-spindle, and it is cultivated on a standing frame. M9 is currently the most widely used apple rootstock in Poland, accounting for about 45% of the current total seedling cultivation. It is commonly used in densely planted orchards. Only for orchards with poor soil or short-branched varieties, semi-dwarf rootstocks are used, such as M26, M7, MM106, and P14, P16, and P60 independently cultivated in Poland. According to the cost analysis under different yields of Polish apples, taking high-yield apples as an example (50 t/hm<sup>2</sup>), pest control, fertilizer input, and mechanical input account for about 38.51% of the total economic cost [79].

Chinese apple orchards are still dominated by vigorous rootstock apple trees. The apple trees are huge, and the spacing between rows is small, which is not convenient for manual and large-scale spraying machinery. The plant-protection UAV can be operated remotely to carry out pesticide spraying above the orchard, without being affected by the gap between the trees. It can achieve uniform, reasonable, and safe spraying, avoiding waste of chemicals. Wang et al. [80] from the IPP of CAAS explored the pesticide utilization rate and the control effect on apple aphids by spraying 40% chlorpyrifos EC with different spray methods during the fruit expansion period. The results showed that the pesticide utilization rate of the five sprayers (UAV, knapsack electric sprayers, knapsack spray dusters, stretcher sprayers, and farmer's self-made traction power sprayers) were 67.9%, 54.7%, 58.3%, 58.3%, and 55.4%, respectively. The pesticide-utilization rate of UAV was significantly higher than that of other sprayers. Seven days after application, the control effects on apple aphids were 62.5%, 72.5%, 68.0%, 87.7%, and 87.1%, and the difference was not significant at the 5% significance level.

Qiao et al. of Northwest A&F University [81] used DJI MG-1P to spray pesticides in the apple orchard and obtained the relevant best technical solution. When spraying pesticide directly at a height of 1.5 m from the top of the tree at a flying speed of 2 m/s, the droplet density is high, the leaf surface has a large amount of pesticide, and the comprehensive control effect is good, which is most economical and effective. At the same time, it was found that the concentration of UAV spraying agent was 15 times that of the manual spraying agent, and the concentration had no significant effect on the apple tree and fruit. UAVs can save 20 times the time compared to manual spraying. The water consumption of manual spraying is 40 times that of UAVs. The cost of UAVs and manual spraying is the same. As shown in Figure 15, Bian et al. [82] conducted spray performance-comparison tests on a single-rotor oil-powered UAV and a round orchard wind-driven sprayer in the hilly mountain orchard. The results showed that the droplets of UAV displayed better on the upper and middle layers of apple trees than the sprayer, but the sprayer was better on the middle and lower layers. The UAV was also better in working efficiency, water saving, and medicine saving.





**Figure 15.** Agricultural spraying machinery working in the orchard. (a) Single-rotor oil-powered UAV; (b) round orchard wind-driven sprayer [82]. Copyright source: reproduced from [A comparative study on the performance of single-rotor oil-propelled UAV and circular air-fed orchard sprayer], with permission from Yongliang Bian, 2021.

Sun et al. [83] from Nanjing Agricultural University took modern standardized apple orchards as the research object and proposed a row and column-detection method based on grayscale projection in orchard index images (RCGP) method. The image of the tree canopy in the apple orchard was collected by the imaging system on the quadrotor UAV, and the 3D point cloud model and vegetation index image of the orchard were generated by the Pix4Dmapper software. When the ground sampling distance was 2.13–6.69 cm/px, the accuracy of row detection in the orchard using the RCGP method was 100.00%. With RCGP, the average accuracy of column detection based on grayscale images of the normalized green index was 98.71–100.00%. These results show that the UAV-based canopy information measurement method in apple orchards can be applied to the remote evaluation of canopy 3D morphological information and it is valuable for the production management of modern standardized orchards. Piotr Boniecki et al., from Poznan University of Life Sciences [84] used MLP, RBF, and DNN neural models to classify and recognize five specific apple tree pests through seven variables containing the characteristic color information of relevant pests. The model can support the computer expert decision-making system for the identification and protection of pests in apple production, especially in apple orchard.

