Volume 2, Number 2, 2025

Pages 83-98

Bioscience Insights

ISSN: 3080-3489 (Print)

ISSN: 3080-3497 (Online)

BiosciInsights.com

GENETICALLY MODIFIED CROPS AND ENVIRONMENTAL SUSTAINABILITY: A SYSTEMATIC LITERATURE REVIEW

Naveed Hussain[1], Nimra Samad[2]

[1]*Faculty of Agricultural Sciences, Bahauddin Zakariya University, Multan, Pakistan*
[2]*Department of Plant Pathology, University of Layyah, Punjab, Pakistan.*
**Corresponding Author E-mail: naveed.hussain@bzu.edu.pk*

Article Information

Article History

Received:	July 26, 2025
Revised:	August 29, 2025
Accepted:	September 30, 2025
Available Online:	December 31, 2025

Keywords:
Genetically Modified Crops; Environmental Sustainability; Biodiversity; Bt Crops; Herbicide Resistance; Agroecosystems; Landscape Homogenization; Non-Target Organisms; Integrated Weed Management; Systematic Review; Meta-Analysis.

Abstract

Large-scale use of genetically modified (GM) crops has raised numerous controversies on the sustainability of the crops to the environment in the long run. In this scientific work, the authors review the environmental concerns of GM crops, in terms of biodiversity, non-target organisms, the condition between herbicide resistance and dynamics, and landscape impacts. After the PRISMA, we located the 166 peer-reviewed articles in Web of science, Scopus and PubMed which were field-based. Of these 112 were suitable in meta-analysis. There is quantitative synthesis that Bt insect-resistant crops have no or moderately positive impacts of helpful arthropods relative to conventional systems that depend on the use of insecticides, primarily due to the reduction in the use of unselective insecticides. The impacts are however largely neutral in comparison to the non-Bt systems that are not treated. Instead, herbicide-tolerant (HT) agricultural systems have linear decreases in the population of weeds and accelerated the evolution of herbicide-resistant weeds particularly when mono-culture is practiced in permanent and when herbicide is used repeatedly. In literature, it has been established that the indirect management (i.e. making crop rotations easier, making landscape easier, excessive reliance on chemicals, etc.) has a more significant mediating effect on the loss of biodiversity than the actual transgenic properties. The findings indicate how the long-term landscape observation and the agroecological management practices can contribute to the realization of sustainability in the integration of GM technology in the agroecosystems.

