Chapter

Optimization of Application Technology for Plant Protection Products in Soybean Crops in Brazil

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Abstract

Soybean is the main commodity of Brazilian agribusiness, and the country stands out for the largest world production of this oilseed. The culture is carried out under two main forms of cultivation, conventional and in the form of no tillage. The possibility of two to three agricultural crops per year contributes to the emergence of various plant protection problems, including soybean rust, the stinkbug complex, defoliating caterpillars, nematodes, in addition to competition with weeds. Thus, the purpose of this chapter is to describe the main application techniques of chemical or biological products in the control of agents that are harmful to the soybean crop, as well as to bring technological innovations involving remote sensing, unmanned aerial vehicle, and other techniques of application in the control of these harmful agents to the crop. Also comment on the benefits of spray adjuvants and the limitations of tank-mixes with plant protection products intended for soybean cultivation.

Keywords: pesticide application methods, remote sensing, unmanned aerial vehicle, chemical and biological control, *Glycine max*

1. Introduction

Soybean [*G. max* (L.) Merrill] is one of the most important crops in the world, principally when it comes to oilseeds. The main product of this commodity after processing is the oil and soybean meal as a protein supplement. The world production of this crop in 2020/2021 season is about 366.23 million tons over 127.88 million ha resulting in a yield of 2.86 kg ha^{-1} [1].

The countries that lead as soybean producers are Brazil and the United States of America, which account for up to 69% of the total world production of the commodity, for both countries soybean is the most exported commodity. The amount (US$) exported of soybean considering the top 10 exporters in 2020 was 54.4 billion US dollars, most of the production going to China [2].

As the biggest producer of soya, Brazil had in the 2020/2021 season a crop production of 135.9 million tons over 38.5 million ha resulting in a productivity of 3.52 kg ha^{-1}. The productivity above the global average indicates high technification of this crop production. In relation to the previous crop season, Brazil has increased the production by 8.9% and productivity by 4.4%. The income to the Brazilian's commercial balance considering all the products from soybean was US$35.2 billion in 2020 [3].

In Brazil, the soybean production depends on biological nitrogen fixation, on the no-tilled area that represents more than 70% of the cultivated area, and on integrated pest management. However, the biggest challenge is the monitoring of crops due to the large extension of cultivated areas.

2. The plant protection problems in soybean crop

In soybean crop plant protection, problems begin at sowing, especially in areas of crop succession with insect pests in the cultural remains of the previous crop, such as stink bugs and pathogens in the soil whose main target is the seeds. Currently, in Brazil, seed treatment is over 95% of all soybeans planted in the country, carried out by manufacturers of plant protection products or companies specialized in this activity.

Initially, soybean seed treatment is aimed to control soil-dwelling fungi as a seed protection measure, but with little curative effect. In Brazil, currently, mixtures containing three or four different fungicides are available to the farmer for the treatment of seeds. The aim is to protect the seed and seedling in the early stages of development. For the control of insect pests that damage seeds for a long period, carbofuran was used, a very toxic product and sometimes toxic to seedlings. Currently, diamide-based products such as cyantraniliprole are used in seed treatment for the control of caterpillars and neonicotinoids such as imidacloprid and thiamethoxam for the control of sucking insects. More recently, chemical or biological products are available for the control of nematodes in seeds, such as abamectin and *Pasteuria nishizawae*, respectively. Other natural products have been associated with biological products for nematode control, such as root growth promoters associated with bacterial spores.

The treatment of the seed with nitrogen-fixing bacteria can be carried out together with the treatment with chemical products or later before sowing, directly in the seed or in the planting furrow. The seed protection period does not exceed 25 days, and depending on the occurrence of caterpillars and other insects in the area, it may be necessary to apply an insecticide to protect the seedlings, which can be associated with the application of non-selective herbicide for weeds control.

2.1 Pathogens

Plants in the initial growth stages can be attacked by soil-dwelling fungi of the *Pythium*, *Rhizoctonia,* and *Fusarium* genera, and depending on the inoculum potential of the fungus *Phakopsora pachyrhizi*, soybean rust disease can be the main plant protection problem of the crop. This fungus is an obligatory or biotrophic parasite as it only survives in living hosts. When environmental conditions are favorable for the development of the fungus, the rust disease is highly destructive and can reduce production by up to 90% [4–6]. It is difficult to control, due to its epidemiology, which starts in the lower parts of the canopy, thus making it difficult for spray droplets to penetrate the lower parts of the plant and to the rapid breakdown of resistance genes by some cultivars.

Disease control is essentially made by use of fungicides with a specific site of action and/or protectors with multiple sites of action. Due to the frequent use of fungicides in the crop, the pathogen's resistance to chemical molecules is of increasing concern. There are reports of selection of populations of *P. pachyrhizi* resistant to triazoles [7], strobilurins [8] and carboxamides [9], three site-specific chemical groups most used in this crop to control soybean rust disease.

In addition to chemical control with fungicides, methods such as sanitary vacuum are also adopted, which aim to reduce the inoculum of the fungus during the off-season due to the absence of a host, some tolerant cultivars, and crop rotation with grass instead of soybean, favoring the management of plants from the previous culture that spontaneously germinated in the area of the current culture (voluntary plant). The sanitary vacuum is a law of the Brazilian Ministry of Agriculture and defined as the period of at least 90 days without the culture and voluntary plants in the field. The purpose of the sanitary vacuum is to reduce the survival of the fungus that causes Asian rust during the off-season and thus delay the occurrence of the disease in the crop.

In addition to the traditional diseases at the beginning and full development of soybeans, a group of diseases is characterized by affecting soybeans mainly at the end of the crop development cycle. This group of diseases are called late season diseases (DFC). The main diseases and pathogens of this group are cercospora leaf blight (*Cercospora kikuchii),* brown spot (*Septoria glycines*), Anthracnose (*Colletotrichum* spp.), and Frogeye leaf spot (*Cercospora sojina*). Cercospora leaf blight and brown spot are commonly found at the same time on soybeans from the R6 development stage and can cause over 30% yield loss. Anthracnose can be found during all soybean cycles, but as a late season disease can be present on the soybean pods, causing them to fall, the soybean seeds can also be infected. Frogeye leaf spot can be observed on the leaves, soybean pods, and seeds [10].

2.2 Insects

After sowing, young forms of beetles, aphids, bugs, and caterpillars that cut the seedlings causing failures in the stand constitute the biggest problems for the establishment of the soybeans crop. Thus, chemical products based on diamides and neonicotinoids have been frequently used both in seed treatment and in spraying up to 30 days after crop emergence. In the initial stages of development, the stink bugs existing in the area may come from the previous culture that remained in the straw and are harmful to plants since the beginning of their development.

In the vegetative development stages, defoliating caterpillars and, depending on the growing region, whitefly can cause direct and indirect damage to the crop with the transmission of viruses. Diamide-based products can be interspersed with active ingredients from other chemical groups or biological products based on *Bacillus* sp. and *Baculovirus anticarsia* for the control of lepidopteran pests. Growth-regulating products, such as pyriproxyfen, have become an important tool in the management of whitefly in soybeans.

