

Allelopathic Mechanisms and Agronomic Potential of Aqueous Sorghum Extract as a Sustainable Bioherbicide: A Critical Review

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Herbicide resistance, environmental contamination, and regulatory constraints increasingly challenge the sustainability of synthetic herbicide-dependent weed management systems. In this context, aqueous sorghum extract (ASE) has emerged as a biologically grounded alternative within integrated weed management (IWM) frameworks. This review synthesizes current evidence on the phytochemical composition, molecular mechanisms, agronomic performance, and translational constraints of ASE as a potential bioherbicide. The bioactivity of ASE is primarily attributed to water-soluble phenolic acids, flavonoids, cyanogenic glycosides, and low-molecular-weight organic acids that collectively impose multi-target physiological stress on susceptible weeds. Mechanistically, ASE interferes with seed germination, hormonal regulation, photosynthetic electron transport, mitochondrial respiration, redox homeostasis, membrane integrity, and protein stability, frequently inducing oxidative stress cascades. Such distributed biochemical interference contrasts with single-site synthetic herbicides and may reduce strong selection pressure for resistance evolution. Laboratory studies report significant inhibition of germination and early seedling growth across monocot and dicot weeds, particularly at concentrations above 10–15% (w/v). However, field-level performance remains inconsistent due to soil adsorption, microbial degradation, environmental instability, and concentration-dependent hormetic responses. Evidence suggests that ASE is most effective as a pre-emergence or early post-emergence suppressive tool and as a complementary component enabling reduced herbicide dosages while maintaining yield stability under moderate weed pressure. Major translational bottlenecks include chemical instability, narrow crop safety margins, lack of standardization, and variability across agroecological contexts. Research priorities include formulation engineering, marker-based standardization, soil-microbiome interaction analysis, and precision deployment. Within diversified IWM systems, ASE offers a promising yet context-dependent strategy for sustainable weed management.

Keywords: Aqueous Sorghum Extract (ASE), allelopathy, bioherbicide, Integrated Weed Management (IWM), oxidative stress mechanisms

1 Introduction

The majority of presently used weed management systems are still reliant on chemical herbicides. Though these resources perform well over the short term, their widespread application has led to both herbicide-resistant weed populations and growing environmental and regulatory challenges. In fact, it is now widely accepted that the over-reliance on individual modes of action is ecologically and agronomically untenable and instead emphasises the requirement to expand

weed control strategies as part of integrated weed management (IWM) approaches (Perotti et al., 2019; Scavo & Mauromicale, 2021; Kostina-Bednarz et al., 2023).

Thus, the use of plant-derived bioherbicides is one of the most encouraging complementary approaches. Among these, the multi-targeted plant-plant interactions that meet the definition of allelopathy (chemically mediated) are less specific than synthetic herbicides but are a kind of herbicide themselves (Khamare et al., 2022). That said, this literature has documented a striking gap

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between conceptual promise and actual field practice. While pronounced phytotoxic effects are typically cited under controlled lab conditions, consistent agronomic performance in a field setting remains elusive. This limitation stems most from the variation and lack of standardization in environment (Mahé et al. 2022; Kostina-Bednarz et al. 2023).

Sorghum bicolor is one of the six most studied allelochemicals crops. Its bioactivity arises from a complex mixture of phenolic acids, flavonoids, and cyanogenic compounds. Those compounds disturb pivotal physiological functions in plant systems including, but not limited to:

1. the process of germination itself;
2. overall photosynthetic efficiency;
3. balance/redox potential;
4. cell membrane integrity (Anwar et al. 2021; Hasan et al. 2022; Waligóra et al. 2024) importantly, the latest research has indicated that sorghum allelopathy can not solely be explained through phytotoxic direct action.

Interactions of soil processes and even microbial communities can also be determining factors for the persistence and activity of these compounds (Scavo et al., 2019; Fadiji & Babalola, 2025).

One potential mode of this allelopathic ability is via aqueous sorghum extract (ASE). With a simple preparation method, it is compatible with low-input systems, potentially integrated with lower herbicide inputs. It has been shown experimentally that ASE inhibited the germination and early seedling growth of weeds, especially at moderate to high concentrations (Tibugari et al., 2022; Susilo et al., 2023). However, when released into the wild, this will end in total failure, and the level of risk is highly variable. This disparity underscores the limitations inherent in these data; many are water-soluble, highly adsorb to soil, and exhibit concentration-dependent behavioral response (e.g. hormesis, where invigorating low levels of herbicides rather than inhibiting plant growth is reported (Duke et al., 2025; Scavo et al., 2019).

The critical gap in the literature is the limited integration between mechanistic understanding and agronomic application. Most studies emphasize either isolated bioassays or general allelopathic concepts without unifying phytochemical compositions, dose response dynamics, soil-mediated dynamics, and field-level outcomes. Moreover, non-standardized extraction methods and non-chemical standardization limit the reproducibility of research results and comparison across studies (Kostina-Bednarz et al., 2023; Waligóra et al., 2024).

ASE should not be considered an individual herbicide in the traditional sense of using conventional herbicides from an agronomic perspective. Rather, evidence indicates that it has the most promise as a tool for early-season weed suppression and also as an additive to integrated weed management (IWM) systems. It should also be useful for limiting herbicide use and diversification of control practices in moderate weed pressure conditions (Mahé et al., 2022; Scavo & Mauromicale, 2021). Yet the practical application of these ideas will require laboratory studies to more closely mirror field conditions. That includes better formulations, optimized application rates, and a more complete understanding of soil-plant-environment interactions.