It is a potential application for plant-protection UAVs to spray apple-sunburn protectors, which can reduce fruit loss caused by warm summer weather. UAV systems can also be suitable for implementing crop-management tools at specific locations, especially where ground sensors or scouts are used to identify problematic areas within a larger area, and then spray chemicals at specific locations. Such applications can reduce production costs (chemicals, fuels) and promote ecosystem management [85].

At present, some apple orchards have used plant-protection UAVs to directly carry out protection operations on fruit trees, such as prevention and control of plant diseases and pests, pest identification, yield forecasting, and spraying apple sunburn protectors. At the same time, plant-protection UAVs can effectively improve the utilization rate of pesticides and spraying efficiency, and greatly reduce labor cost, which has important practical significance for reducing the labor cost of apple planting in Poland, improving disease and insect control, and converting the surplus labor cost into machinery input.

#### 4.3.2. Cherry

At present, cherries are the second most-produced fruit in Poland. Polish cherries' commercial cultivation began in the 1830s to 1840s, and modern cultivation of intensive dwarfing began in the 1890s. With the collapse of the Soviet Union, Poland began to attach importance to the development of the sweet cherry industry. The facility of cultivation of sweet cherries adopts the German Voen covering system, which can prevent frost, hail, bird, rain, wind, and insects. The harvesting machinery is the Continuous Tunnel Covering Harvester. During harvesting, it covers all the trees and operates continuously. The average harvest weight of each harvester was 2770–3430 kg per hour. The harvesting efficiency was 93.9–95.9%, the rate of fruit leakage was 1.0–2.1%, and the rate of fruit landing loss was 3.1–4.0%. Poland and other European agriculturally advanced countries have successfully developed and applied technical systems for cherry trees, such as mechanized harvesting, mechanized spraying, quantitative irrigation, water-collecting irrigation, and integrated irrigation with water and fertilizers [86].

According to statistics from the Polish National Bureau of Statistics, the Polish cherry harvest in 2019 was about 44,400 tons, which was nearly 26% lower than the output in 2018. This was mainly due to great losses caused by spring frost, insufficient soil moisture, and high temperature in summer. According to the survey on the consumption of cherries by the Polish horticulture industry in 2018, cherries consume 5.602 kg of active substances per hectare, an increase of 5.6% compared to 2017, of which 94% are fungicides and 5.2% are herbicides [14].

China mainly grows sweet cherries. In 2018, the national cultivation area reached 200,000 hm<sup>2</sup>, making China the largest cherry-cultivation area in the world [87]. However, the application technology and management level of different fields lead to huge differences in yield. China has applied plant-protection UAV in cherry orchards. Chengcheng County (Shanxi Province, China), which is famous for sweet cherries, has used plant-protection UAVs for flight-spraying control since 2015, and began spraying on cherry trees in 2018. Since cherries need to be sprayed with pesticides to prevent and control various diseases and pests during the whole growing period, remote-control operation can prevent spraying operators from being exposed to pesticides. The downward airflow generated by the rotors can help increase the penetration of the mist to the crops. It can not only save the use of pesticides and water, but also reduce the pollution of pesticides to the environment as well as the secondary harm of operators.

In the demonstration of flight prevention spraying for cherry trees in Chengcheng County in 2019, DJI Spirit 4 RTK was used to survey a 50-acre orchard, the orchard was mapped and processed through DJI Maps, and then the data was imported into eight plant-protection UAVs (DJI T16). As shown in Figure 16a, T16s read the 3D route, completed the recognition of the operation scene, and performed autonomous flight and coordinated spraying. By using the fruit-tree mode to plan the cherry flight spraying program, the whole operation process took about 8 min from mapping to spraying.