In the reproductive development stages, the stinkbug complex becomes the biggest problem, as in addition to causing direct damage to the grains, it can cause physiological disorders in the plant, such as leaf retention. Like defoliating caterpillars, bed bugs in the hottest hours of the day have the habit of staying closer to the ground, and in times with milder conditions, they become more exposed to spraying, which can make a difference for the control of these insects.

2.3 Weeds

Weed control depends on the management adopted in the area, especially in crop succession, and two herbicide applications may be necessary in the initial post emergence of the crop, spaced 15–20 days apart. On weed management in soybeans, there is an initial period that the presence of weeds does not affect soybean yield; this interval is between 11 and 24 days after plant emergence. This interval can vary depending on the cultivar, weed infestation, and weather conditions [11]. The advance of GMO technology in cultivars that are resistant to different types of herbicides (i.e., Roundup Ready® soybean and Intacta 2 Xtend® soybean) allowed the use of post-emergence herbicides. The use of herbicides is the most economical and used technique for weed control. However, the inadequate use of the herbicides can select resistant or less tolerant weeds. In soybean crops, 335 cases of resistance have been reported worldwide since 1996 regarding different modes of action. In Brazil, *Bidens pilosa, Euphorbia heterophylla, Bidens subalternans, Brachiaria plantaginea, Digitaria ciliaris, Eleusine indica, Lolium perenne ssp. multiflorum, Parthenium hysterophorus, Conyza bonariensis, Conyza canadensis, Digitaria insularis, Conyza sumatrensis, Ageratum conyzoides, Amaranthus retroflexus, Chloris elata, Amaranthus palmeri, Amaranthus hybridus, Echinochloa crus-galli var. crus-galli* already had confirmed cases of resistance [12]. With the emergence of transgenic soybeans in Brazil, resistance to glyphosate herbicide applications has increased dramatically. This promoted the selection of weeds resistant to the herbicide, making it difficult to manage and harvest the crop. *D. insularis*, *Conyza* sp., and *A. palmeri* are weeds that are difficult to control in soybeans.

Weeds resistant to the 5-enolpyruvylshikimate-3-phosphate synthase (EPSPs) enzyme inhibitor herbicide started to be controlled with acetolactate synthase (ALS) enzyme inhibitor herbicides and are currently resistant to these two chemical groups.

3. Application techniques of plant protection products on soybean crops

In no-tillage cultivation areas, the application of plant protection products begins with the desiccation of the crop that precedes the soybean crop. Self-propelled sprayers, tractor-pulled or mounted on the three points of the hydraulic system are quite common in soybeans.

In the more advanced vegetative growth stages and in the reproductive stages, the high leaf area index, in some cultivars, reaches its maximum at the R2 development stage, making it difficult to control pests and diseases by the leaves forming a barrier to the penetration of spray droplets inside the crop canopy. The use of air assistance and transfer of electrical charge to the droplets at the spray boom can contribute to the reduction of these harmful agents to culture.

The adoption of technologies in a combined way can allow greater penetration of the droplets inside the canopy of the culture, favoring the contract of the chemical or biological product with the target to be reached. During this period, depending on the climatic conditions in the field, the appearance of soybean rust is common and, in Brazil, the existence of cultivars with an indeterminate growth habit makes it difficult to place the product in the lower parts of the canopy.

In some countries due to the use of early cultivars with determinate growth habits and greater spacing between planting rows, single or double, it is common to use hose drops. The hose drops are pendulum artifacts in the spray boom, and commonly with two spray tips at the distal end of the structure, spraying laterally, and providing better distribution of fungicides in the lower portion of the canopy.

The applications of plant protection products with drones are complementary to those carried out with self-propelled and aircraft on borders or specific points, depending on the harmful agent to be controlled. In the Midwest, Northeast, and North regions of Brazil, the predominance of large properties and the short interval between applications favor the use of agricultural aircraft and self-propelled for plant protection treatments in soybean crops. In areas of crop succession, anticipating the harvest through desiccation with herbicides has been a common practice.

4. Advances in ground boom sprayers

In Brazil, sprayers coupled to the tractor's hydraulic system, dragging and self-propelled, are still the most used equipment in the protection of the soybean crop. Self-propelled equipment appeared in Brazil in 1987 [13] and is currently the most widespread equipment in large agricultural properties. In recent years, boom sprayers have increased boom sizes from 9 m to up to 58 m. On the national market, boom supports or parts of the boom support made of metal, aluminum, or carbon fiber are available, thus making the structure lighter. The boom supports started to be developed with coil spring and shock absorber and the frame for fixing the spray boom in the system in a pendulum or trapezoidal shape, providing greater stability to the boom and greater uniformity in the application of phytosanitary products.

With the increase in the size of the spray boom and in an attempt to improve the stability of the entire system, some sprayer manufacturers opted for placing the spray boom in the front or middle part of the self-propelled. The new system for spray boom opening and closing is no longer mechanical and has become electronic. However, the greatest difficulty is the opening of the crop canopy to allow greater penetration of spray droplets in the lower parts of the canopy, especially in cultivars with indeterminate growth habits.

Soybean rust, due to the epidemiology of the disease, starts in the lower parts of the canopy, and the placement of the chemical in this region of the crop canopy becomes essential to control the disease. Different devices were developed for canopy opening, such as hose systems dragged over the crop and roller boom attached to the spray boom "canopy opener" [14]. These devices can potentially spread the pathogen's inoculum faster in the growing area, in addition to causing the flower to fall in the crop's reproductive development stage. Although the use of air assistance at the spray boom appeared in the 1980 [15], only in 1996, in Germany, air-assisted sprayers were shown at the spray boom manufactured by the Hardi company [16].

In 1997, the biggest Brazilian manufacturer of sprayers started the production of sprayers mounted on the tractor's hydraulic system and pulled by an air-assisted tractor at the spray boom. Air assistance at the spray boom gives additional kinetic energy to those smaller droplets, making it possible to reach into the crop canopy by plant movement, provided there is sufficient leaf area index in the crop. The characterization and benefits of this technology associated with the spray boom are reported in research carried out by many researchers [17–23]. With the use of technology in different crops and plant protection problems, the limitation of the use of air assistance at the spray boom on bare soil or in crops at early stages of development was evident, as drift by air deflection through the soil can be incremented. Currently, for the acquisition of equipment with this technology, it is essential for the farmer to analyze the cost-benefit ratio, considering that the use of the technology is limited.

In recent decades, another technology that was definitely adopted in the spraying of agricultural crops with the possibility of reducing application rates, drift, and environmental impact was the transfer of electrical charge to the drops (by indirect induction). This technology is dependent on the load-mass ratio and the distance from the target for good functioning, when not associated with air assistance. However, using only the transfer of electrical charge to the droplets is not enough to improve the penetration of spray droplets inside the crop canopy. The attraction of droplets by the plants promotes better spray coverage only at the top of the crop. Thus, in 2019, at Show Rural in the city of Cascavel, PR, Brazil, the self-propelled device was shown with air assistance at the spray boom and transfer of electrical charge to the drops combined.