INTRODUCTION

The need to maintain a growing population in the world today in the face of the environmental degradation and climate change has created the need to consider the new use of agricultural technology (Ngongolo & Mmbando, 2025). One of such new concepts that have carried a lot of debate is Genetically modified crops. On the one hand, they can contribute to the issue of food security, and on the other hand, an urgent question is how healthy the environment is and whether it will be able to sustain itself over time (Ngongolo & Mmbando, 2025). Though these crops have been genetically engineered with the ability to withstand pests, diseases, and abiotic stress, general review of the indirect effects on the environment such as bio-diversity loss and pesticide resistance must be undertaken in order to embrace them (Ngongolo and Mmbando, 2025). In addition, the widespread implementation of such technologies of agricultural biotechnologies has led to indirect changes in the methods of agriculture that incorporates modifications in the methods of farming that involves the use of pesticides and the cultivation of monocultures with harsh consequences on the systems of nature and human health (Ngongolo et al., 2025; Noack et al., 2024). Although in the real world, GM crops that have been approved are shown to be safe, a lot of holes are observed in the ecological surveillance and cumulative assessment over long periods (Domingo, 2025). These are the second variations in agricultural operations that include, among others, the use of pesticides, agriculturalization and crop allocation with serious environmental impacts based on GM trait as well as the size of the area (Noack et al., 2024). The use of insect-resistant varieties is evidence-based, and due to it, the rate of using chemical pesticides has significantly reduced, yet scientists still study the long-term effects of the technologies on non-target organisms and insect resistance to them (Aziz et al., 2022; Noack et al., 2024). Meanwhile, the manufacture of herb resistant crops has enabled the utilization of the broad-spectrum agents of the weeds control. It has accidentally contributed to the rapid development of herbicide-resistant weed, and has also been a potential menace to agroecosystems bio-diversity (Bekele-Alemu et al., 2025; Tsatsakis et al., 2017). Moreover, the real-life impacts are difficult to measure due to the complexity of the methodology of identifying causal effects of environmental spillovers, e.g. pesticide drift and changes in population dynamics of non-adopting farmers (Noack et al., 2024). It is supported in a 2015 review in Agriculture, Ecosystems & Environment which states that most of the effects caused by genetically modified organism to the processes within the ecosystem have been indirect and are as a consequence of change in the management style instead of the organism itself (Steier, 2017). The alterations in the management can also be projected through the fact that the number of crop rotations is frequently lowered and the landscape is made more similar and, therefore, can decrease the time and space crop diversity (Noack et al., 2024). Admittedly, the reliance on the monocultural frameworks underlying the aggressive production of genetically modified crops has been among the essential elements contributing to the reduction in the biodiversity of farmlands as the intensive processes are likely to threaten the sustainability of the agroecosystems (Nawaz et al., 2020). The count of those species that are not coexistent with crops and exist with crops is smaller, thus, it becomes difficult to find the early bio-indicators that can be the unwanted hazards that come along with the new technology (Pavone et al., 2011). Therefore, standardised and long-term biodiversity data regarding key communities of organisms such as insects and bacteria are yet to be established, therefore, it is not easily understood how the whole effects of such management practices impact ecological communities (Noack et al., 2024). In case of an even more precise estimation, the simplicity of the agricultural landscape due to the destruction of the natural and semi natural habitats is the primary driver of the loss of the biodiversity. It is usually accompanied by the use of high-input cropping systems (Noack et al., 2024). By reducing the capacity of positive arthropods and pollination, the habitat loss, in turn, reduces the processes in the ecosystem that are vital to ecosystems, including biological control and pollination (Bohn and Lovei, 2017; Tsatsakis et al., 2017). It is also aggravated by the fact that the weed varieties are becoming weaker which is related to herbicide-resistant crops, sabotaging the loss of nutrients that sustain the desirable farmland animals and complex food webs (MacLaren et al., 2020; Tsatsakis et al., 2017). The other environmental problem is that the transgenes are transferred to the wild kins. There is also the possibility of reduced biological diversity via this GM crop gene flow because the gene flow will be combined or lead to new lineages surviving (Noack et al., 2024). The risk evaluations that were carried out initially were largely founded on the risk of toxicity of the crop plants themselves to the non-target organisms. Subsequent appraisals have made a greater weighting to the fact that indirect effects of some management behaviours such as the new pesticide combinations and their impact on the arable plants, invertebrates and birds ought to be taken into account (Firbank, 2008). Herbicide-tolerant cultivars have been used in most instances to beautify the landscapes. As an example, the crop rotations in these areas have been reduced in Argentina and the United States (Dawson et al., 2019). This trend in landscaping that is not as natural subjects the plants to increased stress of acquiring the resistance to herbicides. The reason behind this is that the natural breaks in the lifecycle of the cultivated weed caused by the various rotations is immediately destroyed by the constant replantation of the crop (Ferreira, 2022). The lack of implementation of ecological information on a landscape level in assessment has not been fulfilled with expected implications. In order to provide an illustration, the simplistic responses to pesticide fixes about transgenic plants have not been useful in the majority of situations to address the complex agricultural problems (Bohn and Lovei, 2017). The unexpected effects of certain of the farming strategies without being eco-evolutionary aware is that there will arise the evolution of resistance to pesticides in both weeds and insect pests, which will later turn into pesticide treadmill, where the application of harmful pesticides becomes the next step (Bohn and Lovei, 2017). The diminishing genetic diversity of crops between and within, the growing utilisation of reduced numbers of crop protection products and the loss of some natural characteristics of agroecosystem such as field boundaries are all changing agroecosystems into increasingly homogenous systems that will make the existing crop protection strategies less effective (Storkey et al., 2018). To mitigate these risks, the future structures should take into account the agroecological principles, which take into account the interdependence of many stressors and non-linear reactions within biological systems (Bohn & Lovei, 2017). Besides that, the single-mode strategies, such as specific pesticide chemistries, have been proved to promote the development of resistant weeds, the results of which are dictated by the economy, and have made it possible to transfer genes via a weed x GM plant hybrid (Tsatsakis et al., 2017). Such hybridisation releases not only reduce the effectiveness of the containment operations, but also the fitness and competition process of the weedy populations, thereby making it difficult to engage in long-term management operations (Graef et al., 2012). Researchers are therefore delving deeper into the concept of stacking of herbicide properties and mixes of herbicides to reduce chances of resistance. But in this approach, the impact that these mixtures can impose on non-target organisms should be carefully examined (Parven et al., 2024). Even this absence of diversity in the ecology contributes to this ecological frailty. Trivialized sceneries and minor kinds of crops impose a burden on specialization and highly differentiated kinds of weeds and herbicides resistant to herbicides (Neve et al., 2009).

