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Could adjuvants serve as an agroecological tool?

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Adjuvants are agrochemicals or natural substances, commonly mixed with pesticides to increase their efficacy or reduce off-target movement by modifying the physical properties of the spray solution, such as surface tension, droplet size, and spreadability, which ultimately improve pesticide adhesion and coverage on target surfaces. Adjuvant use across Europe remains less widespread compared to regions like the USA, where adjuvants are often recommended or required with certain herbicide applications. This paper highlights the potential benefits of incorporating adjuvants with herbicides in weed control, particularly as a strategy to reduce overall herbicide use. Findings from dose-response research on available adjuvants suggest they may enable the application of lower herbicide rates than typically recommended, without sacrificing effectiveness, thereby contributing to the goal of reducing herbicide use by 50% by 2030 in Europe. Furthermore, literature findings indicate that adjuvants significantly improve weed control by enhancing the performance of active ingredients, with efficacy increases of up to 50% compared to using herbicides alone. The integration of adjuvants into herbicide tank mixtures offers considerable promise, especially for managing herbicide-resistant weeds and achieving effective weed control.

KEYWORDS
adjuvants, herbicides, tank mix, sustainable agriculture, agroecology

1 Introduction

The viability and future of agriculture is threatened globally by climate change and pressing factors such as the spread of invasive weeds and the expansion of herbicide resistance weeds. Crop yields are more prone to decline, and crop production is more challenging than ever, especially on degraded soils and among smallholder farmers. For decades farmers, in particular in Global North, have depended heavily on synthetic herbicides and chemical inputs to "feed" a production model that is no longer attractive or even profitable, that of industrial agriculture. Furthermore, a lack of new herbicide active ingredients on the market along with the rapid spreading of herbicide resistant weeds recently, made imperative the pursuit of new solutions to reduce the dependency on chemical weed control and strategies that work with nature, and not against it, to reduce the weed pressure. In Europe, the European Commission has required the reduction of the use of pesticides (including herbicides) by 50% by 2030 (Tataridas et al., 2022), in order to reduce the negative impacts of their use on soil health, biodiversity, and human health. Currently, there is a growing movement in Europe towards more sustainable and environmentally friendly farming practices to alleviate the effects of decades of harmful practices such as excessive use of pesticides, extensive soil disturbance and monocropping. Although very challenging, there are several options on how to reduce the herbicide load. This perspective article will not list already existing and well-documented strategies and practices that lead to herbicide reduction and eventually elimination (e.g., cover crops, mechanical means, biological agents, crop diversification, new technologies etc.). Instead, it will explore and highlight the role of adjuvants in herbicide reduction as a tool to assist the transition of conventional farming systems towards agroecology (Figure 1). Adding adjuvants into the tank and mixing them with herbicides can help in obtaining higher efficacy on the weeds, even when herbicides are applied in reduced rates or in unsuitable conditions.

The potential to use lower herbicide rates with the help of adjuvants was recognized two decades ago. Adjuvants are agrochemicals or natural substances commonly used to improve pesticide efficacy and reduce particle drift by altering the physical properties of the spray solution. Adjuvants can be classified based on their composition and functional properties as surfactants, oils, solvents, polymers, salts, diluents, humectants, and water conditioners (Hazen, 2000). Some of them, like surfactants, can increase the spreading and wetting area of droplets on the leaves of plants (Buffington and McDonald, 2006). Likewise, some adjuvants increase herbicide penetration and adsorption through cuticles and improve the homogeneity of spray coverage, particularly on waxy and leaf surfaces with trichomes (Xu et al., 2010). Oils, especially methylated seed oils are adjuvants as well, mixed with an emulsifier to allow for dispersion in water (Bunting et al., 2004). Furthermore, polymers as adjuvants enhance droplets spreading and change their evaporation dynamics (Katzman et al., 2023). Literature reports using lower herbicide rates together with adjuvants, where results did not differ from the same treatments containing the same herbicide at full rate without adjuvants (Brankov et al., 2023b).

As herbicides are registered for application at specific recommended rates, any deviation causes much discussion, especially among scientists. The reason for this might be found that exposure to sub-lethal doses of herbicide may directly lead to resistance evolution in weeds (Gressel, 2011). As documented earlier, in drift simulation studies, several weeds may develop lower susceptibility to some herbicides (Vieira et al., 2020). If weeds are exposed to those doses and survive, they will likely establish target site insensitivity. Management of those weeds might be even more complicated as they can resist wider spectra of herbicide groups (Vieira et al., 2020).