In China and the United States, other companies also develop sprayers with the combination of both technologies (air assistance combined with the transfer of electrical charge to the drops). The first self-propelled prototype with a combination of both technologies compared with air assistance and conventional spraying on spray deposits on soybean crop was evaluated by our team in the Midwest region of Brazil, and the results are reported in [23].

5. Spray adjuvants in soybean crop

Adjuvants can be defined by “a product added to the formulation or the spray application mixture that helps or modifies the pesticide action aiming to guarantee efficacy and safety of the application process.” The real role of the adjuvants in the spray process needs yet to be more discussed. However, the main characteristics of the adjuvants can be divided in modifiers of the compatibility, solubility, stability, foam formation and pH of the spray mix, reducer of drift and evaporation, also can interfere in the process of retention, adhesion, wetting, scattering, and mobility (absorption, penetration, and translocation) in the target (**Table 1**) [24].

A study [25] using different adjuvants mixed with the fungicide mancozeb conducted to evaluate the retention of the spray mix in soybean leaves showed that each adjuvant has a different interaction with the foliar surface. The adjuvants that promoted a greater retention, compared with the others tested, were a mineral oil and a polymer and the lower retention a surfactant. Also, this study concluded that the retention was associated with the surface tension of the spray mix, where both variables had a positive linear relationship, when both variables increase or decrease concurrently and at a constant rate.

Classification	Recommendation	Examples
Spreader	Increase leaf surface covered by spraying	Surfactants
Adhesives and penetrating agents	Increase penetration, absorption or adhesion of the	Mineral oils, vegetable oils, latex derivatives
Drift reducers	Decrease of very fine droplet size formation or increase the size of the droplet	Polymers, polysaccharides, oils, phospholipids

Table 1.
Classification, recommendation of use and examples of adjuvants used in soybean crops.

Another variable frequently added to the use of adjuvants is the reduction of the spray volume, a technique often used to increase the operational capacity of sprayers, which may impact on the leaf coverage. The leaf area covered can increase exponentially as droplet diameter increases. However, doubling droplet diameter requires an eightfold of spray volume. The use of a soybean methylated oil, nonylphenol ethoxylate blend, for example, can increase the average wetted area in plant surfaces from 0.055 mm^2 (water only) to 0.229 mm^2. The addition of the adjuvant results in 4.16 times reduction in spray volume with equal spray coverage [26].

The control of soybean rust, one of the most important diseases for soybean crop, showed greater dependence of the surfactant at low spray volumes applications, which provided increases in the leaf surface coverage [27]. A big concern regarding spray application, even more important for nonselective herbicides, is spray drift and volatility. A study conducted to evaluate dicamba volatilization and drift showed that the addition of adjuvants (lecithin + propionic acid, lecithin + soybean methylated ester + ethoxylated alcohol or soybean methylated oil) can decrease droplet size and increase driftable droplet percentage [28]. However, when also considering surface tension and contact angle results also measured, the dicamba-only treatment has low droplet spread potential, which may negatively affect herbicide efficacy. These results demonstrate that it is not adequate to consider only one variable, but the interaction among them when choosing an adjuvant to mix. Therefore, the choice of which adjuvant is best in each situation should take in consideration the whole scenario.

6. Application techniques of biological control agents

When it comes to biopesticides (i.e., natural organisms, including their genes or metabolites or substances derived from natural materials, for controlling pests), the application technique is one of the most challenging steps because originally the concepts involving spraying were designed to synthetic molecules and not live organisms such as the biocontrol agents. Therefore, the correct method of delivery is as crucial as it is for synthetic molecules for an optimal performance, once its control efficacy against many pathogens and pests has been already proven throughout many years of research, not only on soybean but many other crops. Therefore, the concepts of spray application technology must be improved or modified to attend to the needs of the biocontrol agent.

There are three major types of augmented biological control: classical, inoculative and inundative. In this section of the chapter, the application techniques are going to regard mostly the inundative method, which is the massive production and release of biocontrol agents or natural enemies to control the pest or pathogen quickly. In this method, no significant reproduction by the natural enemy is expected in order to control the pest population. The disease/pest control is only a result of the released individuals. This strategy can be compared with those used for synthetic chemical pesticides.

The first step when spraying biocontrol agents is to understand the life cycle of the pathogen/pest and its dynamic in the environment to decide which is the better application technique for that specific target and is crucial to understand if the methodology chosen is adequate for the biocontrol agent, beyond that, the knowledge of the biocontrol agent mode of action is also a factor that should be accounted for.

Among the application techniques, there are three that stand out for biopesticides: spraying over the crop, seed treatment, and in furrow application, where each of them has its particularities.

The spray application over the crop is recommended mostly for most of the bioinsecticides and the biofungicides recommended to control foliar diseases and white mold. As an example of the importance of understanding the biocontrol agent and its target, white mold (*Sclerotinia sclerotiorum*) a soilborne disease, the recommended technique is the spray application once the mode of action of the *Trichoderma sp.* a biocontrol agent recommended to control this plant disease, attacks the sclerotia, a survival structure of the fungus that stays above the soil surface. This technique's efficacy is very influenced by the application conditions, once the biocontrol agents are subject to the environmental conditions such as UV light, temperature, and relative humidity.

The seed treatment application recommendation for biocontrol agents follows almost the same principles of disease control as the synthetic fungicides. Biocontrol agents can be precoated or encapsulated onto the seed, the formulation of the biopesticide should guarantee a surviving period of desiccation. The seed encapsulation involves enveloping the seed, the biocontrol agent, and possibly other components such as pesticides or micronutrients, in a gelatinous or polymer gel matrix, promoting an enhancement of survival of the biocontrol agents on seed [29]. The products used in the seed treatment must be compatible with the biocontrol agent. Moreover, the seed has a maximum amount of product that can be added onto it, usually 10 mL per soybean seed.

In furrow application, targets are commonly nematodes and soilborne pathogens, this methodology applies the biocontrol agent during the soybean sowing directly on the seed. The seeder is adapted with a tank specific for this purpose, and in each row a solid stream nozzle is placed and the biopesticide is applied in a furrow. This technique when compared with seed treatment delivers the biopesticide in a more precise dose and at the correct moment.

7. Remote sensing on diseases and weed control in soybean

Remote sensing is the process to retrieve important information from an object without physical contact between the sensor and the target [30, 31]. Along with the global positioning system (GPS) and geographic information system (GIS), remote sensing is part of the precision farming techniques. Remote sensing works by capturing information from a specific area (data or imaging), while GPS is responsible for georeferencing it to locate field variables as precisely as possible, and GIS is used to interpret the data obtained to produce the final outcomes, such as application maps. Therefore, through the integration of these techniques, it is possible to obtain sufficient data to interpret and decide on the most appropriate management for a field [31, 32].