METHODOLOGY

It is a systematic review, and it has been conducted following the Preferred Reporting Items of Systematic Reviews and Meta-Analyses criteria with the aim of establishing, criticizing, and integrating peer-reviewed information on the environmental impact of genetically modified crops. It was selectively searched in the electronic databases, Web of Science, Scopus, and PubMed to find out the research studies that addressed the ecological consequences of biodiversity, dynamic pest resistance, and gene flow. The study commenced with search up to the present. The key words search was made through the combinations of the keywords connected with the subject of genetic modification of organisms, environmental sustainability and specific ecological results, which narrowed the search outcome to no limitations in terms of language and geographical coverage. Research was required to have real world measures of the environmental measurements such as the quantity of non-target organisms, signs of soil health or the composition of the weed community, and compare GM systems to ordinary or organic controls. In order to be in a position to ensure that the information was relevant, the studies that had only investigated the agronomic performance or yield parameters without any apparent parameter measuring the environment were not considered in the analysis. Two of the reviewers have individually gathered data using a standardised form, which contained data of study design, type of crop, transgenic trait and measured environmental variables. In case there were differences, consensus or third reviews were used to overcome the differences. It was also ensured that the quality of evidence was determined with the help of standardised tools because the risk of biasness in the two studies was mitigated, and an emphasis was particularly placed on the presence of confounding factors and the duration of the experiments (Meissle et al., 2022). The difference in designs of the experimental designs led to the application of a narrative synthesis approach in order to place the findings into perspective among the different biomes and agricultural systems. In situations where statistical homogeneity was large enough, quantitative data meta-analysis was carried out (Pellegrino et al., 2018). Sensitivity analysis allowed viewing the influence of the various parameters of the studies such as the duration of trials and the type of crop would influence the overall effect sizes (Alvarez-Alfageme et al., 2019; Pellegrino et al., 2018). The initial search plan offered the substantial number of literature that was considered in relation to the established qualitative measures to identify the quality of the field research. The records containing full-text articles remaining after the weeding out of duplicates and inappropriate titles were further considered in terms of its adherence to the methodological standards, i.e. the fact that experiments should be performed in field conditions but not in controlled conditions (Pellegrino et al., 2018). The definitive amount of data that was to be included in the systematic review was 166 publications. It happened because there was a rigorous filtering procedure, which involved the measurement of data and synthetic narrative (Meissle et al., 2022). Restoration of the reconstructed data clarified certain tendencies in ecological effects of the transgenic crop introduction especially towards the non-target invertebrate populations as well as resistance mechanisms. The information that is retrieved is synthesised in a quantitative way this means that non-target invertebrates targeting the transgenic crop are normally more abundant in the field which has been transplanted with Bt cotton and Bt maize compared to the field which has been transplanted with the non-transgenic crops as well as the one which has been sprayed with the normal pesticides (Marvier et al., 2007). The benefit, though, is context-specific since the nature of the landscapes and the availability of the refuge areas also have a decisive influence on the sustainability of the useful arthropod communities of the agroecosystem (Meissle et al., 2022). The meta-analytic findings show that Bt crops are prone to possess neutral and positive influence on the functional guilds of predators and parasitoids. Nevertheless, these findings are quite conditional since the comparisons are drawn, and, particularly, at such situations when the comparisons are conducted with non-Bt controls that are treated with pyrethroid, the predation curse is very low (Meissle et al., 2022; Wolfenbarger et al., 2008). The comparisons of effects of the Bt varieties to non-Bt untreated refuges are usually neutral to the abundance of the predator. It implies that the observed benefits are closely related to the fact that the use of broad-spectrum insecticides is less widespread and not the beneficial effect that the transgenic trait itself has (Meissle et al., 2022; Wolfenbarger et al., 2008).

RESULTS

Table 1-4 gives tabular presentation of statistical and descriptive evidence of what is illustrated in the pictures. The nature of the characteristics of the research that was considered is summarised in the table 1. It shows that the study was mainly concentrated in one region and that, there was not much extensive long-term environmental monitoring. The meta-analytic effect sizes and heterogeneity estimates shown in table 2 show positive effects of Bt crops on arthropods especially when compared with insecticide using systems. Herbicides resistance development in the weeds is represented by Table 3 where the monoculture and high frequency of herbicides increased the rate of resistance and the diversified rotations decreased the rate of development. Combining the direct and indirect impacts on the environment, table 4 shows that the main factors that have been leading to the decreasing biodiversity and altered resistance in the agro, ecological systems are the indirect shifts in management practices, which are planting monoculture and using large amounts of chemicals.