This paper sought to highlight the effects of mixing herbicides with adjuvants on weed control and to emphasize adjuvants as an often-underestimated tool for increasing herbicide efficacy and ultimately reducing the need for unnecessary sprayings.

2 Adjuvants: concept and characterization

As written in the latest Shaner (2014) published by the Weed Science Society of America (WSSA), there is a need to assign common names for adjuvants to reduce confusion when they are

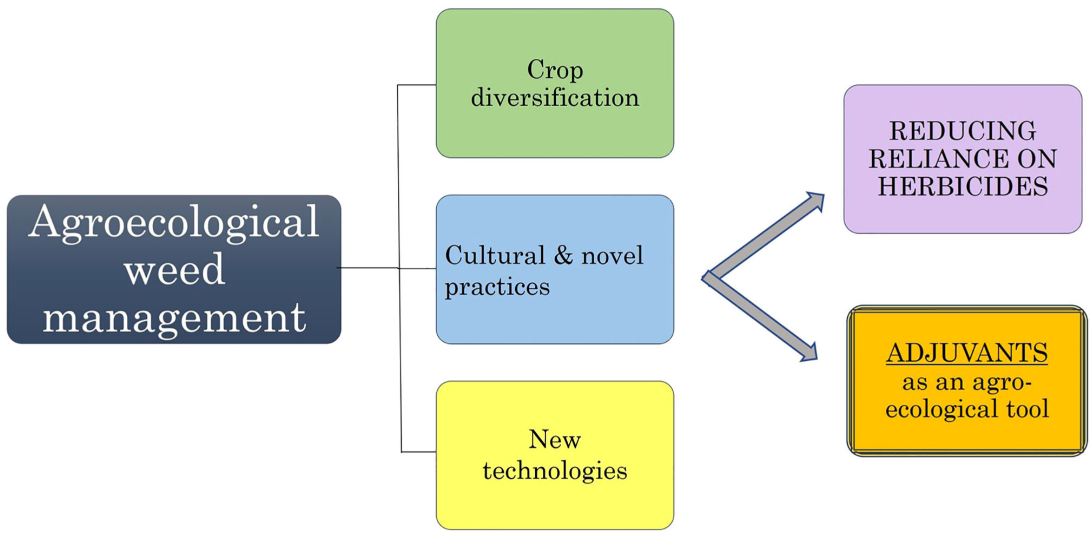

FIGURE 1
The significance of adjuvants in agroecological weed management.

mentioned. The nomenclature task is difficult, as many existing adjuvants are mixtures of different constituents. To date, WSSA uses the chemical names of adjuvants used by EPA (Environmental Protection Agency) or FDA (Food and Drug Administration). Adjuvant recommendations are specific for each herbicide product, based on research and developed by the herbicide manufacturers, trying to address different regional and/or environmental needs. Some herbicides are generally formulated with sufficient adjuvants and may not require additional adjuvants. However, other herbicides have specific adjuvant recommendations that must be added to the spraying mixture. Herbicide glyphosate is a good example. There are variabilities between glyphosate products in the type of glyphosate salt in the formulation, as well as in the additives added in the product, which can improve handling, safety and solubility of products (Leaper and Holloway, 2000).

Since adjuvants do not have any pesticide properties, they are not required to be registered by the EPA. A similar situation is across the EU, where adjuvants fall within the scope of Regulation (EC) No 1107/2009. No specific requirements (including data necessities, notification, evaluation, assessment, and decision-making procedures) for the authorization of adjuvants have been set at the EU level. Therefore, the potential of adjuvants to increase herbicide efficacy is high. Owing to the need to solve problems in weed control and increase herbicide efficacy, the manufacturing industry constantly develops various adjuvants and provides recommendations for their integration across various tank mixtures.