**Figure 16.** Operating status of different UAVs over cherry trees. (a) Agricultural UAVs perform autonomous flight and coordinated spraying on cherries [88]; (b) Test cherry trees are trained to Y-trellised canopy architecture. During field trials, the unmanned middle-size helicopter flies above the canopy at different altitudes and speeds [89]. Copyright source: (a) reproduced from (<http://www.chengcheng.gov.cn/ccdt/dzdt/38397.htm> (accessed on 20 May 2019)), with permission from Chengcheng Country People's Government, 2019. (b) reproduced from [Efficacy of unmanned mid-sized helicopter in rainwater removal from cherry canopies], with permission from Elsevier, 2021.

In addition to spraying, plant-protection UAVs have the potential to be used for loss management. In sweet cherry orchards, summer rain will cause the fruit to crack, and the crack will cause the fruit to rot prematurely. Traditional helicopter precipitation to remove rainwater from the surface and canopy of cherries is expensive and dangerous. As an alternative, Jian et al. [89] used the Yamaha MAX plant-protection UAV hovering over the Y-shaped cherry tree to make the rotor wind field effectively wash the rainwater onto the fruit surface, which is shown in Figure 16b. When the UAV is fully loaded, flying at a speed of 2.7 m/s and a height of 6.1m from the ground, it can effectively remove 88–96% of the rainwater. During the flight, the wind field of the UAV will disturb the warm air in the upper and the cold air on the ground, reducing the effect of frost on the temperature of fruit buds or flowers.

With the growth of the Chinese–Polish cherry industry, both countries can conduct continuous and in-depth exchanges on cherry planting, management, and harvesting. Using advanced technologies, such as UAV spraying and RS, to explore the correlation among growth, yield, quality of cherry, and the best regulation mode, will effectively improve the overall planting level of cherries in two countries.

#### 4.3.3. Corn

Corn is an important food and feed crop. Poland's corn acreage decreased by 3.1% in 2019, but the purchase volume remained the same as in 2018. In China, chemical control is still the main means for preventing and controlling weeds in large-scale corn fields, but the traditional manual knapsack spraying and walking mechanical spraying are relatively backward, so China begins to use agricultural drones to spray herbicides on corn fields; as shown in Figure 17, it is time-saving, labor-saving, and pesticide-saving. In eastern Gansu province, Yue [90] et al. used 40% B-atrrium SE as an indicator herbicide to determine the reduction effect of agricultural UAV spraying on corn-field soil. The results showed that when the applied amount of UAV was reduced to 2400 mL/hm<sup>2</sup>, which is 46.47% less than the recommended dosage (4500 mL/hm<sup>2</sup>), the control effects on *Chenopodium album* L., *Setaria viridis* (L.) Beauv. and other weeds were still as high as 93.31%, 65.51%, and 86.40%, respectively. Additionally, the control effect of fresh weight was up to 99.12%, 78.61%, and 93.44%, respectively. The impact on corn ear traits, yield, and net income was



also reduced to a lower or lowest level. Compared with artificial weeding and knapsack sprayer, the yield of UAV weeding was reduced by 0.17% and increased by 5.61%, and the net income was 652.08 CNY/hm<sup>2</sup> and 1076.85 CNY/hm<sup>2</sup> higher than that of above two methods. The modern agriculture demonstration project of Heilongjiang Academy of Agricultural Sciences, “Demonstration of High-efficient Green Plant Protection and Prevention Technology in Corn Field”, achieved a yield increase of 11.7% and reduced fertilizer by 21% through precise variable fertilization technology. At present, weeds in the field can be well-controlled only by spraying once, which can save 30–50% of herbicide use.