The aim of this review is therefore to provide an integrative synthesis of aqueous sorghum extract linking phytochemical composition with physiological mechanisms, environmental fate, and agronomic performance. This study critically assesses the opportunities and limitations of ASE in clarifying its practical role as a bioherbicide that varies according to context within sustainable weed management systems

1.1 Phytochemical Composition of Sorghum Aqueous Extract

Water-soluble phytochemicals are major contributors to the bioactivity of ASE. By contrast, petrol ether-extractable ASE contains:

- a) high levels of phenolic acids and flavonoids,
- b) much lower to very low amounts of glucosidic phenolic compounds usually found in root exudates, such as cyanogenic glycosides like prunasin, and at most only trace levels of other classically known main.

These compounds differ in terms of polarity, reactivity, and persistence; together they determine the extract's soil behavior and effectiveness as a bioherbicide (Hussain et al., 2021; Le et al., 2018; Kostina-Bednarz et al., 2023).

The composition of phytochemicals is highly dynamic, which depends on genotype, plant developmental stage, environmental conditions and extraction protocol. Consequently, ASE should not be regarded as a chemically homogenous material, but rather as an active mixture of substances whose activity is given by the interactions between different compounds (Scavo & Mauromicale 2021; Waligóra et al. 2024). This variability accounts for one of the main challenges to reproducibility among studies and field conditions.

The main bioactive compounds in ASE are phenolic acids. This includes hydroxycinnamic acids (e.g., ferulic and caffeic acid), which typically present the most phytotoxic properties because they are chemically more

reactive and able to interact with lipid membranes. Conversely, hydroxybenzoic acids are predominantly more soil mobile but decompose faster (Anwar et al., 2021; Mushtaq & Fauconnier, 2024). The activity of these compounds is determined by structural details, such as the degree of hydroxylation or methoxylation, which governs their redox behavior and membrane permeability, and/or adsorption to soil particles. Nonetheless, their function is commonly constrained under field conditions because rapid adsorption to soil particles and microbial degradation reduces the concentration of active ingredients in biopesticides in the soil, thereby decreasing their effectiveness (Scavo et al., 2019). A summary of the major phytochemical constituents of ASE, their chemical characteristics, biological target sites, and proposed modes of action is presented in Table 1.

Redox modulation and hormonal signaling interference comprise the two main mechanisms of how flavonoid exert their effects to contribute to ASE activity. Although their concentrations are lower than those of phenolic acids, they act synergistically by increasing the oxidative stress in target plants and also affecting auxin-regulated growth processes. They play a synergistic rather than a dominant role, and reinforce multi-target physiological disruption (Staszek et al., 2021; Mushtaq & Fauconnier, 2024).

Cyanogenic glycosides such as dhurrin act as a latent source of phytotoxicity. Although these compounds are considered inactive substances, they can liberate toxic elements (toxicity) in soil due to hydrolysis or microbial transformation. This also indicates that the bioactivity of ASE is dynamic and may continue to change after application depending on environmental conditions

and biological processes (Hussain et al., 2022; Kostina-Bednarz et al., 2023).

Low-molecular-weight organic acids such as citric and malic acid show a low level of phytotoxicity themselves, but they can exert their effects on weed suppression through indirect modification of the rhizosphere (pH, nutrient profiles). Such effects that can complement or antagonize the action of other allelochemicals have demonstrated that ASE activity is more a result of multi-chemical–multi-trophic interactions rather than single-compound toxicity (Rahaman et al., 2022).

There is one significant gap in the current body of research regarding chemical data: standardization. Extract concentrations are most often expressed as a percentage (w/v), which does not reflect the real dose of bioactive compounds for any given plant tissue. This caveat lowers reproducibility and makes it difficult to compare dose response relationships between studies in different environments. One way to overcome this problem is through marker-based standardization, for example the phenolic equivalent concentrations (Kostina-Bednarz et al., 2023; Waligóra et al., 2024).

In summary, ASE should be considered as a complex and context-dependent phytochemical system. The bioherbicidal action depends on the additive and synergistic action of different compounds, but their effectiveness is significantly affected by environmental conditions and soil processes. This complexity represents an opportunity for multi-target weed suppression and a significant hurdle to predictability at the field-scale.

1.2 Mechanisms of Weed Suppression

Extracts of sorghum, in aqueous solution (where water may be replaced with other liquids), exert their bioherbicidal activity by a multi-target mode of action

Table 1 Major phytochemical constituents of aqueous sorghum extract and their proposed biological roles in weed suppression

Compound class	Representative compounds	Chemical properties	Primary target site	Proposed mode of action	Persistence in soil
Hydroxycinnamic acids	ferulic acid, p-coumaric acid, caffeic acid	moderate polarity, conjugated structure	membrane systems, redox pathways	ROS induction, membrane interaction	short (microbial degradation)
Hydroxybenzoic acids	gallic acid, syringic acid	high aqueous mobility	early germination processes	enzyme inhibition, oxidative modulation	very short
Flavonoids	luteolin derivatives	polyphenolic, redox-active	hormonal & redox regulation	ROS modulation, auxin interference	moderate
Cyanogenic glycosides	dhurrin	conjugated storage compound	cellular respiration	post-hydrolysis toxicity	variable
Organic acids	citric, malic acid	highly polar	rhizosphere chemistry	pH modification, nutrient chelation	short

that threatens different interlinked physiological processes within the plant. In contrast to the specific biochemical pathways targeted by synthetic herbicides, ASE clearly imparts a broader impact by promoting stress on hormonal, metabolic, and cellular systems. This mode of action is thought to integrate and explain both its broad-spectrum efficacy as well as the variation in field performance under distinct environmental conditions (Hasan et al., 2022; Kostina-Bednarz et al., 2023).