3 Positive effects of mixing adjuvants with herbicides in the tank

It is generally known that adjuvants could improve the efficacy of herbicide-active ingredients. As adjuvant changes in the physical properties of herbicide solutions, they might increase penetration and adsorption into the plant. Sobiech et al. (2020) (Sobiech et al., 2020) reported that added MSO (methylated seed oil) adjuvant could mitigate the adverse effects of the low pH of herbicide sulcotrione. Combining the adjuvant and reduced rate of sulcotrione affected barnyardgrass the same way as the full recommended rate of sulcotrione without the adjuvant. Moraes et al., 2021 (Moraes et al., 2021) showed that adjuvants have the potential to overcome the antagonistic interaction between herbicides, taking into account that it is dependent on the weed species. In their study, addition of a NIS (non-ionic surfactant) adjuvant to glyphosate plus lactofen tank-mixture increased common lambsquaters control. Pratt et al. (2003) (Pratt et al., 2003) reported that using tap water glyphosate solution containing 2% of AMS (ammonium-sulfate) adjuvant increased velvetleaf control (up to 53% compared to glyphosate solution alone). Idziak et al., 2023 (Idziak et al., 2023) indicated that high efficacy of herbicides could be achieved even by using reduced rates of herbicides while needed to add certain adjuvants into the tank. In their study, effective control of Echinocloa crus-galli was achieved using reduced rate of nicosulfuron, when adding MSO adjuvant. Using lower herbicide rates to obtain satisfactory weed control was also confirmed by Brankov et al. (2023b). In their study, they used ED_{50} values of tested herbicides while adding MSO and NIS adjuvants delivered 98 and 99% of biomass reduction in *Echinochloa crus-galli*, which is an increase in herbicide efficacy up to 38%. In another study, the use of various herbicides with the NIS adjuvants to control weedy sunflowers was significantly increased, especially when half of the recommended rates were used for glyphosate and nicosulfuron. In the study with nicosulfuron, Brankov et al. (2023a) reported that using NIS adjuvant in field conditions significantly increased efficacy, allowing the use of nozzle-producing coarse droplets. Significantly reduced surface tension and contact angle was achieved with three sulfonylurea herbicides by adding five bio-ionic liquids as adjuvants (Marcinkowska et al., 2018) (Table 1).

4 Some antagonistic effects of mixing adjuvants and herbicides on weeds and crops

Adding adjuvants may not always increase herbicide efficacy; in some cases, it could reduce it. Literature reports suggest that certain adjuvants can reduce weed control efficacy when tank-mixed with herbicides. Brankov et al. (2024b) reported that using AMS with nicosulfuron led to 20-30% reduced efficacy on the *Chenopodium album*. Cases of adding AMS to glufosinate lead to reduced efficacy in *Abutilon theophrasti*, also reported by Maschhoff et al., 2000 (Maschhoff et al., 2000). Furthermore, in control *Cyperus rotundus*, adding NIS and COC (crop oil concentrate) surfactants to glufosinate ammonium reduced the efficacy, again (Devendra et al., 2004). Presented evidence showed that, in some cases, adding adjuvants into the tank can be problematic and even negatively influence weed control (Table 2).

5 Negative effects of adjuvants on crops

In cases when adjuvants decrease weed efficacy, consequence are present in yield loss. However, in some cases adding adjuvants directly influence crops, making injuries due to increased herbicide intake by the crop. Listed are some evidences. Evaluating bentazone efficacy adding adjuvants on green pea, adding the adjuvant NIS (Sylgard 309) adjuvant combined with bentazone resulted in highest injury on green pea (Al-Khatib et al., 1995). Richardson et al., 2014 (Richardson et al., 2004) reported injuries on cotton following applications with CGA 362622 adding the COC adjuvant. In soybeans, adding NIS or COC adjuvant induced injuries with AC 263222 in post applications (Wixson and Shaw, 1991). In potatoes, mixing metribuzin and rimsulfuron caused higher injuries when adding MSO or COC, while lower injuries occurred when mixing it with NIS adjuvant (Hutchinson et al., 2004) (Table 3).

TABLE 1 Examples of positive effects of adding of adjuvants on herbicide efficacy.