From an electromagnetic flux emitted in different wavebands, there is an interaction with the object that can be manifested in reflectance, transmittance, absorbance, fluorescence, and phosphorescence [33]. Sensors have the ability to detect differences in these values, generating indicative data regarding its physical characteristics [31, 32, 34]. These characteristics are used to identify morpho-physiological changes in plants or vegetation, such as the incidence of pathogens or insects [35] and to distinguish between plant species, biomass level, and soil, helping to identify weeds within the crop [36]. The processes of acquiring spectral data, data modeling, and detection model construction are usually extensive and require a great amount of time and research.

For pesticides technology application, remote sensing is a powerful tool for a specific branch of precision agriculture known as spot spraying or site-specific spraying [37]. Firstly, it is necessary to acquire spectral data in the field, which is usually conducted through a passive sensor that does not have its own source of energy, such as satellites and spectroradiometers, but instead is capable of retrieving information through spectral analysis (spectral signature) or imaging [31]. All information from a field is gathered with the geographical positions of certain points of interest and finally supplied to the spraying system to spray locally only where it is necessary. These places can be defined based on the incidence of disease, pests, or weeds in the field. One of the greatest benefits is the savings of product waste where application is not necessary, environmental preservation, and a more conscious application toward a sustainable agriculture [36]. The capacity of identifying diseases even prior to visual symptoms is also a great opportunity to improve control efficacy as well as the spraying technology [33].

Another example for fungicides and insecticides application is to use remote sensing to identify different biomass levels of the crop canopy during the application and using this information to adjust the water volume according to its foliage density [38]. In the study [38], a mechanical sensor was used in front of a sprayer to evaluate the crop canopy density and to vary the spraying volumes based on the canopy foliar density. This operation allowed them to reduce 13% of insecticide use, while maintaining pest control efficacy and improving natural enemies' preservation.

Nowadays, a more common monitoring by remote sensors is the one applied to herbicide treatments in preplant or over-the-top applications. An active sensor is placed at different sections of the sprayer boom and is capable of detecting weeds incidence as it moves through the field (real time monitoring), transmitting the information to a data center analyzer that uses it to make the application at the exact spot where the weed is located (**Figure 1**). These systems are equipped with dedicated valves at each spray nozzle in order to allow a unique nozzle control, such as actuated ball valves, solenoids, or PWM (pulse width modulation) valves.

Few innovations have been applied to these real-time sensors for herbicide management in soybean. At first, most of the systems were dependent on the weed detection in contrast to the soil (Green-on-Brown), therefore could only be applied to fallow lands [37]. Due to similarities in morphologies, physical characteristics, and

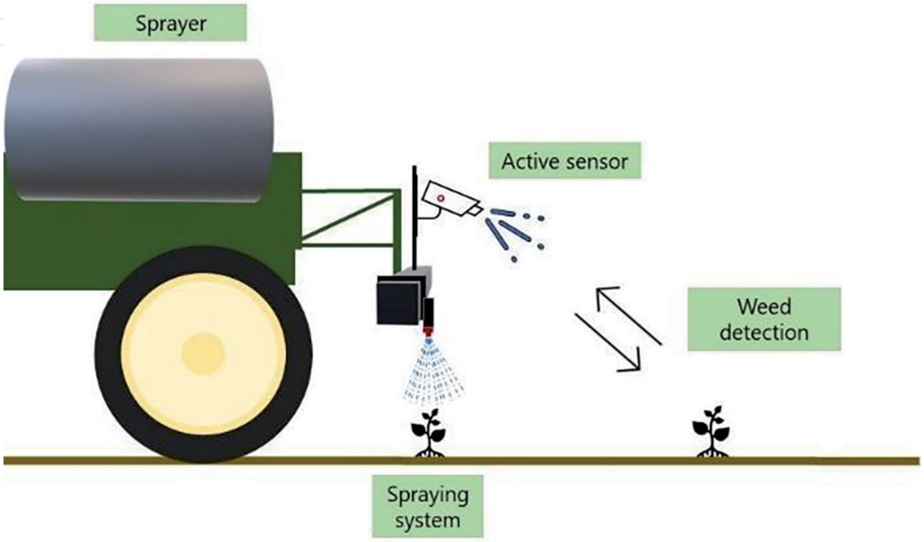

Figure 1.
Schematic demonstration of the real-time weed detection in the field by an active sensor, sending the signal to the spraying system that opens the spray nozzle right onto the weed.

colors, differentiation between plant species required advanced technology such as hyperspectral imaging sensors and deep learning algorithms [39]. This new system enables the differentiation of weeds from the main crop and is known as Green-on-Green technology.

Moreover, spot spraying application is promising to promote a proper pesticide resistance management of weeds and pathogens populations due to minimal exposure to the herbicides [40]. These technologies have potential to significantly improve spraying techniques toward a more sustainable application, acting heavily on chemicals waste reduction, resistance management, and a more precise application for a better control efficacy.

8. Tank mix of pesticides for soybean crop applications

Tank mixing seeks to improve spraying operational capacity and reduce application costs by associating different plant protection products, fertilizers, as well as other products in the spray tank moments before application [41]. This practice was regulated in Brazil only in 2018 (Normative Instruction N°. 40, October 11, 2018) [42], although it was widely performed a long time before this period, often with complex mixtures of products [43]. According to [43], 97% of applications in Brazil contained at least two products mixed in the spray tank.

Many applications of herbicides, insecticides, and fungicides in soybean crop are conducted at the same period, making it more convenient to combine the products in a single application. Therefore, it reduces the cost and time spent in operations, the movement of machines in the fields and, thereby, saves fuel, water and even reduces the number of machines needed [44]. Another great advantage of tank mixing different products is to help reduce pesticide resistance of pathogens and weeds. In Ref. [45], it is reported that applications of more than two modes of action of herbicides in tank mix reduce 83 times the likelihood of herbicide resistance selection.

Although very beneficial in terms of practicality, tank mixing requires guidelines to be correctly conducted, especially due to chemicals compatibility in the tank and positioning of technology application parameters, such as spray volume and droplet size. Overall, chemical compatibility is the main factor defining whether certain products can be mixed in the spray tank, regarding its physical and chemical compatibility [46].

Physical incompatibility may cause loss of spray solution stability, leading to the formation of precipitates, complexation, and phase separation. These changes are influenced by the pH, electrical conductivity, and surface tension of the spray liquid [46]. Furthermore, degradation of active ingredients is possible due to oxidation, hydrolysis, and encapsulation reactions [41]. On the other hand, chemical compatibility is related to the product effectiveness, in which certain products, when mixed, may vary the control efficacy it was expected to have when used alone [47]. Among several factors, incompatibilities can also occur due to improper agitation systems, water quality, application rate, and the solution pH [41].

Physical compatibility can be quickly tested in the field or laboratory through a common test known as "the jar test" [41]. The compatibility can be evaluated in a small proportion by mixing all products into a jar at the same rate or dose that it would be used in the tank, as well as the proportion of water and order added in the tank. Although it does not represent entirely how this mixing process would happen in the sprayer due to additional effects of pumps and accessories, it can be a great advantage to foresee any formation of precipitates or phase separation. Chemical compatibility can be evaluated through an efficacy test in laboratory or in the field.