One of the major effects of ASE is manifested during seed germination and seedling root development. Phenolic compounds also influence hormonal regulation, mainly by downregulating the enzyme activation mediated by gibberellins involved in the mobilization of reserves. The disruption hinders the hydrolysis of starch and proteins, delays radicle protrusion, and reduces early seedling growth. Simultaneously, alterations in auxin signaling as well as membrane permeability further suppress cell division and elongation, ultimately leading to a reduction in seedling competitiveness during particular crop weed interactions (Susilo et al., 2021; Rahaman et al., 2022; Alanaz et al., 2023).

ASE disrupts plant energy metabolism by impacting photosynthesis and respiration. Phenolic and quinone-like compounds inhibit photosystem II, leading to decreased ATP and NADPH production due to low electron transport efficiency. Alternatively, mitochondrial respiration can simultaneously be compromised leading to a global energetic deficit that limits biomass accumulation. Unlike single site inhibitors, the simultaneous interference of chloroplast and mitochondria functions with energy-generating pathways by ASE contributes to

the recently suggested that malate and pyruvate are downstream substrates involved in inducing aerobic seedlings acclimation toward salt stress.

Induction of oxidative stress is one of the main mechanisms behind these effects. ASE exposure induces reactive oxygen species (ROS) formation that exceeds the effective neutralization capacity of cellular antioxidant systems. This imbalance results in oxidative damage that causes lipid peroxidation, protein oxidation, and not keeping cells integrity. For example, oxidative damage to membranes induces permeability and causes an imbalance in ions; protein modification considerably affects important metabolism

pathways (Staszek et al. 2021; Singh et al., 2022).

At the cellular level, membrane destabilization and protein dysfunction exacerbate growth inhibition. This increase in lipid peroxidation destroys the structure and function of membrane lipids, resulting in leakage of cell contents and decreased nutrient absorption. Simultaneously, protein oxidative damage diminishes enzymatic activity and contributes to metabolic collapse in susceptible plant species. (Estévez et al., 2021).

Crucially, these physiological responses are highly concentration-dependent. ASE at low concentrations may trigger adaptive

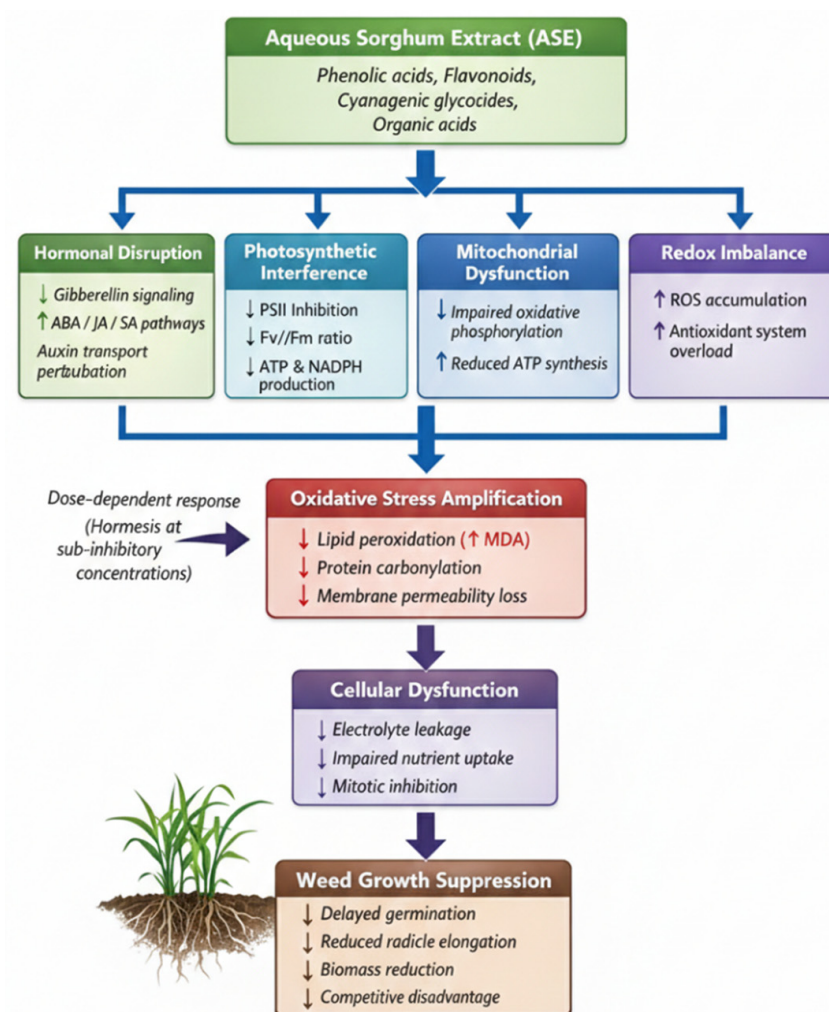


Figure 1 Multi-target mechanistic cascade underlying weed suppression induced by ASE

stress responses or hormesis, thereby promoting limited growth. Overcoming detoxification thresholds represents both contradiction and irreversible destruction at higher doses. This non-linear dose response relationship is a major restriction for agricultural use (Duke et al., 2025). The multi-target mechanistic pathways involved in ASE-induced weed suppression are summarized in Figure 1.