**Figure 17.** Agricultural drone sprays herbicides on corn fields. Copyright source: own work.

Drones also can be used in the biological control of corn fields. Malgorzata Bzowska-Bakalarz et al. [91] from the University of Life Sciences in Lublin used gyroplane for the application of *Trichogramma* spp. against the European corn borer. A 6-year experiment was conducted on a maize monoculture located in south-western Poland. The results indicate that the low-height aerial application allows precise dosing and satisfactory distribution of the biopesticide. The efficacy of 60–85% (depending on the year) of the gyroplane-based spraying operations was comparable with that observed for ground application. Considering the speed and high efficiency of the treatment, using a gyroplane as a carrier of the biopesticide application system is a good alternative to the other methods. At present, many Chinese enterprises have developed plant-protection drones that can put *Trichogramma* to control corn borers (as shown in Figure 18), and demonstrated them in many counties in China, reducing the use of pesticides and planting costs, and increasing corn quality. In addition, plant-protection drones can also be used to carry out corn aphids (mainly tassel aphids), corn-leaf diseases (rust, *Curvularia lunata* Boedijn, corn southern leaf blight, *Cercospora sojina*, and corn spot, etc.) and other pests and diseases, and regulate the growth of corn.





**Figure 18.** Agricultural drone drops the *Trichogramma* capsule. Copyright source: own work.

## 5. Enlightenment for Poland

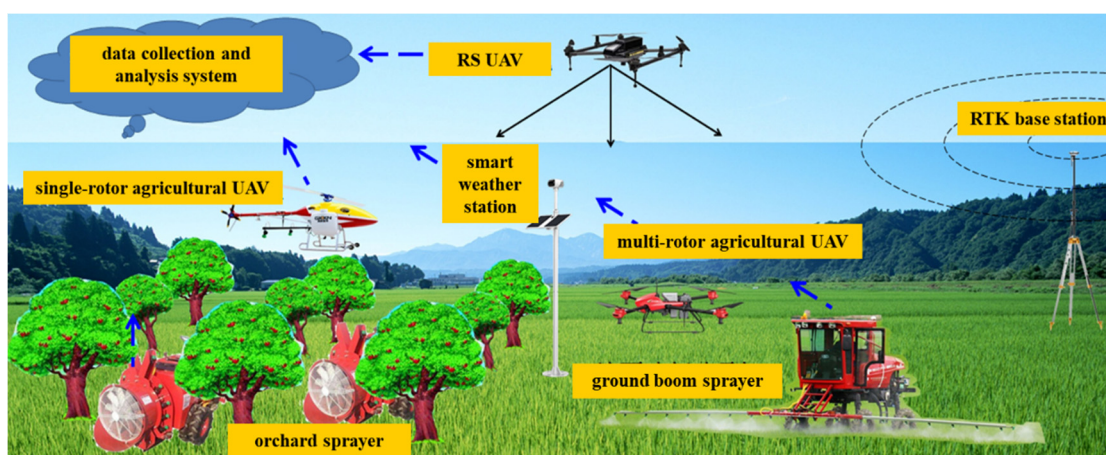
### 5.1. Building RS-Aviation-Ground Spraying System

Since the 1950s, the development of agricultural production and food economy in Poland has been inextricably linked to the use of PPPs. Poland has an official quality control system of PPPs and extensive experience of the control and assessment in counterfeit and other illegal pesticides [92]. The objectives set out in the National Action Plan are oriented towards reducing the risk associated with the use of PPPs and their rational and sustainable use, which should not be equated with quantitative reduction in the use of such products. In Poland, aerial spraying is carried out exclusively over forests, which occupy 29.4% of the country's territory and overgrow an area of 9.1 million ha. Such treatments are mainly applied to control *Lymantria monacha*, *Dendrolimus pini*, *Panolis flammea*, *Acantholyda posticalis*, *Diptirion* sp., *Melolontha* sp., *Tortricidae*, and *Geometridae* [93]. Poland can use UAVs to build an RS-aviation-ground spraying system to detect crop-growth status and estimate yield, identify forest pests and disease data through aerial RS, establish forest health models, and generate spraying prescription maps to realize forest pesticide variable spraying and forest refinement management.