One of the most important factors is the order that each product is added to the tank. In general, oily solutions are added lastly to the tank using water as a carrier. Among several methodologies, one of the most common is the addition of compatibility agents firstly, then water-dispersible granules, wettable powder, concentrated suspension, concentrated solution, and emulsifiable concentrate [41]. The product label should always be followed in this mixing process.

Tank mixes of different products are a common activity in soybean crops and have the potential to develop even more. More studies need to be conducted to assess different chemicals compatibility as well as to instruct farmers and operators on how to do it properly. However, its benefits are evident, and the need to gain operational conditions will still increase, which makes it even more important and applicable nowadays.

9. Insecticide application on planting furrow

Several species of pests can attack during the initial development of the soybean/ reduction in the crop stand and/or harming plant development, which consequently negatively affects the production of grains and/or seeds [48]. Among the soil pests, insects and nematodes may occur throughout the entire crop cycle, causing severe damage in the early stages of development of plants.

The preventive insecticide application on sowing furrowing is a promising alternative to avoid or minimize the damages caused by some pests on soybean plants [49–51]. In crop areas with high soil pest infestations, the application on planting furrows can be an option to ensure better distribution of pesticides [52]. Spraying pesticides in a planting furrow, especially when the pests are located nearby of the soil surface, can provide a good pest control [53].

In general, the insecticide application on sowing furrows is performed at the time of sowing and before covering the furrow with soil by the use of a sowing—fertilizer machine with a tank to store the pesticide solution or pesticide granules. This equipment may at the same operations fertilizer, planting and apply pesticide..

In Brazil, the application of insecticides in the seed furrow is still little used by soybean farmers with few studies in this area. However, it is noted that the insecticides application in the seed furrow has a great potential in soil pests control, promoting an initial protection to the plants with an adequate initial stand [54].

The use of insecticides applied in the seed furrow is limited, due to the need to use special machines for this operation, in addition to the higher costs of granules formulations available on the pesticide market [54]. Although this application technique is limited, some studies reported that this method of applying insecticides at label doses is effective in controlling pests that attack seeds, plants, or other subterranean plants parts for a period of 35–49 days [55].

As mentioned above, the use of pesticides on furrows to control soil pests and nematodes is not usually practiced by farmers. Most of the studies aimed to verify the effectiveness of insecticides. The effects of insecticides spraying on sowing furrow and seed treatment in order to control the insect *Phyllophaga cuyabana*, an important soil pest that consumes the soybean roots reducing the absorption of water and nutrients, were studied [49]. The authors concluded that insecticide applications are important tactics, and it may be employed in the management of *P. cuyabana* larvae in soybean crops. In this context, the insecticides fipronil, thiamethoxam, imidacloprid, and clothianidin, applied to soybean seeds, and chlorpyrifos, applied on the seed furrow, can ensure satisfactory soybean yields in areas with high pest infestation.

The same authors mentioned that the compatibility of insecticides with nitrogen fixing bacteria (*Bradyrhizobium*) should be considered and investigated, since the largest amount of nitrogen required by the crop is obtained through biological fixation.

Greater grain yield values have been reported when the insecticides fipronil, clothianidin, endosulfan, and chlorpyrifos were applied in the sowing furrow of soybean in order to control larvae of *P. cuyabana* and *Liogenys fuscus* [56]. All insecticides treatments mentioned exceeded statistically the yields of the treatment control (no insecticide application).

Increased soybean yield (approximately 20%) by application of disulfoton to the sowing furrow against two-striped leaf beetles (*Medythia nigrobilineata*) was reported [57]. According to the authors, this method can be easily applied to the use of fertilizing equipment mounted on the seed sowing machine with lower costs. The authors also believe that this pest control method is a key method for maximizing soybean yield with the labor-saving feature demanded by large-scale farming.

The performance of insecticide efficiency applied in the sowing furrow against *Sternechus subsignatus* in soybean crop was studied [54]. The author verified control up to 80% 31 days after plants emergence although this insecticide had affected negatively the final stand. The application of thiamethoxam (granule formulation) increased the soybean yield. Reduction of nematode population *Heterodera glycines* both in soil and soybean roots by nematicides/insecticides application in sowing furrow with greater soybean yield values in the treatments with nematicides was reported [50].

The applications of insecticides in sowing furrows in soybean crops can be a viable and economic alternative to be used as one more tool in Integrated Pest Management (IPM). Studies with new insecticides molecules, recently available on the pesticide market, should be encouraged in order to elucidate the control effectiveness and compatibility with nitrogen-fixing bacteria, which is widely used by Brazilian farmers. The appropriate method of applications also should be considered to maximize the insecticide performance and reduce environmental contamination.

10. Unmanned aerial vehicles (UAVs): sprayer drone in soybean crop

nlike aircraft with the presence of an on-board pilot, UAVs are used as a tool for applying pesticides in more complex terrain, with the surface with greater undulation, presence of obstacles, and in smaller areas [58]. In addition to spraying plant protection products, UAVs can also be used for image capture and remote sensing [59–62].

The use of UAVs in spraying, already well established in some countries such as China and Japan, is due to the compatibility with the farms that predominate in the region [60]. In the year 2018, there were about 30,000 spraying UAVs in China, covering an area of approximately 17.8 million hectares [63].

It is possible that, even in large areas, as in the case of soybean crops that require a large number of applications, the use of UAVs can optimize the operational capacity of the application, reduce costs, and ensure the effectiveness of phytosanitary management, which can be used in localized applications for the control of weeds, pests, and diseases.

UAVs can be classified into two segments, fixed wing and rotary wing. Fixed-wing UAVs follow the same operating principle as an airplane and are primarily used in remote sensing to capture images and map creation used in precision agriculture. The rotary wing UAVs are divided into helicopters and multirotors, which have shown a high growth in use, presenting models that are widely used to obtain images and also in the application/spraying of agricultural pesticides. Rotary-wing UAVs, especially multirotor UAVs, have the advantage of remaining stable in the air even with fluctuating winds and perform maneuvers with greater precision [58, 62, 64, 65].

The majority of spray drones available are capable of carrying 10–15 kg of liquids corresponding to 10–15 L of spray liquid. Ability to spray from 1 to 4 ha h^{-1} (10–50 ha day^{-1}), which can be 40–60 times faster than a manual operation. They have 4–6 spray nozzles, where each one can be positioned directly below a rotor or arranged on a spray boom. The application range can vary from 3 to 7 m in width [61–63]. Nozzles can be hydraulic (same as those used on land sprayers and airplanes) and also rotatory. As in airplanes, in UAVs, the electrostatic spraying system can also be used [66].

The drone's flight time is highly dependent on its weight and the presence and/or intensity of winds, but in general, it varies from 10 to 30 minutes with a fully charged battery [63, 64].

The main limitation in the use of UAVs for spraying agricultural pesticides is related to the flight autonomy provided by the batteries. One solution would be to increase the capacity and size of the batteries; however, the greater the capacity and size, the greater the weight and consequently reducing autonomy [62, 64].