The activity of ASE is also strongly regulated by soil processes in addition to its direct effects on plants. The availability and persistence of its allelochemicals are regulated by multiple factors including adsorption to soil particles, microbial degradation, and environmental conditions. Microbial transformation can, in some cases, reduce phytotoxicity, whereas in other cases it may generate new bioactive compounds. Herein, synergistic or antagonistic interactions have been found to be responsible for the typical differences between strong effects *in vitro* versus variable performance *in vivo* (Scavo et al., 2019; Fadiji & Babalola, 2025).

Responses specific to the species will also impact. Tolerances levels differ between weeds and crops based on antioxidant capacity, detoxification mechanisms, and membrane stability. Therefore, ASE selectivity is not directly toward one target but based on differential physiological resilience, which makes prediction under field conditions complicated (Mahé et al., 2022). A summary of the physiological and biochemical responses induced by ASE in weed species is presented in Table 2.

In conclusion, the consensus regarding weed suppression by ASE is that it depends on a combination of hormonal disruption, energy limitation, oxidative stress, and membrane damage, all of which are influenced by environmental and biological factors. While this multi-layered mode of action provides ASE with broad-spectrum potential, it also introduces variability that needs to be overcome for consistent and reliable performance in the field.

1.3 Efficacy Against Different Weed Species

When used for weed control the efficacy of ASE is determined not only by intrinsic phytotoxicity but also, species-specific sensitivity to exuding phytotoxins as well as environmental conditions resulting in synergistic or antagonistic interactions, and finally allelochemical-based application strategy. In contrast to synthetic herbicides that possess clearly defined target sites, ASE operates as a multicomponent system, and its effectiveness arises from multiple physiological disruptions across multiple processes. Consequently, weed responses are heterogeneous and should be regarded as a continuum rather than a susceptible–resistant dichotomy (Scavo & Mauromicale, 2021; Mahé et al., 2022).

Much experimental evidence has demonstrated that ASE is a potent inhibitor of seed germination and early seedling growth in many important weed species. The species-dependent response is influenced more by phylogenetic and physiological characteristics than by taxonomic classification. Some studies have showed that comparatively much more sensitivity occurred in dicotyledonous weeds, but other researchers indicated either similar responses or even significantly higher levels of this effect in the monocots than measurement values under given concentrations of extracts (Hussain et al., 2021; Tibugari et al., 2022). The differences, in sensitivities, indicate that seed size, the metabolism during germination, antioxidant activity, and its capacity to detoxify phenolic compounds supply variation (Singh et al., 2022). A summary of the reported inhibitory effects of ASE on representative weed species under laboratory and field conditions is presented in Table 3. Consistently, the earliest seedlings are found to be the most vulnerable life stage. Radicle elongation and biomass accumulation are affected more than germination percentage, possibly because of the high metabolic demand and direct exposure of meristematic tissues at early growth. Some researchers argue that even partial suppression at this stage can reduce weed

Table 2 Physiological and biochemical responses of weed species exposed to aqueous sorghum extract

Biological level	Observed effect	Biomarker/indicator	Mechanistic interpretation
Hormonal	reduced germination	↓ α -amylase activity	GA suppression
Photosynthetic	reduced photochemical efficiency	↓ Fv/Fm ratio	PSII interference
Respiratory	energy deficit	↓ ATP content	mitochondrial inhibition
Oxidative	ROS accumulation	↑ H_2O_2 , ↑ O_2^-	redox imbalance
Membrane	lipid peroxidation	↑ MDA	membrane destabilization
Protein	carbonyl accumulation	↑ protein carbonyl	oxidative modification

Table 3 Reported inhibitory effects of aqueous sorghum extract on representative weed species under laboratory and field conditions

Weed Species	Type	ASE concentration (% w/v)	Germination inhibition (%)	Biomass reduction (%)	Experimental condition
<i>Echinochloa colonum</i> (L.) Link	monocot	15–20	60–80	50–70	laboratory
<i>Eleusine indica</i> (L.) Gaertn.	monocot	20	65–85	60–75	laboratory
<i>Amaranthus</i> L. spp.	dicot	10–15	40–70	30–60	laboratory
<i>Phalaris minor</i> Retz.	monocot	15	50–75	45–65	field
Mixed weed flora	mixed	10–20	variable	30–60	field

competitiveness during the critical period of crop establishment, despite incomplete mortality throughout all stages of grain development (Yar et al., 2020; Susilo et al., 2023; Susilo et al., 2025).

The potency of ASE also shows a strong concentration-dependence and often non-linear dose–response relationship. In the case of hormetic effects, low concentrations may promote growth while higher concentrations will exert a strong inhibitory action. This biphasic response complicates dose optimization and helps to explain some of the variability in results across studies and environments (Duke et al., 2025). A schematic representation of comparative dose-response patterns of weed sensitivity to ASE is presented in Figure 2.