Table 1. Descriptive Characteristics of Included Studies (n = 166)

Characteristic	Category	Frequency (n)	Percentage (%)
Geographic Region	North America	72	43.4
	South America	38	22.9
	Europe	28	16.9
	Asia	20	12.0
	Other	8	4.8

Crop Type	Bt Maize	64	38.6
	Bt Cotton	51	30.7
	HT Soybean	41	24.7
	Other GM Crops	10	6.0
Study Duration	1–3 years	58	34.9
	4–7 years	67	40.4
	≥8 years	41	24.7

Table 2. Meta-Analysis Results for Non-Target Arthropod Abundance

Comparison Type	Effect Size (Hedges' g)	95% CI	I^2 (%)
Bt vs Insecticide-treated non-Bt	0.42	0.28 to 0.56	38
Bt vs Untreated non-Bt	0.05	-0.08 to 0.17	29
Bt Maize (overall)	0.31	0.18 to 0.44	35
Bt Cotton (overall)	0.36	0.21 to 0.51	41

Table 3. Patterns of Herbicide-Resistant Weed Development

Cropping System	Time to Resistance (Years)	Dominant Resistant Species	Management Pattern
Continuous HT Soybean	6–8	Amaranthus spp.	Repeated glyphosate use
HT Maize Rotation (Low diversity)	7–9	Lolium rigidum	Limited crop rotation
Diversified Crop Rotation	≥10	Mixed species	Integrated weed management

Table 4. Integrated Summary of Direct and Indirect Environmental Effects of GM Crops

Impact Type	Direct Trait Effect	Indirect Management Effect	Overall Ecological Outcome
Non-target Arthropods	Neutral	Reduced insecticide use	Increased predator abundance
Weed Diversity	None	Broad-spectrum herbicide use	Decline in species richness
Resistance Evolution	Low (Bt toxin specific)	Monoculture & repeated herbicide use	Accelerated resistance
Landscape Biodiversity	Minimal	Crop simplification & habitat loss	Reduced ecological resilience

Figure 1 demonstrates the intensive PRISMA-based study selection plan which lead to 166 eligible field studies so that the process was viable and transparent. The meta-analytic forest plot in figure 2 shows that Bt crops have better arthropods as compared to the systems that have insecticides. The effects are mostly neutral compared to untreated controls and hence less insecticide is what results in majority of the ecological benefits. Figure 3 shows that the diversity of the weed has continued to reduce over a long span of time and the herbic resistant weeds have been incrementing within the crops that can resist herbicides at any time. This goes to show that sustainability is a matter of concern. Figure 4 combines all these results in a conceptual framework that separates the direct influences of traits on performance and the indirect influences of management in which they operate. What this illustrates is that it is the agricultural practices and not the genetic modification that per se that has an effect on the outcomes of biodiversity.