The RS-aviation-ground spraying system, among them, RS, namely space RS observation, has the characteristics of large-scale and space continuity, and is composed of space, hyperspectral, microwave, laser radar, and so on. Aviation, namely aerial RS observation, characterized by high precision and temporal continuity, is composed of optics, multispectral, thermal infrared, and laser. Ground, i.e., terrestrial IoT observation, with high frequency and real-time observation characteristics, is composed of environmental and crop sensors, video, and farmers' perception [94]. Through the integration of RS-aviation-ground information acquisition technology and equipment, the perception can be realized, including farmland big data (multidimensional information), physical information (location, form, and area), ecological environment, planting type, input and output, and farmers' main attributes. Diagnosis includes temporal and spatial dynamic monitoring, diagnosis, analysis, and prediction; and decision making, namely precise planting and intelligent management.

The system diagram is shown schematically in Figure 19. In actual production, the smart weather station can detect real-time meteorological conditions and relevant param-

eters of the growth environment, and determine whether it is suitable for agricultural machinery operations. RS UAV collect hyperspectral and multispectral images to obtain crop-growth status in target areas, detect pests and diseases, and estimate yields. The data-collection and analysis system has been integrated into IoT, big data, cloud computing, and other emerging technologies. After processing the meteorological information and RS information, the system can generate the crop health-status model and the field-operation prescription map. After receiving the prescription map, the agricultural machines, such as single-rotor UAV, multi-rotor UAV, ground boom sprayer, and orchard sprayer, can communicate with the RTK base station through the RTK module on board, so they can obtain accurate positioning information to carry out variable spraying along the preset route, which is a good manner to realize the refined management of the field.



**Figure 19.** RS-aviation-ground spraying system in farm. Copyright source: own work.

At present, China has built a national public service platform for agricultural IoT, with nearly 50,000 IoT monitoring points. In October 2020, during the exhibition of ‘Human-machine intelligent collaboration technology for large-scale vegetable production’ held by the MOARA, technicians only needed to take out their mobile phones to give instructions to arrange unmanned harvesting operations of open-field cabbage, which involved intelligent unmanned agricultural machinery and unmanned operation image data in key links, such as open-field cabbage plowing, preparation, ridging, transplanting, water and fertilizer irrigation, plant protection, and harvesting [95]. This technology was aimed at the intelligent management and operation needs of tillage, seeding, transplanting, plant protection, irrigation, fertilization, and harvesting of large-scale vegetable production, and it built a 3D RS-aviation-ground monitoring and sensing network with satellite, radar, UAV, and sensors. It also created a human-machine intelligent collaborative brain and develops an unmanned intelligent agricultural machinery operation cluster. Therefore, it can establish a human-machine intelligent collaborative solution for large-scale vegetable production. The solution can reduce the cost of artificial input by 55%; reduce the amount of water, fertilizer, and medicine application by 25.4%, 31.2%, and 70.5% on average; and save CNY 112 per mu for open-field vegetables and CNY 220 per mu for facility vegetables. China is actively promoting the development and application of agricultural big data, building agricultural RS observation constellations and ground application facilities. It can meet the needs of integrated development of RS-aviation-ground system in rural areas, and form agricultural RS observation capabilities for conventional monitoring and rapid response [96]. After the system establishment, the production diagnosis and operation-decision system for vegetables and orchards can be realized, and it can optimize the allocation of agricultural resources and achieve effective monitoring and early warning of forest pests and diseases, forest inspection, and other forestry law enforcement [97,98].

In the future, the development and application of RS-aviation-ground spraying systems in Poland can be focused on the following aspects: First, to accelerate the deep integration and application of the new generation of information technology with all aspects of agricultural production and management in Poland; Second, to promote the construction of agricultural big data, and explore the establishment of a data-collection system covering the whole industrial chain based on Poland's actual situation; Third, to encourage universities and enterprises to establish university–industry cooperation in science and technology, so as to continuously promote innovation and transformation in the future and lead the modernization of smart agriculture in Poland.