In 2021, the Ministry of Agriculture, Livestock and Supply—MAPA, Brazil, through Ordinance No. 298, of September 22, 2021, established rules for the operation of remotely piloted aircraft intended for the application of pesticides and the like, adjuvants, fertilizers, inoculants, correctives, and seeds [67].

In the soybean crop, research has been conducted comparing weed control, soybean rust and stink bug control by conventional spraying methods (tractor-mounted sprayer) and with drones varying the application rate. Although research has been conducted on soybean crop with spraying, its aim is to obtain information to support applications in areas with difficult access with land sprayers, greater assertiveness in localized applications and in borders in soybean crop.

Some studies show the potential of using UAVs in soybean crops, evidencing that the deposition of the marker in the upper and middle thirds of soybean plants in applications carried out with UAV was similar to the deposition obtained with a CO2-propelled knapsack boom sprayer [68].

Recently, a field trial was installed on soybean crops at V4 stage crop to compare weed control between spraying performed with Sky Drones Pelicano 2020 drone (application rate 15 L ha^{-1}, flight height 3.0 m, displacement velocity of 18 km h^{-1}) and with the boom sprayer (application rate 120 L ha^{-1} and displacement velocity of 8.5 km h^{-1}). At 7 days after application (DAA), weed control with both application techniques was very similar after application of the herbicide mixture clethodim plus glyphosate. In the next evaluations, the differences in the control can be better evidenced.

In Brazil, the potential for use is greater for small farmers and agricultural crops with greater added value. The biggest difficulty in using this technology is in the adjustment and calibration of the equipment in view of the variation in the application rate, flight height, droplet size, and spray tips more suited to the target to be reached.

Other challenges are the size of the plots and the experimental design, as the dimensions of the plots are larger when compared with spraying with terrestrial equipment. The potential risk of drift is little known with remotely piloted aircraft. In this sense, research has been conducted with adjuvants to minimize problems with drift in drone spraying. The use of rotating nozzles has also been adopted in this technology for providing a more homogeneous droplet spectrum and, depending on the droplet size, with greater control of spray drift.

Considerable advances have been made with another one tactic within the IPM using remotely piloted aircraft, which is the distribution of parasitoids in capsules in different crops for the control of insect pests. The use of this technique presupposes knowledge of the parasitoid's ability to disperse, and through georeferenced points in the sites, the release of these insects is established.

11. Final considerations

In order to optimize the pesticide application technology in plant protection, it is necessary to overcome challenges such as connectivity in the field to better use the available resources of precision agriculture, as well as the training of people with specialized labor and the joint use of techniques of integrated management in the control of harmful agents to plants. In Brazil, especially in soybean, due to the existence of large areas of cultivation, the implementation of integrated management in plant protection has been a constant challenge, from the monitoring of pests, diseases, and weeds to decision-making and selection of techniques of control. From the south to the north of the country, the climatic conditions are very different, requiring different procedures for specific regions. In this sense, the Brazilian agricultural research company Embrapa has contributed significantly to the diffusion of technology to different regions. Regulatory activities in the commercialization of adjuvants with the inspection of the actual functionality of the adjuvants, the implementation of periodic inspection of agricultural machines, and the establishment of spray drift limits for manual, land (mounted, trailed, or self-propelled), and aerial (unmanned or with on-board pilot) applicator equipment could significantly contribute to the optimization of the entire national agricultural production process.

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References

[1] USDA. World Agricultural Production [Internet]. 2021. Available from: https://downloads.usda.library.cornell.edu/usda-esmis/files/5q47rn72z/wp989m25f/9z904211s/production.pdf [Accessed: December 12, 2021]

[2] FAOSTAT. Countries by Commodity [Internet]. 2021. Available from: https://www.fao.org/faostat/en/#rankings/countries_by_commodity_exports [Accessed: December 26, 2021]

[3] CONAB. Boletim da safra de grãos [Internet]. 2021. Available from: https://www.conab.gov.br/info-agro/safras/graos/boletim-da-safra-de-graos [Accessed: December 26, 2021]

[4] Yorinori JT, Paiva WM, Frederick RD, Costamilan LM, Bertagnolli PF, Hartman GL, et al. Epidemics of Soybean Rust (*Phakopsora pachyrhizi*) in Brazil and Paraguay from 2001 to 2003. Plant Disease. 2005;**89**:675-677

[5] Henning AA, Almeida AMR, Godoy CV, Seixas CDS, Yorinori JT, Costamilan LM, Ferreira LP, Meyer MC, Soares RM, Dias WP. Manual de identificação de doenças de soja. 5.ed. Londrina: Londrina: Embrapa Soja; 2014. 76p (Embrapa Soja Documentos 256). Available from: https://ainfo.cnptia.embrapa.br/digital/bitstream/item/105942/1/Doc256-OL.pdf [Accessed: August 08, 2022]

[6] Hartman GL, Sikora EJ, Rupe JC. Rust. In: Hartman GL, Rupe JC, Sikora EJ, Domier LL, Davis JA, Steffey KL, editors. Compendium of Soybean Diseases and Pests. 5th ed. Saint Paul: APS Press; 2015. pp. 56-59

[7] Godoy CV. Risk and management of fungicide resistance in the Asian soybean rust fungus *Phakopsora pachyrhizi*. In: Thind ST, editor. Fungicide Resistance in Crop Protection. India: Punjab Agricultural University; 2012. pp. 87-95. DOI: 10.1079/9781845939052.0087

[8] Klosowski AC, May de Mio LL, Miessner S, Rodrigues R, Stammler G. Detection of the F129L mutation in the cytochrome b gene in *Phakopsora pachyrhizi*. Pest Management Science. 2016;**72**:1211-1215

[9] Simões K, Hawlik A, Rehfus A, Gava F, Stammler G. First detection of a SDH variant with reduced SDHI sensitivity in *Phakopsora pachyrhizi*. Journal of Plant Diseases and Protection. 2018;**125**(1):21-26. DOI: 10.1007/s41348-017-0117-5

[10] Godoy CV, Almeida AMR, Costamilan LM, Meyer MC, Dias WP, Seixas CDS, et al. Doenças da soja. In: Amorim L, Rezende JAM, Bergamin Filho A, Camargo LEA, editors. Manual de Fitopatologia, v.2. Doenças de plantas cultivadas. 5th ed. São Paulo: Ceres; 2016. pp. 657-676

[11] Silva AF, Concenço G, Aspiazú I, Ferreira EA, Galon L, Freitas MAM, et al. Period before interference in soybean-RR crop under low, medium and high infestation level conditions. Planta Daninha. 2009;**27**(1):57-66. DOI: 10.1590/S0100-83582009000100009

[12] Heap I. The International Herbicide-Resistant Weed Database. 2022. Available from: www.weedscience.org [Accessed: August 02, 2022]

[13] Boller W. Tecnologia de Aplicação de Defensivos II. Passo Fundo: RS; 2007. pp. 23-35