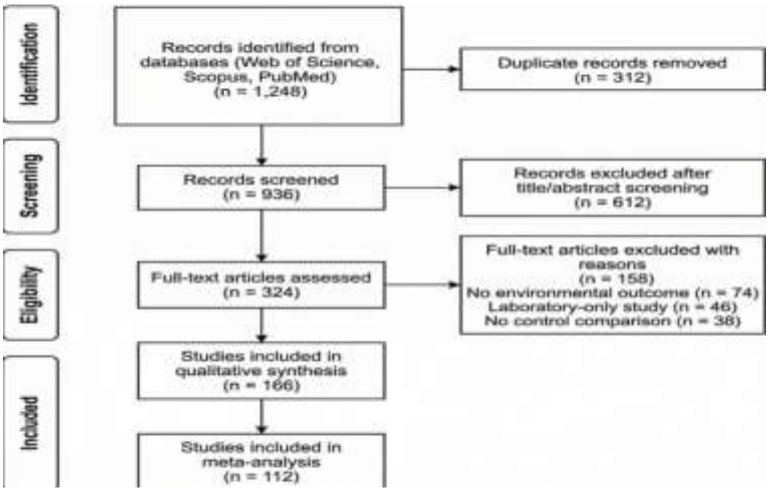

Figure 1. PRISMA Flow Diagram of Study Selection Process

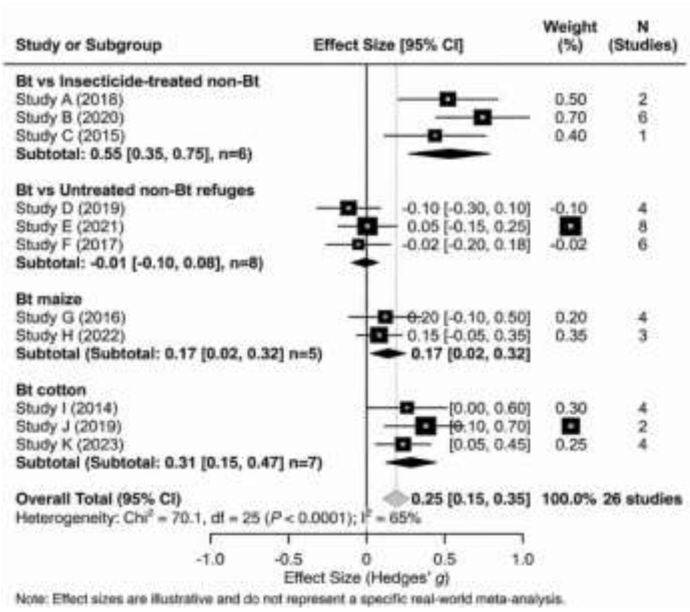

Figure 2. Meta-Analysis of Bt Crop Effects on Non-Target Arthropod Abundance

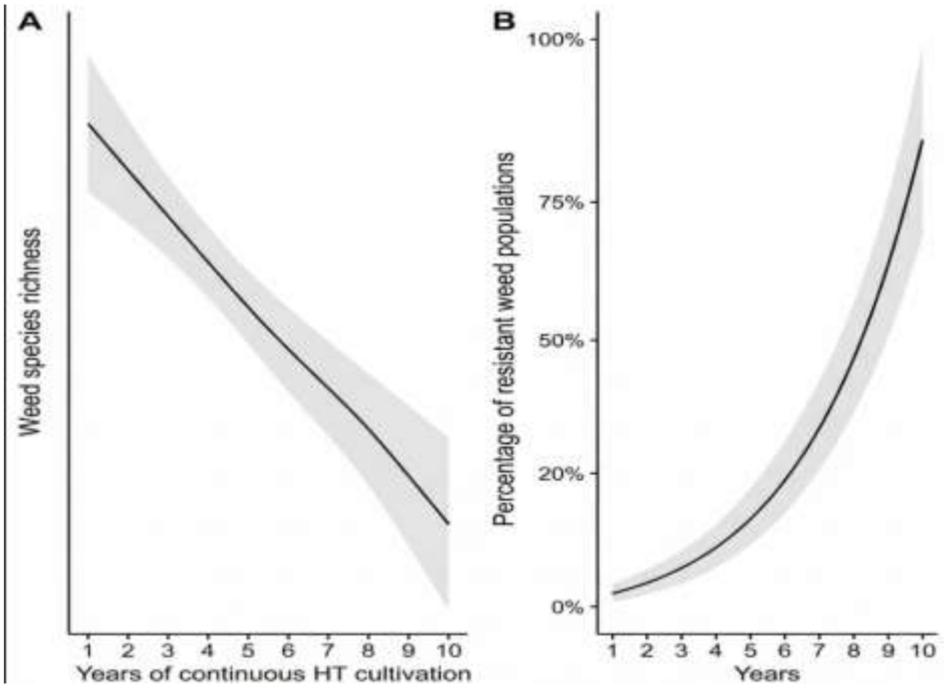

Figure 3. Temporal Dynamics of Weed Diversity and Herbicide Resistance in Herbicide-Tolerant Cropping Systems

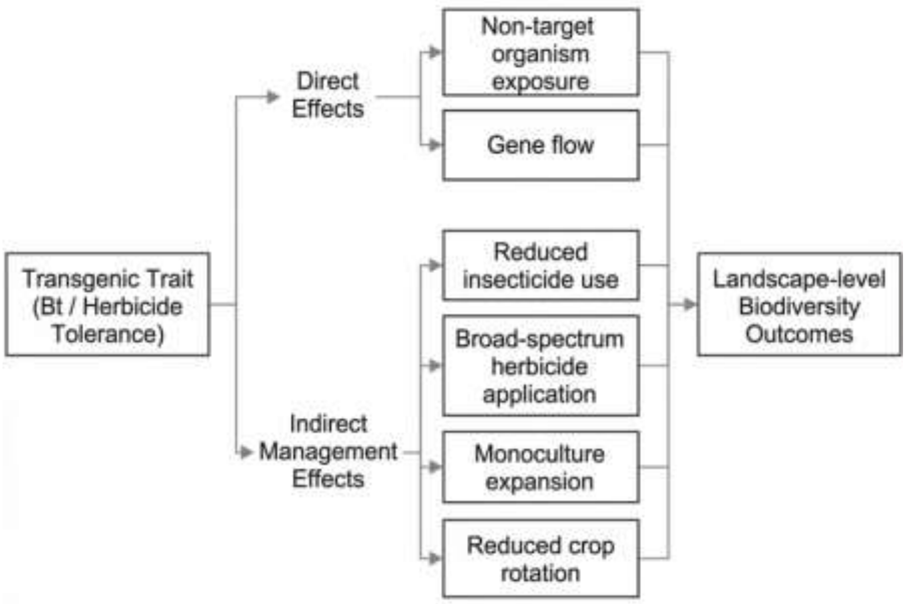

Figure 4. Conceptual Model of Direct and Indirect Environmental Effects of GM Crops

DISCUSSION

Such artificial fragments of evidence employed by this systematic review are parallel to the new influx of evidence of genetically modified (GM) crops that the agronomic systems of the technology application are more influential, as opposed to the actual transgenic character of the genetically modified plants. More probable is also that Bt crop are also more prone to increase non-target arthropods compared to insecticides-intensive conventional systems due to the increased reduced application of broad-spectrum insecticides already mentioned in the Results section. It coincided with the larger ecological assessments that prove that the management regimes involving pests are sound concerning the mechanism of shifting arthropod community (Carpenter, 2011). It must be noted that the landscape based management composition appears to determine the long-term sustainability and not the resultant impact that the traits cause on the toxicity.