### 5.2. Building Domestic Aviation Industry and Service Team

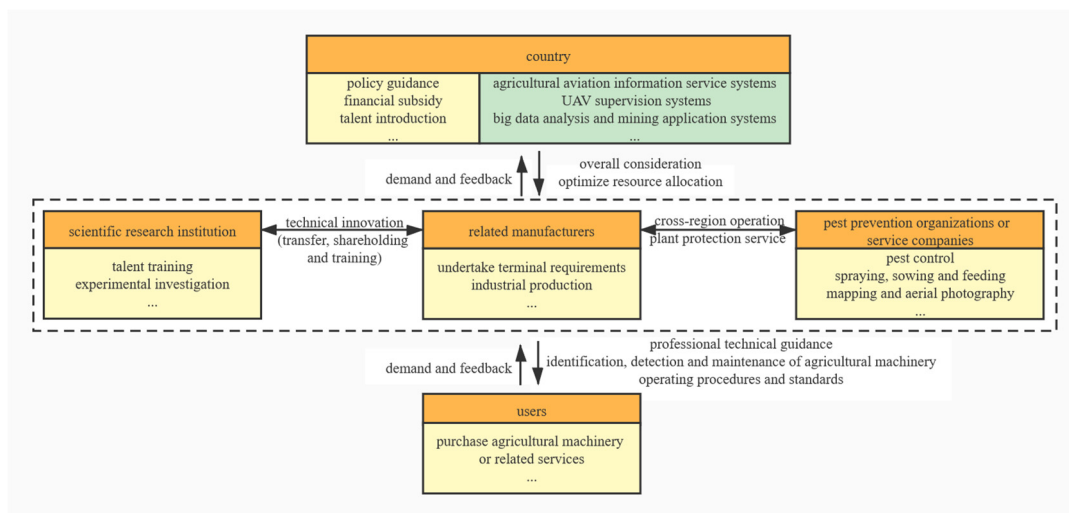
In recent years, China's agricultural aviation applications have developed rapidly, and corresponding agricultural aviation service information systems, supervision systems, big-data analysis and mining application systems have also been gradually established. Agricultural UAV enterprises directly undertake the terminal needs of farmers for plant-protection operations, and provide professional technical guidance and cross-regional operations, which can promote the development of China's aviation industry and service team to the greatest extent, in terms of big-data supervision and optimization, deployment management, operation quality and demand, operation process and standards, etc. For farmers, purchasing UAV technical services, such as seed sowing, pesticide spraying, aerial mapping, and agricultural UAV testing and maintenance, can save production costs, reduce the threshold for using advanced agricultural tools, and improve production efficiency.

With the rapid development of mobile smart terminals, user needs interact with technological development, and users put forward higher requirements for service flexibility and convenience. At present, the layout of China's agricultural aviation industry is to integrate the new generation of information technology, such as ways of thinking, design methods, and application into the 'Internet + agriculture' information service system, which can provide technical support for the sustainable development and service promotion of agricultural aviation-service platforms [99].

China Agricultural Aviation takes industrialized research and development of applied technology as the main line and takes the cooperative research, technology transfer, shareholding, and training with related enterprises as the entry point, to realize the operation mode of multiple input forms and cooperation forms between institutions of higher education or research institutions and enterprises. Based on this architecture, as shown in Figure 20, the platform developed using mobile Internet technology has good scalability and can provide continuous enrichment of value-added services through big-data analysis and mining, which can realize an effective virtuous cycle of agricultural aviation services.