Adjuvants	Herbicides	Weeds	Increased efficacy	Source
AMS, COC, DRA, MSO, NIS	Mesotrione, rimsulfuron + thifensulfuron-metlyl	Amaranthus palmeri, *Amaranthus tuberculatus, Abuthilon teophrasti, Chenopodium album, Echinocloa cruss-galli*	Up to 38%	(Brankov et al., 2023b)
NIS	Nicosulfuron	*Sorghum halepense, Chenopodium album*	Up to 15%	(Brankov et al., 2023a)
NIS	Bentazone, dicamba, foramsulfuron, glyphosate, mesotrione, nicosulfuron, rimsulfuron, tembotrione	*Helianthus annuus*	Up to 41%	(Brankov et al., 2024a)
MSO, NIS	Nicosulfuron	*Chenopodium album, Geranium pusillum, Fallopia convolvulus, Viola arvensis, Echinochloa crus-galli…*	Up to 30%	(Idziak et al., 2023)
AMS	Dicamba, glyphosate	*Chenopodium album, Amaranthus palmeri, Erigeron canadensis, Bassia scoparia, Amaranthus tuberculatus*	Up to 47%	(Polli et al., 2021)
AMS, COC, DRA	Glyphosate, fomesafen, lactofen	*Amaranthus palmeri*	22%	(Moraes et al., 2021)
NIS, MSO	Sulcotrione	*Echinochloa crus-galli*	20%	(Sobiech et al., 2020)
AMS	Glyphosate	*Abuthilon teohprasty*	53%	(Pratt et al., 2003)
BILs	Metsulfuron-methyl, iodosulfuron-methyl-sodium, tribenuron-methyl	*Chenopodium album, Centaurea cyanus, Papaver rhoeas, Brassica napus*	Up to 40%	(Marcinkowska et al., 2018)

AMS, ammonium-sulfate; COC, crop oil concentrate; DRA, drift reducing adjuvant; MSO, methylated seed oil; NIS, non-ionic surfactant; BIL, bio-ionic liquids.

TABLE 2 Examples of negative (antagonistic) effects of addingof adjuvants on herbicide efficacy.

Adjuvants	Herbicide	Weeds	Source
AMS	Nicosulfuron	*Sorghum halepense, Chenopodium album*	(Brankov et al., 2024b)
AMS	Glufosinate ammonium	*Abutilon theophrasti*	(Maschhoff et al., 2000)
non-ionic COC	Glufosinate ammonium, 2,4 D	*Cyperus rotundus*	(Devendra et al., 2004)

AMS, ammonium-sulfate; COC, Crop oil concentrate; DRA, drift reducing adjuvant; MSO, methylated seed oil; NIS, non-ionic surfactant.

6 Conclusions

The fundamental advantage of using adjuvants is reflected in the possible reduced use rates of herbicides. This short review highlights various effects of adding adjuvants into the tank with herbicides. In many cases, adding adjuvants increased herbicide efficacy compared to the sole active ingredient, even with lower herbicide rates than recommended. Combinations of weed management practices (e.g., cover crops, grazing, mechanical means etc.) are needed to ensure that herbicides with adjuvants remain the last option to manage noxious weeds and secure a sufficient yield. Thus, adjuvants could be an agroecological tool to reduce herbicide usage while not sacrificing overall product performance. Having increased efficacy directly means increasing crop yields and, presumably, profit. However, caution is required when using lower rates than labeled, as it could directly lead to herbicide resistance occurrence in weeds. Up to now, adjuvant use across the EU is less widespread than in the US. Therefore, increasing their status as environmentally friendly agrochemicals throughout Europe's agroecological regions would be crucial as one of several tools in reducing rates of herbicides. Consequently, more European research is required to integrate various controlled or in-field conditions with different herbicide rates and a more comprehensive range of crops and weeds to confirm the broader insight, provide details, and give recommendations for adjuvant use across diverse environments. That information could be valuable for farmers (especially conventional ones) and advisors since combined use of herbicides in lower rates and adjuvants might theoretically result in a satisfactory weed control. This is in full agreement with the goals of Green Deal and agroecology approaches. Up to now, adjuvant use across the EU is not so popular like in the US.

TABLE 3 Examples of negative effects of adding of adjuvants on herbicide selectivity.

Adjuvants	Herbicide	Crop	Source
NIS	Bentazon	Green pea	(Al-Khatib et al., 1995)
COC	CGA 362622	Cotton	(Richardson et al., 2004)
NIS, COC	AC 263222	Soybean	(Wixson and Shaw, 1991)
MOS, COC	Metribuzin, rimsulfuron	Potato	(Hutchinson et al., 2004)

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

MB: Conceptualization, Writing – original draft, Writing – review & editing. MS: Conceptualization, Writing – original draft, Writing – review & editing. JV: Methodology, Supervision, Writing – original draft, Writing – review & editing. MZ: Supervision, Writing – original draft, Writing – review & editing. AT: Supervision, Writing – original draft, Writing – review & editing. SB: Validation, Writing – original draft, Writing – review & editing. VD: Conceptualization, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing.

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