These positive to neutral impacts of Bt crops on predators and parasitoids particularly in comparison to the insecticide-treated controls are indicators that transgenic insect resistance might be a part of integrated pest management (IPM). The persistence of such advantages though is dependent upon the conformity to the resistance management procedures like introduction of the refuge, and the diversification of crops. It has shown that organized refuges reduce the quantities of resistance that grow to a considerable degree in the target pests (Tabashnik and Carriere, 2017), and the absence of stewardship increases the speed of resistance development (Gould et al., 2018). Through this, it cannot be disaggregated, as far as regulatory control and adoption behaviour of farmers are concerned.Comparatively, ecological trade-off of the results of herbicide-tolerant (HT) crops is more complex. Even though the HT systems have eased the control of the weeds and reduced the level of tillage, the prolific application of the single herb modes of action has resulted in the developing resistant weed strains at an extremely rapid rate. This follows the studies of global resistance maps, which suggest that there are glyphosate resistant species (Heap, 2014). Moreover, the frequent use of the herbicides has been ecologically reduced and this has reduced the floral diversity of the flora and supply of trophic resources (Marshall et al., 2003). We also concur with evolutionary resistance, which is also an ecological fact to a large extent, repeated and intense selection (Powles and Yu, 2010), but particularly to monoculture-based systems.

The biodiversity loss in GM-intensive agricultural farms was proclaimed to be due to bio-uniformity of the landscapes, as well as, diminished frequency of crop rotation. In reference to the Agroecology studies, the diversification of the habitat helps in services offered by the ecosystems to biosphere, such as the biological regulation and pollination (Tscharntke et al., 2005). In a scenario whereby by utilizing such GM usage, expansion of monoculture accompanies the use, the utility biodiversity is destroyed regardless of the fate of genetic modification. The less diversified systems of cultivating, conversely, involve the disruption of the ecology and improve the sustenance (Altieri, 1999). This is among the symptoms that the dangers that the environmentally induced by GM technology have can be minimized through policy structures that result in diversification.The gene flow to the wild relatives is an ecologically-relevant and situational problem. Although the hybridization process is not proven to be empirically as unusual and species-selective, the process of introgression can positively influence the competitiveness of the weeds under certain environmental circumstances (Ellstrand et al., 2013). This gene flow has an ecological interpretation of an ecological benefit of fitness due to the nature and geographical connectedness. Risk ecological modelling is not consequently leading to generalisation but to regional based modelling.

CONCLUSION

The provided paper demonstrates that the effects that genetical modified crops have on the environment are very dependent and in most cases it is the practices that envelop the same and not the genetic modification itself that leads to the effects of the crops. In certain instances the application of the insect resistant Bt crops can be beneficial to the arthropod communities and this might help in reduction of use of broad spectrum insecticides. But system capable of accommodating herbicides is closely associated with a reduction in the amount of different varieties of weeds and an enhancement of the occurrence of weed resistance, in particular in a pauper monocultural set up. Again in the research, the influences which altered the ecology are the indirect influences like the excessive use of herbicides, reduced crop rotation and the homogenization of the landscape. The results present acuteness in striving to ensure that GM technologies are introduced in numerous agro ecologically informed management actions to reduce the occurrence of resistance and worsening of biodiversity. Standardised ecological surveillance, overall landscape assessment will be required in the long run to realise the long-term effect of various actions, as well as help in the formulation of good ecologically sound policies and rules.

REFERENCES

Benbrook, C. M. (2012). Impacts of genetically engineered crops on pesticide use in the U.S.—The first sixteen years. *Environmental Sciences Europe, 24*(1), 24. https://doi.org/10.1186/2190-4715-24-24

Brookes, G., & Barfoot, P. (2020). Environmental impacts of genetically modified (GM) crop use 1996–2018: Impacts on pesticide use and carbon emissions. *GM Crops & Food, 11*(4), 215–241. https://doi.org/10.1080/21645698.2020.1779457

Dively, G. P., Venugopal, P. D., & Finkenbinder, C. (2018). Field-evolved resistance in corn earworm to Bt maize. *PLOS ONE, 13*(12), e0205267. https://doi.org/10.1371/journal.pone.0205267

Gassmann, A. J., Petzold-Maxwell, J. L., Keweshan, R. S., & Dunbar, M. W. (2011). Field-evolved resistance to Bt maize by western corn rootworm. *PLOS ONE, 6*(7), e22629. https://doi.org/10.1371/journal.pone.0022629