[14] Zhu H, Derksen RC, Ozkan HE, Reding ME, Krause CR. Development

of a canopy opener to improve spray deposition and coverage inside soybean canopies: Part 2. Opener design with field experiments. Transactions of the ASABE. 2008;**51**(6):1913-1921

[15] Robinson TH. Large-scale ground-based application techniques. In: Matthews GA, Hislop EC, editors. Application Technology for Crop Protection. Wallingford, Oxon, UK: CAB International; 1993. pp. 163-186

[16] Koch H. The evolution of application techniques in Europe. In: Proceedings of 1rst Simpósio Internacional de Tecnologia de Aplicação de Produtos Fitossanitários, Águas de Lindóia, São Paulo, Brazil. 26-29 March 1996. pp. 30-38

[17] Cooke BK et al. Air-assisted spraying of arable crops in relation to deposition, drift and pesticide performance. Crop Protection. 1990;**9**(4):303-311

[18] Taylor WA, Andersen PG. A review of benefits of air assisted spraying trials in arable crops. Aspects of Applied Biology. 1997;**48**:163-174

[19] Bauer FC, Raetano CG. Assistência de ar na deposição e perdas de produtos fitossanitários em pulverizações na cultura da soja. Scientia Agricola. 2000;**57**(2):271-276

[20] Matthews GA. Pesticide Application Methods. 3rd. ed. Oxford, UK: Blackwell Science; 2000

[21] Christovam RS, Raetano CG, Aguiar-Júnior HO, Dal Pogetto MHFA, Prado EP, Júnior HOA, et al. Assistência de ar em barra de pulverização no controle da ferrugem asiática da soja. Bragantia. 2010;**69**(1):231-238

[22] Prado EP, Raetano CG, Aguiar-Júnior HO, Dal Pogetto MHFA, Christovam RS, Gimenes MJ, et al. Velocidade do ar em barra de pulverização na deposição da calda fungicida, severidade da ferrugem asiática e produtividade da soja. Summa Phytopathologica. 2010;**36**(1):45-50

[23] Raetano CG, Rezende DT, Prado EP. Application technologies for Asian Soybean rust management. In: El-Shemy HA, editor. Soybean Physiology and Biochemistry. Rijeka, Croatia: InTech; 2011. pp. 117-138

[24] Raetano CG, Chechetto RG. Adjuvantes e formulações. In: Antuniassi UR, Boller W, editors. Tecnologia de aplicação para culturas anuais. 2nd ed. Passo Fundo: Aldeia Norte; Botucatu: FEPAF; 2019. pp. 29-40

[25] Silva FN. Spray Retention of Mancozebe with Adjuvants and Application Rate on Soybean Rust Control [thesis]. Botucatu: State University of Sao Paulo; 2020

[26] Gimenes MJ, Zhu H, Raetano CG, Oliveira RB. Dispersion and evaporation of droplets amended with adjuvants on soybeans. Plant Protection. 2013;**44**: 84-90. DOI: 10.1016/j.cropro.2012.10.022

[27] Roehrig R, Boller W, Forcelini CA, Chechi A. Use of surfactant with different volumes of fungicide application in soybean culture. Engineering Agriculture. 2018;**38**(4): 577-589. DOI: 10.1590/1809-4430-Eng. Agric.v38n4p577-589/2018

[28] Ferreira PHU, Thiesen LV, Pelegrini G, Ramos MFT, Pinto MMD, Ferreira MC. Physicochemical properties, droplet size and volatility of dicamba with herbicides and adjuvants on tank-mixture. Scientific Reports. 2020;**10**:18833. DOI: 10.1038/s41598-020-75996-5

[29] Bharti V, Ibrahim S. Biopesticides: Production, formulation and application

systems. International Journal of Current Microbiology and Applied Science. 2020;**9**(10):3931-3946. DOI: 10.20546/ijcmas.2020.910.453

[30] Nilsson HE. Remote sensing and image analysis in plant pathology. Canadian Journal of Plant Pathology. 1995;**17**:154-166

[31] Shiratsuchi LS, Brandão ZN, Vicente LN, Victoria DC, Ducati JR, Oliveira RP, et al. Sensoriamento Remoto: conceitos básicos e aplicações na Agricultura de Precisão. In: Bernardi ACC, Naime JM, Resende AV, Bassoi LH, Inamasu RY, editors. Agricultura de precisão: Resultados de um novo olhar. 2nd ed. Brasília: Embrapa; 2014. pp. 58-73

[32] Kelly M, Guo Q. Integrated agricultural pest management through remote sensing and spatial analyses. In: Ciancio A, Mukerji KG. editors. General Concepts in integrated Pest and Disease Management. Dordrecht: Springer; 2007. pp. 191-207

[33] Ahmed MR, Yasmin J, Mo C, Lee H, Kim MS, Hong SJ, et al. Outdoor applications of hyperspectral imaging technology for monitoring agricultural crops: A review. Journal of Biosystems Engineering. 2016;**41**(4):396-406

[34] Mahlein AK. Plant disease detection by imaging sensors: Parallels and specific demands for precision agriculture and plan phenotyping. Plant Disease. 2016;**100**(2):241-251. DOI: 10.1094/PDIS-03-15-0340-FE

[35] Ali MM, Bachik NA, Muhadi NA, Yusof TNT, Gomes C. Non-destructive techniques of detecting plant diseases: A review. Physiological and Molecular Plant Pathology. 2019;**108**:101426

[36] Genna NG, Gourlie JA, Barroso J. Herbicide efficacy of spot spraying systems in fallow and postharvest in the pacific northwest dryland wheat production region. Plants. 2021;**10**(12):2725

[37] Calvert B, Olsen A, Whinney J, Rahimi Azghadi M. Robotic spot spraying of Harrisia Cactus (*Harrisia martinii*) in grazing pastures of the Australian Rangelands. Plants. 2021;**10**(10):2054

[38] Dammer KH, Adamek R. Sensor-based insecticide spraying to control cereal aphids and preserve lady beetles. Agronomy Journal. 2012;**104**(6):1694-1701

[39] Hasan AM, Sohel F, Diepeveen D, Laga H, Jones MG. A survey of deep learning techniques for weed detection from images. Computers and Electronics in Agriculture. 2021;**184**:106067

[40] Ghanizadeh H, Harrington KC. Herbicide resistant weeds in New Zealand: State of knowledge. New Zealand Journal of Agricultural Research. 2021;**64**(4):471-482

[41] Raetano CG, Chechetto RG. Misturas em tanque. In: Antuniassi UR, Boller W, editors. Tecnologia de Aplicação para Culturas Anuais. 2nd ed. Passo fundo: Aldeia Norte; 2019. pp. 49-86

[42] Brasil. Instrução Normativa n° 40, de 11 de outubro de 2018. Instrução Normativa N° 40. 2018

[43] Gazziero DLP. Misturas de agrotóxicos em tanque nas propriedades agrícolas do Brasil. Planta Daninha. 2015;**33**(1):83-92

[44] Santra G, Mohant A, Rout S. A survey on chemical sprayer influenced by various parameters of AAS. International Journal of Modern Agriculture. 2020;**9**(3):544-549