Timing and application method are also critical drivers of effectiveness. Soil-applied (pre-emergence) treatments tend to be more consistent because they kill seeds and seedlings at their most vulnerable point. Foliar applications perform poorly (lower penetration, high environmental exposure and low translocation of active compounds in the plant) compared to soil application approaches (Roberts et al., 2022). Moreover, the combination of ASE with residue incorporation or mulching systems facilitates a slow and continuous release of allelochemicals into the soil (Scavo et al., 2019), thus

prolonging the weed suppression potential.

One central limitation is the gap between laboratory and field performance. Whereas, strong inhibitory effects are frequently reported by controlled bioassays, such effects are infrequently replicated in the field. Soil adsorption, microbial degradation,

and their environmental variability significantly lower the bioavailability and persistence of active compounds. Moreover, interactions with crop plants and competition for resources can mask the direct contribution of allelopathy to weed inhibition (Mahé et al., 2022; Fadji & Babalola, 2025).

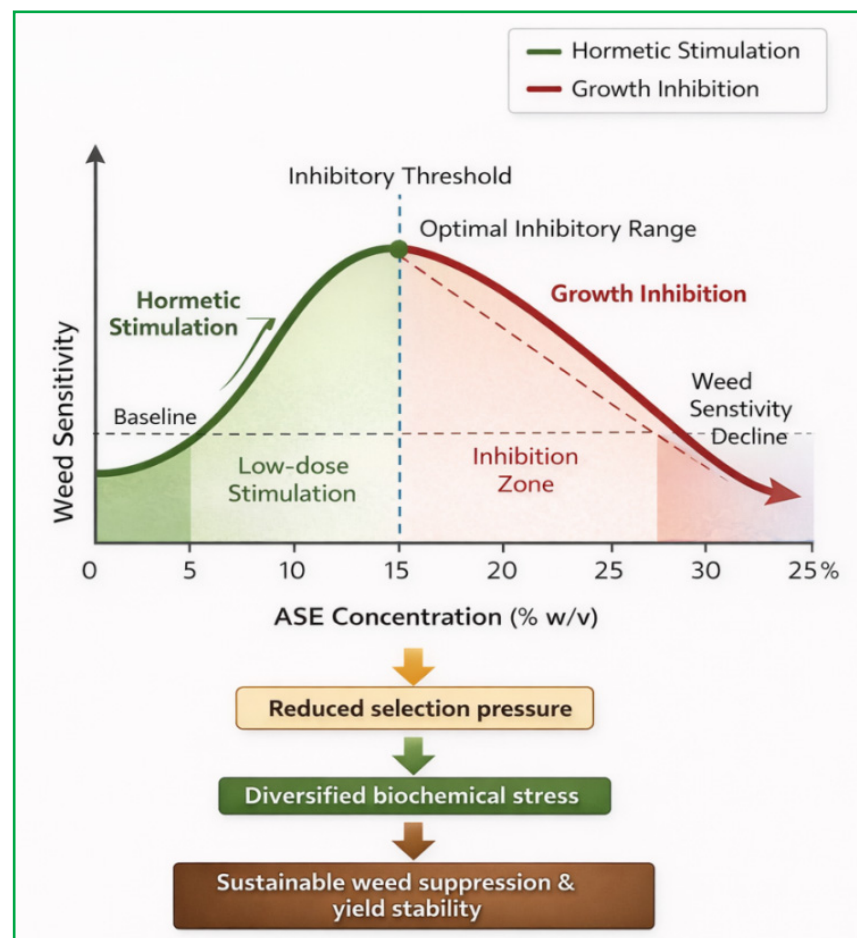


Figure 2 Comparative dose-response patterns of weed sensitivity to ASE

ASE exhibits the greatest performance under conditions of moderate weed pressure and when applied in the early crop development stages across studies. This ability to delay emergence of weed and suppress early biomass accumulation is important for protecting crop yield, especially when used in conjunction with additional weed management strategies. However, it is less effective when weed density is high or when weeds emerge later, making it less suitable as a standalone weed

management strategy (Scavo & Mauromicale, 2021).

Thus, generalizations regarding the efficacy of ASE depend tightly on species traits, environmental conditions and total management regimes. Although it is capable of delivering substantial early control, its main value is in combination with other weed control methods as part of integrated systems, rather than outcompeting conventional herbicides.

1.4 Role in Sustainable and Integrated Weed Management

The integration of ASE into weed management systems is representative of a movement from input heavy chemical control towards more diversified, ecologically based approaches. Instead of being used as a stand-alone herbicide, ASE is considered more effective when placed in an integrated weed management (IWM) systems approach, integrating chemical and cultural tools along with biological strategies (Scavo & Mauromicale 2021; Hickman et al., 2023). A conceptual framework for integrating ASE into integrated weed management systems is presented in Figure 3.

The eliminated labour from harvesting saves fuel, time, provides more efficient resource management, and is beneficial for various practices such as mulching and reduced tillage systems which is one of the biggest assets associated with ASE. Physical suppression of weeds through residue cover in these systems is backed-up by biochemical interference provided by allelochemicals released from sorghum. This joint influence can improve weed emergence control during the early phase of crop establishment and extend suppression during initial stages of crop development, particularly in low-input or organic farming systems (Lewis et al., 2020; Scavo et al., 2019). The persistence and intensity of this effect is likely to vary considerably depending on rates of residue decomposition and environmental conditions, among other factors.