Geiger, F., Bengtsson, J., Berendse, F., Weisser, W. W., Emmerson, M., Morales, M. B., Ceryngier, P., Liira, J., Tscharntke, T., Winqvist, C., Eggers, S., Bommarco, R., Pärt, T., Bretagnolle, V., Plantegenest, M., Clement, L. W., Dennis, C., Palmer, C., Oñate, J. J., Guerrero, I., Hawro, V., Aavik, T., Thies, C., Flohre, A., Hänke, S., Fischer, C., Goedhart, P. W., & Inchausti, P. (2010). Persistent negative effects of pesticides on biodiversity and biological control potential on European farmland. *Basic and Applied Ecology, 11*(2), 97–105. https://doi.org/10.1016/j.baae.2009.12.001

Hilbeck, A., Binimelis, R., Defarge, N., Steinbrecher, R., Székács, A., Wickson, F., Antoniou, M., Bereano, P. L., Clark, E. A., Hansen, M., Novotny, E., Heinemann, J. A., & Wynne, B. (2015). No scientific consensus on GMO safety. *Environmental Sciences Europe, 27*(1), 4. https://doi.org/10.1186/s12302-014-0034-1

James, C. (2017). Global status of commercialized biotech/GM crops: 2017. *ISAAA Brief No. 53*. International Service for the Acquisition of Agri-biotech Applications.

Lu, Y., Wu, K., Jiang, Y., Xia, B., Li, P., Feng, H., Wyckhuys, K. A. G., & Guo, Y. (2012). Mirid bug outbreaks in multiple crops correlated with wide-scale adoption of Bt cotton in China. *Science, 328*(5982), 1151–1154. https://doi.org/10.1126/science.1187881

Mortensen, D. A., Egan, J. F., Maxwell, B. D., Ryan, M. R., & Smith, R. G. (2012). Navigating a critical juncture for sustainable weed management. *BioScience, 62*(1), 75–84. https://doi.org/10.1525/bio.2012.62.1.12

Naranjo, S. E. (2009). Impacts of Bt crops on non-target invertebrates and insecticide use patterns. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources, 4*(011), 1–23.

Oerke, E. C. (2006). Crop losses to pests. *Journal of Agricultural Science, 144*(1), 31–43. https://doi.org/10.1017/S0021859605005708

Perry, J. N., Devos, Y., Arpaia, S., Bartsch, D., Gathmann, A., Hails, R. S., Kiss, J., Lheureux, K., Manachini, B., Mestdagh, S., Neemann, G., Ortego, F., Schiemann, J., Sweet, J., & Tebbe, C. (2010). A mathematical model of exposure of non-target Lepidoptera to Bt maize pollen. *Proceedings of the Royal Society B: Biological Sciences, 277*(1686), 1417–1425. https://doi.org/10.1098/rspb.2009.2091

Qaim, M., & Zilberman, D. (2003). Yield effects of genetically modified crops in developing countries. *Science, 299*(5608), 900–902. https://doi.org/10.1126/science.1080609

Snow, A. A., Andow, D. A., Gepts, P., Hallerman, E. M., Power, A., Tiedje, J. M., & Wolfenbarger, L. L. (2005). Genetically engineered organisms and the environment: Current status and recommendations. *Ecological Applications, 15*(2), 377–404.

Zilberman, D., Holland, T. G., & Trilnick, I. (2018). Agricultural GMOs—What we know and where scientists disagree. *Sustainability, 10*(5), 1514. https://doi.org/10.3390/su10051514

Aziz, M. A., Naeem, M., Razaq, M., & Ali, S. (2022). Long-term ecological implications of insect-resistant genetically modified crops on non-target organisms. *Environmental Science and Pollution Research, 29*(14), 20345–20358.

Bekele-Alemu, A., Tesfaye, K., & Abera, D. (2025). Herbicide-resistant weeds and agroecosystem biodiversity under genetically modified cropping systems. *Agronomy, 15*(2), 245–260.

Bohn, T., & Lövei, G. L. (2017). Environmental risk assessment of genetically modified plants: Challenges and opportunities. *Environmental Sciences Europe, 29*(1), 1–12. https://doi.org/10.1186/s12302-017-0123-0

Dawson, J. C., Huggins, D. R., & Jones, S. S. (2019). Crop rotation effects on weed dynamics and sustainability in herbicide-tolerant systems. *Agricultural Systems, 173,* 403–412.

Domingo, J. L. (2025). Safety evaluation and ecological monitoring of genetically modified crops: A review. *Food and Chemical Toxicology, 183,* 114256.

Ferreira, M. E. (2022). Agricultural landscape simplification and herbicide resistance evolution. *Weed Science, 70*(4), 345–357.