In summary, the combination of agricultural aviation-technology development and service-industry development will help Poland build a new agricultural aviation production and management system, develop agricultural aviation precision-production methods and improve the level of efficient agricultural aviation services. The top-level design of the Polish precision agriculture aviation service platform can refer to China's existing development situation and proceed from the following four aspects: Firstly, Poland can build an agricultural UAV-manufacturing industry and plant-protection service system with Polish characteristics based on its national conditions and policies, and it can improve the competitiveness of related enterprises and user stickiness, and train compound agricultural science and technology talents to solve the problem of labor shortage in Poland. Secondly, through agricultural UAV-related skills training and equipment empowerment to drive the development of local agriculture and improve production efficiency in Poland, it will help solve the problem of a lack of agricultural background and professionalism among some agricultural workers, and increase the employment opportunities and income of agriculture-related personnel, with a view to creating new agricultural economic benefits for society [100]. Thirdly, it can develop a comprehensive platform for agricultural aviation technology and provide end-to-end diversified services. Through continuous optimization

of technology and services, it can further promote the maximum value of agricultural aviation technology in various agricultural and forestry applications [3,101,102]. Finally, it is necessary to build a set of ecosystem demonstration bases jointly built by multiple parties, including government regulators, inspection and quarantine departments, UAV manufacturers, plant-protection service providers, production cooperatives or large producers, scientific research institutes, etc., so as to realize resource sharing, technological empowerment, and industrial innovation.



**Figure 20.** Government-industry-college-institute-application cooperation in agricultural aviation. Copyright source: own work.

### 5.3. Technological Innovation and Application Expansion

Demand is the fundamental driving force for technological development and industrial upgrading. According to statistics, in 2020, the cumulative sales volume of plant protection UAV in China reached 60,000 units for the whole year, and the ownership is expected to reach 110,000 units. With the spraying area exceeding 66.67 million  $\text{hm}^2$ , plant-protection UAV has also developed from an early experimental product to a common agricultural production machine [103]. The overall technology of the UAV industry is developing rapidly, and the manufacturers launch new products every year, driving a rapid leap in plant-protection UAV application technology. The maximum daily operating efficiency of one UAV and one operator has reached 150  $\text{hm}^2$ . Service prices will also tend to be stable. In the early stage, although the efficiency of plant-protection UAV is much higher than that of manual operation, the market price is still benchmarked against manual and other simple instruments. As the efficiency of plant-protection UAV gradually increases, prices will continue to fall. This series of innovative changes in agricultural UAV has important implications for Poland in solving seasonal labor shortages, and it is conducive to the formation of a two-way push for agricultural technology innovation and the increase in production efficiency and benefits.

At present, China's agricultural-drone market demand is differentiated and products are diversified. Early plant-protection UAV models were mainly based on 10 KG load, such as DJI's MG series. With the development of the industry, the load of UAVs has increased year by year and it has developed to 30 kg, 40 kg, or even higher today, and the model design has also been constantly upgraded, as shown in Figure 21. The double-rotor structure greatly improves the penetration of pesticides compared with traditional drones. The increase in load capacity is conducive to the increase in spraying area, thereby ensuring spraying effectiveness. The planting characteristics in southern China are small plots of land and scattered planting, so large aircraft usually face problems such as transportation, take-off, and handling. Therefore, according to the actual operating scenario and consumer needs, various manufacturers have also formulated different types of agricultural UAV.



Small UAVs are mainly for scattered plots and self-use; medium-sized UAVs are more adaptable; while large-sized UAVs are mainly for sowing and fruit-tree spraying.



**Figure 21.** XAG's new agricultural UAV of 2021. (a) V40 with double-rotor [104]; (b) P80 with a load capacity of 40 kg [105]. Copyright source: reproduced from (<https://www.xa.com/v40-2021> (accessed on 20 January 2022), <https://www.xa.com/p80-2021> (accessed on 20 January 2022)), with permission from XAG, 2021.

The majority of Polish farms are UAA small farms, similar to the farmland characteristics in southern China, which are suitable for small UAVs, while large UAVs can meet the spraying needs of Polish forests. Poland can enter into partnerships with local technology enterprises and invest more in key links, such as key components, data transmission, obstacle avoidance, and integration of various application systems, so as to build a technical support system with Polish characteristics [106]. Taking advantage of Poland's industrial strengths and talent in the agricultural aircraft-manufacturing industry, Poland will vigorously promote the construction of Aviation Valley, encourage Polish enterprises to become the main part of innovation, and strive to form a Polish core technology and product system, especially in aircraft portability, operator training, and aftersales service to form a stable promotion and service system.