ASE occurs in cropping systems, such that residue from sorghum used in crop rotation and the release of allelochemicals can reduce weed emergence in other crops. The rotation effect might also assist in developing diverse modes of action

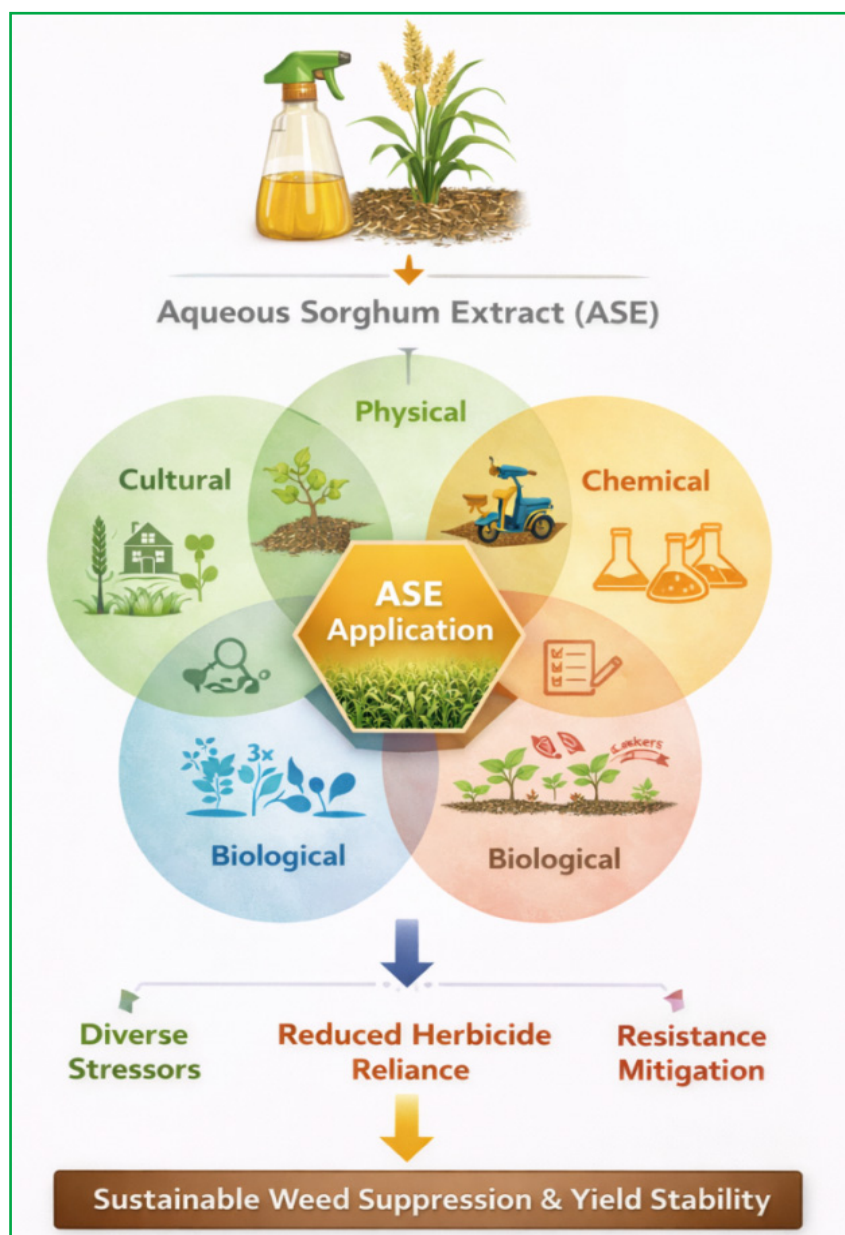


Figure 3 Integration framework of aqueous sorghum extract within integrated weed management systems

for weed suppression to reduce repeated applications of herbicides with similar mechanisms. However, there may be potential conflicts because surviving phytotoxicity can remain a risk for sensitive crops if decomposition periods are not appropriately controlled (Mahé et al., 2022; Scavo et al., 2019).

ASE potentially increases efficacy with reduced-dose chemical methods while reducing the use of conventional herbicides (one of the major agronomic advantages). Accumulated research demonstrated that the weed suppression and crop yield could remain under moderate weed pressure when ASE was combined with sub-lethal herbicide rates. This is due to the additive effects of multi-targeted biochemical action of ASE and well-known activity of traditional herbicides which aims one target will be able to minimize total chemical input (Tibugari et al., 2022; Hussain et al., 2021). Yet, this advantage is context dependent to high weed density and temperature variability.

Working from a resistance management standpoint, ASE adds to the potential for alternative mechanisms in weed control systems. The multi-target effectiveness of HPPD inhibitors means that they have a lower probability of resistance development at any one site compared with most typical herbicides. Nevertheless, adaptive tolerance could persist as frequent re-sampling to herbicides may select for more effective detoxification or stress-response mechanisms (Perotti et al., 2019; Duke et al., 2025). To this end, ASE should not be viewed as a standalone solution, but rather as part of a broader resistance management strategy.