[45] Evans JA, Tranel PJ, Hager AG, Schutte B, Wu C, Chatham LA, et al. Managing the evolution of herbicide resistance. Pest Management Science. 2016;**72**(1):74-80

[46] Petter FA, Segate D, Almeida FA, Alcântara Neto F, Pacheco LP. Incompatibilidade física de misturas entre inseticidas e fungicidas. Comunicata Scientiae. 2013;**4**:129-138

[47] Petter FA, Segate D, Pacheco LP, Almeida FA, Alcântara NF. Incompatibilidade física de misturas entre herbicidas e inseticidas. Planta Daninha. 2012;**30**:449-457

[48] Hoffmann-Campo CB. Pragas iniciais da soja: tamanduá-da-soja, piolho-de-cobra e torrãozinho. In: Seminário de Manejo de Pragas e Doenças Iniciais das culturas de soja e milho em mato grosso do sul, 1., 2002, Dourados. Anais... Dourados: Embrapa Agropecuária Oeste; 2002. pp. 45-54 (Embrapa Agropecuária Oeste. Documentos, 48)

[49] Ávila CJ, Gomez SA. Efeito de inseticidas aplicados nas sementes e no sulco de semeadura, na presença do coró-da-soja, *Phyllophaga cuyabana*. Dourados: Embrapa Agropecuária Oeste; 2003. (Embrapa Agropecuária Oeste. Documentos, 55)

[50] Santos PS. Aplicação em sulco de nematicidas em soja [masters dissertation]. , Santa Maria/RS: Universidade Federal de Santa Maria; 2015. Available from: https://repositorio.ufsm.br/handle/1/7622 [Accessed: December 28, 2021]

[51] Guarnieri CCO et al. Eficácia de tiodicarbe, cadusafós e condicionador de solo via tratamento de sementes e/ou sulco de plantio no controle de nematoides na cultura da soja. In: Brazilian Congress of Nematology. Brazil: Bento Gonçalves, RS; 2018

[52] Corte GD. Tecnologia de aplicação de agrotóxicos no controle de fitonematoides em soja [masters dissertation]. Santa Maria: Universidade Federal de Santa Maria; 2013. p. 61. Available from: https://repositorio.ufsm.br/bitstream/handle/1/7572/DALLA%20CORTE%2C%20GERSON.pdf

[53] Ávila CJ, Grigolli JFJ. Pragas de soja e seu controle. Embrapa Agropecuária Oeste-Chapter in Scientific Book. 2014 (ALICE)

[54] Possebon SB. Desempenho de uma semeadora-adubadora e métodos de aplicação de inseticidas no sulco em plantio direto [thesis]. Universidade Federal de Santa Maria; 2011. 113p. Available from: http://repositorio.ufsm.br/handle/1/3592

[55] Gassen D. Aula prática: pequenas e rápidas dicas sobre o uso de inseticidas em lavouras sob plantio direto podem economizar dinheiro e evitar dores de cabeça para o produtor. Revista Cultivar Grandes Culturas. [Internet]. 2015. Available from: https://revistacultivar.com.br/artigos/aula-pratica [Accessed: December 26, 2021]

[56] Vivan LM et al. Eficácia de inseticidas aplicados no sulco de semeadura no controle dos corós *Phyllophaga cuyabana* e *Liogenys fuscus* na cultura da soja. In: Reunião Sul-Brasileira sobre pragas de solo, 10., 2007, Dourados. Anais... Dourados: Embrapa Agropecuária Oeste; 2007. pp. 199-202 (Embrapa Agropecuária Oeste. Documentos, 88)

[57] Takei M et al. Assessment of damage caused by two-striped leaf beetle (*Medythia nigrobilineata* Motschulsky) larval feeding of root nodules in soybean

and its control during furrow cultivation at seeding time. Plant Production Science. 2014;**17**(3):276-283. DOI: 10.1626/pps.17.276

[58] Chen H, Lan Y, Fritz BK, Hoffmann WC, Liu S. Review of agricultural spraying technologies for plant protection using unmanned aerial vehicle (UAV). International Journal of Agricultural and Biological Engineering, Beijing. 2021;**14**(1):38-49. DOI: 10.25165/j.ijabe.20211401.5714

[59] Inamasu RY, Bernardi AC de C. Agricultura de precisão. In: de Bernardi AC, de Naime JM, de Resende AV, Bassoi LH, Inamasu RY. (Ed.). Agricultura de precisão: resultados de um novo olhar. Brasília, Embrapa, 2014: p. 21-33

[60] Xiongkui H, Bonds J, Herbst A, Langenakens J. Recent development of unmanned aerial vehicle for plant protection in East Asia. International Journal of Agricultural and Biological Engineering. 2017;**10**(3):18-30. DOI: 10.3965/j.ijabe.20171003.3248

[61] Xin F, Zhao J, Zhou Y, Wang G, Han X, Fu W, et al. Effects of dosage and spraying volume on cotton defoliants efficacy: A case study based on application of unmanned aerial vehicles. Agronomy. 2018;**8**(6):15p. DOI: 10.3390/agronomy8060085

[62] Grammatikis PR, Psarigiannidis P, Lagkas T, Moscholios I. A compilation of UAV applications for precision agriculture. Computer Networks. 2020;**172**:107148. DOI: 10.1016/j.comnet.2020.107148

[63] Xiao O, Xin F, Lou Z, Zhou T, Wang G, Han X, et al. Effect of aviation spray adjuvants on defoliant droplet deposition and cotton defoliation efficacy sprayed by unmanned aerial vehicles. Agronomy. 2019;**9**:217. DOI: 10.3390/agronomy9050217

[64] Kim J, Kim SC, Ju C, Son HI. Unmanned aerial vehicles in agriculture: A review of perspective of platform, control, and applications. IEEE Access. 2019;**7**:105100-105115. DOI: 10.1109/ACCESS.2019.2932119

[65] Chen HB, Fritz KB, Lan YB, Zhou ZY, Zheng JF. An overview of spray nozzles for plant protection from manned aircrafts: Present research and prospective. International Journal of Precision Agricultural Aviation. 2020;**3**(2):1-12

[66] Zhang Y, Huang X, Lan Y, Wang L, Lu X, Yan K, et al. Review: Development and prospect of UAV-based aerial electrostatic spray technology in China. Applied Science. 2021;**11**(4071):15p. DOI: 10.3390/app11094071

[67] MAPA – Ministério da Agricultura, Pecuária e Abastecimento. Portaria N° 298, 09-22-2021. D.O.U. Ed. 182, Sec. 1, p. 14. Available from: https://www.in.gov.br/en/web/dou/-/portaria-mapa-n-298-de-22-de-setembro-de-2021-347039095 [Accessed: December 28, 2021]

[68] Cunha JPAR, Silva MRA. Deposition of spray applied to a soybean crop using an unmanned aerial vehicle. International Journal of Precision Agricultural Aviation. 2021;**4**(2):8-13. DOI: 10.33440/j.ijpaa.20210402.167