Plant-protection UAVs are multi-purpose. In addition to the spraying mode of operation, with the popularization of spreaders, seeding applications have become a major use of agricultural UAV. Application scenarios include rice-fertilizer spraying and seeding, rapeseed sowing, grassland-seed sowing, fish and shrimp pond-feed spreading, etc. Furthermore, UAV applications also include practical functions, such as mapping and aerial photography. Operators do not need to enter the farmland to formulate spraying routes, which significantly improves planning efficiency. Aerial photography by multispectral UAV can monitor farmland and crop conditions in real time, facilitating farmers to monitor plot flatness, crop-growth monitoring, and crop-nutrient analysis. As shown in Figure 22, it is worth mentioning that during the 2020 outbreak of COVID-19, plant-protection UAV has been transformed to carry out antiepidemic prevention operations safely in many countries, such as China, Spain, Chile, Colombia, Indonesia, and Dubai. Compared to traditional disinfection methods, UAV disinfection allows for full coverage and 3D spraying, which can effectively save manpower and ensure the safety of disinfection personnel [107].



**Figure 22.** Agricultural UAV assisting in street antiepidemic prevention in Dubai [107]. Copyright source: reproduced from (<https://uav.huanqiu.com/article/3xee3AoPyv8> (accessed on 1 April 2020)), with permission from Global Times. 2020.

## 6. Prospect

Due to the current labor drain and the need for intelligent agricultural production in China and Poland, the use of agricultural UAV is expected to further unlock production potential. At this stage, there is huge market space for unmanned agricultural production in China and Poland. Poland should firmly grasp the opportunity of the “Belt and Road Initiative” to develop its own agricultural aviation industry as the following points.

Firstly, Poland can fully refer to China’s current mature application, such as agricultural UAV production and operation model, test data, service system, and promotion, and establish a highly adaptable and targeted agricultural UAV R&D, application, and promotion system on the premise of combining Poland’s own characteristics. Agricultural UAVs can be first promoted in the loss management and special protection of the Polish fruit industry, such as spraying sunburn protectors, removing rainwater on the fruit surface, reducing the temperature effect of frost on the fruit buds or flowers, and chemical control. After the initial effect of promotion, Poland can gradually build its own RS-aviation-ground spraying system for further application.

Secondly, Poland can fully take advantage of the successful foundation of more than 70 years of cooperation between China and Poland in business exchanges, technological collaborative R&D, policy exchanges, etc., and deepen the cooperation in the industry–university–research think tanks of agricultural UAVs, such as holding precision agricultural aviation technology international training workshops, and establishing transnational cooperation in universities, enterprises and experts, so as to form a situation of complementary talents and win-win cooperation.

Thirdly, the Polish government can continue to increase its support for the agricultural aviation industry in research investment, policy guidance, talent training, and technology development. More institutions, talents, funds, and technologies can enter Poland’s aviation industry by setting up special R&D funds and talent-introduction policies.

Finally, in future international cooperation, Poland can further strengthen agricultural machinery cooperation on the basis of original agricultural technology and agronomy, take advantage of Poland’s agricultural aviation industry to develop agricultural UAVs suitable for its own organic agriculture or small farms, and then develop its own 5G unmanned intelligent organic farms and build related service teams. Based on the use of agricultural

UAVs and unmanned vehicles in unmanned farms, combined with technologies such as IoT, big data, cloud computing, and artificial intelligence, a truly unmanned operation is formed to improve the efficiency and quality of agricultural production.

Poland should regard the research and development of agricultural unmanned equipment as an important measure to realize the technological upgrading of smart agriculture. It will enable Poland to realize the intelligent transformation of agriculture 4.0 in time, with a view to becoming a pioneer in the application of smart agriculture in the organic industry.

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