Soil microbiome interactions are key determinants of the establishment and function of ASE in IWM systems. While microbial degradation can result in the reduced persistence of

allelochemicals, it may also produce transformation products with varying degrees of bioactivity. Such processes may be responsible for the variability that is frequently observed in field performance, highlighting the need to develop adaptive application strategies based on soil biological dynamics (Fadiji & Babalola, 2025; Scavo et al., 2019).

At the system level, we can use ASE as a tool for supporting sustainable ag practices that build on common themes such as reducing reliance on synthetic inputs, enhancing ecological interactions and diversifying weed control strategies. The main benefit from it is in early weed control at critical

periods of crop weed competition. For consistent and sustainable performance, it should be intimately linked to other tactics such as regimes of timing, dose and crop-growth stage (Mahé et al., 2022; Scavo & Mauromicale, 2021).

In conclusion, ASE should be integrated into IWM systems. Its success depends on a coordinated integration of herbicide with agronomic practices rather than use in isolation to achieve reliable sustainable weed management outcomes. A conceptual framework describing the systems-level integration of ASE within integrated weed management systems is presented in Figure 4.



Figure 4 Systems-level integration of aqueous sorghum extract within integrated weed management (IWM) frameworks

1.5 Limitations and Challenges

Key limitations on the chemical stability, environmental variability, and agronomic reliability of ASE which promises bioactivity but limits large scale application. These limitations provide an explanation for the case of a strong laboratory performance accompanied with weak field results (Roberts et al., 2022; Mahé et al., 2022).

The major obstacle of ASE is its water-soluble allelochemicals that are intrinsically unstable. Phenolic compounds and their metabolites are prone to photodegradation, oxidation, and microbial degradation rapidly diminishing the bioactive concentration after their application. Consequently, the duration of effective soil exposure is usually short and difficult to control, thus affecting consistent weed biocontrol under field conditions (Scavo et al., 2019; Anh et al., 2021). This loss attempts to offset it with increased application rates, which as we know raises costs and risks of crop injury.

Another challenge is that their high variability across studies and environments leads to low reproducibility. Understanding the composition of ASE is an important question as a better understanding can formulate new methods in extracting it, which would be influenced by the sorghum genotype used for extraction, the plant growth stage at which ASE-containing tissues are harvested followed by physicochemical and environmental conditions as well as extraction methods and solvents. Consequently, extracts labelled in a similar manner may differ widely in their chemical make-up and biological properties. Furthermore, the non-linearity of most dose response relationships means that minute differences in concentration or environmental conditions can result in disproportionately larger biological effects (Duke et al., 2025; Waligóra et al., 2024). The absence of standardized chemical markers also impairs comparability across studies and restricts practicable applicability in the field.

While considering the loss of ASE, from a plant physiological level, any performance in terms of weed pressure and crop yield should be taken collectively on agronomic and not only on physiological inhibition outcomes. The partial suppression seen in lab studies may not be enough to adequately control at moderate to high densities weed competition occurs early enough to reduce yield. Low to moderate weed density confirmation that these works also in the field (Chauhan et al., 2017; Mahé et al., 2022) are less reliable because ASE is most effective when applied during the early stages of growth, limiting its potential as a standalone weed management strategy.

ASE performance is also affected by environmental factors. Soil properties such as organic matter, soil texture and microbial potential are critical determinant of the sorption, transformation and persistence of allelochemicals. Moreover, climatic factors like temperature and moisture also impact degradation rates as well as bioavailability which results in substantial spatial and temporal variability in efficacy (Scavo et al., 2019; Fadji & Babalola, 2025). This complexity consequently hampers reliable predictions of how the fluxes will perform in-situ relative to local conditions without time-consuming calibration on a site-by-site basis.

Another big limitation is crop selection. Since ASE operates at a multitude of physiological pathways, the tender balance between essay rot and weed aye injury is fragile and exceedingly context-dependent. This heterogeneity in crop tolerance, developmental stage, and environment makes dose optimization more challenging. Field applications with variable/patchy distribution may yield hormetic responses that further add to variability in both weed suppression and crop safety (Duke et al., 2025).

Even though the risk of resistance due to single-site herbicides is less with ASE there still remains the potential for adaptive tolerance due to repeated exposure within weed populations. With time, weeds can evolve improved antioxidant defenses or more potent detoxification systems that may lessen the long-term efficacy of ASE. This highlights the need to regulate its use and implement it in combination within cropping systems with diverse weed management tools instead of consecutive individual applications (Perotti et al., 2019).

Then it has regulatory and technical barriers to commercialization and large-scale adoption. This chemical heterogeneity presents challenges for standardization, quality control, and regulatory approval of ASE. Moreover, large-scale production needs continuous biomass supply, effective extraction technologies and stabilisation processes which are still not optimised (Kostina-Bednarz et al., 2023; Roberts et al., 2022).

Ultimately, the development of ASE is hindered by challenges related to chemical instability, diversity across agroecological environments, and limited predictability in their performance in the field. Rising above these challenges will need an integrated approach in terms of enhancing formulation processes, developing standardisation protocols, increasing knowledge on soil-ecological interactions, and improving field-validation efforts. These enhancements are crucial to facilitate the application of ASE in reliable and scalable sustainable weed management systems. A summary of the major

Table 4 Translational constraints limiting large-scale field deployment of aqueous sorghum extract

Constraint category	Underlying mechanism	Agronomic consequence	Research priority
Chemical instability	photodegradation, oxidation	reduced field persistence	encapsulation systems
Soil adsorption	binding to clay/om	lower bioavailability	soil-specific calibration
Microbial degradation	phenolic metabolism	short exposure window	microbiome profiling
Hormesis	sub-lethal stimulation	weed vigor enhancement	dose optimization
Crop safety margin	narrow tolerance window	phytotoxicity risk	selectivity engineering

translational constraints affecting large-scale field deployment of ASE is presented in Table 4.

1.6 Future Research Directions

This necessitates an evolution in research focus from largely descriptive studies towards integrative and application-oriented research that takes ASE from experimental to a reliable agronomic tool. Existing evidence emphasises that the major challenge is not entirely the lack of phytotoxic effects, but the variability and reproducibility under field conditions.

The development of better formulations is a main research focus. Improving stability and controlled release of allelochemicals is important to prolong their activity in soil and to time the releasing with critical phases of weed emergence. Encapsulation and carrier-based delivery systems are being investigated on postharvest performance, but their agronomic performance (Gali et al., 2023; Roberts et al., 2022) and cost effectiveness have not yet been meaningfully evaluated under field conditions.

Standardization is another critical requirement. Most studies provide ASE concentration in crude extract percentage ratio which does not represent the actual amount of bioactive compounds present. Future studies should implement marker-based approaches connecting phytochemical composition and biological activity. This would enhance reproducibility, allow for dose response modelling, and enable regulatory acceptance (Kostina-Bednars et al., 2023; Waligóra et al., 2024).

Another important aspect is building an understanding of soil-mediated processes. Field performance critically depends on how allelochemicals behave in soil, determined by their adsorption-desorption characteristics, microbial transformations, and the environmental conditions. Future experimental designs that develop the combination of soil chemistry and microbiome analyses would provide opportunities to predict ASE traits within diverse agroecological contexts (Scavo et al., 2019; Fadji & Babalola, 2025).

Also, from a mechanistic view, growth should shift to systems-type investigations. The integration of

physiological, transcriptomic, and metabolomic analyses allows for a deeper understanding of how multiple stress pathways interact and assists in identifying biomarkers of sensitivity or tolerance. This would enable specific predictions for species to allow for improved selectivity management (Zhang et al., 2025).

Field validation remains an important gap in the existing literature. Less permissive relationships between these variables in the future will allow for predictions of weed density-related effects on crop yield that are more realistic than those made from controlled bioassays alone, as was the case in this study. Bridging the gap between laboratory and agronomic thresholds is essential to define the practical utility of ASE under real cropping systems (Mahé et al., 2022).

Lastly, there is a need for long-term studies to evaluate ecological and evolutionary consequences. While sulfonylureas are widely used for certain weed species, ongoing monitoring of possible changes in weed tolerance as well as potential effects on soil microbiome dynamics will be essential to facilitate sustainable use within integrated weed management (IWM) systems.

Overall, future research should focus on bridging the gap between mechanistic understanding and field application through coordinated advances in formulation, standardization, and systems-level evaluation.

2 Conclusions

The multi-target mode of action and compatibility with IWM systems make ASE a sustainable plant-based herbicide for weed management. *Rosa rugosa* extract bioactivity is mediated, at least in part, by diverse water-soluble phytochemicals that can disrupt several key physiological processes such as germination, energy metabolism, and redox balance.

But its real-world use continues to be limited by chemical instability, environmental variability, and field performance inconsistency. The impact of ASE is highly context-specific, being dependent on soil processes, climatic conditions, and taxon-specific responses. Therefore, ASE cannot yet be seen as a substitute for synthetic herbicides.

Rather, its ultimate potential would be as a complementary tool that supports herbicide-free weed control early in the growing season, and when combined with other management practice reduces reliance on chemical inputs. ASE, under the right context, can help maintain crop yield while improving the sustainability of weed management systems as a whole.

Future advances require increased formulation stability and chemical standardization, as well as a greater connection between laboratory bioactivity and field-level efficacy. Incorporating an ASE into IWM calls for an approach where systems-based thinking embraces agronomic thresholds, interactions with the environment, and long-term sustainability.

With these developments, ASE can be a valuable ingredient among wedges of diversified weed management systems that reduce reliance on chemical inputs and increase agroecosystem resilience.

Conflict of Interest

The authors declare that there is no conflict of interest.

Author Contributions

Edi Susilo: Conceptualization, Methodology (searching literature and developing a strategy and framework), Data curation (literature screening and curation), Formal analysis (critical synthesis and studies integrated analysis), Visualization (tables and a framework), Writing – original draft, Writing – review & editing. Hesti Pujiwati: Conceptualization, Methodology (refining design of the review), Supervision, Validation (critically appraising the interpretations and theoretical integration), Administrative supervision of the project, Managing resources and finances, Writing – review & editing.

AI and AI-assisted technologies use declaration

This manuscript benefited from the use of artificial intelligence (AI)-assisted technologies during its preparation. Specifically, ChatGPT (developed by OpenAI) was employed to improve the readability and linguistic clarity of the text. The authors affirm that all intellectual content, data analysis, interpretation, and scientific arguments were conceived, written, and verified by the authors themselves. The use of AI was limited to language refinement and did not involve any generation of original research content or interpretation of scientific findings.

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