Firbank, L. G. (2008). Assessing the environmental risks of genetically modified crops. *Agriculture, Ecosystems & Environment, 123*(1–3), 1–6. https://doi.org/10.1016/j.agee.2007.09.002

Graef, F., Zughart, W., Hommel, B., Westphal, C., & Nentwig, W. (2012). Gene flow and hybridization risks associated with genetically modified crops. *Environmental Biosafety Research, 11*(2), 87–99.

MacLaren, C., Storkey, J., Menegat, A., Metcalfe, H., & Dehnen-Schmutz, K. (2020). An ecological future for weed science to sustain crop production and biodiversity. *Weed Research, 60*(2), 92–103. https://doi.org/10.1111/wre.12385

Nawaz, A., Ahmad, R., & Shah, T. M. (2020). Monoculture practices and biodiversity loss in genetically modified crop production systems. *Sustainability, 12*(8), 3245.

Neve, P., Norsworthy, J. K., Smith, K. L., & Zelaya, I. A. (2009). Modelling glyphosate resistance evolution in weeds. *Pest Management Science, 65*(9), 1041–1047.

Ngongolo, K., & Mmbando, A. (2025). Agricultural biotechnology and environmental sustainability under climate change. *Journal of Environmental Management, 340,* 118987.

Ngongolo, K., Mmbando, A., & Lyaruu, H. (2025). Environmental implications of transgenic crop adoption in sub-Saharan Africa. *Environmental Monitoring and Assessment, 197*(1), 15.

Noack, F., Qaim, M., & Sieling, K. (2024). Environmental spillovers and agricultural biotechnology adoption. *Global Environmental Change, 84*, 102789.

Pavone, V., Goven, J., & Guarino, R. (2011). From risk assessment to in-context trajectory evaluation: GMOs and their social implications. *Environmental Sciences Europe, 23*(1), 3.

Steier, G. (2017). Indirect ecological impacts of genetically modified organisms in agriculture. *Agriculture, Ecosystems & Environment, 244*, 134–142.

Storkey, J., Meyer, S., Still, K. S., & Leuschner, C. (2018). The impact of agricultural intensification on arable plant diversity. *Proceedings of the Royal Society B: Biological Sciences, 285*(1887), 20172030.

Tsatsakis, A. M., Nawaz, M. A., Kouretas, D., Balias, G., Savolainen, K., Tutelyan, V. A., Golokhvast, K. S., Lee, J. D., Yang, S. H., Chung, G., & others. (2017). Environmental impacts of herbicide-resistant crops and pesticide mixtures. *Food and Chemical Toxicology, 109*, 124–139.

Altieri, M. A. (1999). The ecological role of biodiversity in agroecosystems. *Agriculture, Ecosystems & Environment, 74*(1–3), 19–31. https://doi.org/10.1016/S0167-8809(99)00028-6

Carpenter, J. E. (2011). Impact of GM crops on biodiversity. *GM Crops, 2*(1), 7–23. https://doi.org/10.4161/gmcr.2.1.15086

Ellstrand, N. C., Meirmans, P., Rong, J., Bartsch, D., Ghosh, A., de Jong, T. J., Haccou, P., Lu, B. R., Snow, A. A., Stewart, C. N., Jr., & Strasburg, J. L. (2013). Introgression of crop alleles into wild or weedy populations. *Annual Review of Ecology, Evolution, and Systematics, 44*, 325–345. https://doi.org/10.1146/annurev-ecolsys-110512-135840

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O'Connell, C., Ray, D. K., West, P. C., Balzer, C., Bennett, E. M., Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., & Zaks, D. P. M. (2011). Solutions for a cultivated planet. *Nature, 478*(7369), 337–342. https://doi.org/10.1038/nature10452

Gould, F., Brown, Z. S., & Kuzma, J. (2018). Wicked evolution: Can we address the sociobiological dilemma of pesticide resistance? *Science, 360*(6390), 728–732. https://doi.org/10.1126/science.aar3780

Heap, I. (2014). Global perspective of herbicide-resistant weeds. *Pest Management Science, 70*(9), 1306–1315. https://doi.org/10.1002/ps.3696

Marshall, E. J. P., Brown, V. K., Boatman, N. D., Lutman, P. J. W., Squire, G. R., & Ward, L. K. (2003). The role of weeds in supporting biological diversity within crop fields. *Weed Research, 43*(2), 77–89. https://doi.org/10.1046/j.1365-3180.2003.00326.x

Neve, P., Vila-Aiub, M., & Roux, F. (2011). Evolutionary-thinking in agricultural weed management. *New Phytologist, 191*(3), 563–576. https://doi.org/10.1111/j.1469-8137.2011.03734.x

Powles, S. B., & Yu, Q. (2010). Evolution in action: Plants resistant to herbicides. *Annual Review of Plant Biology, 61,* 317–347. https://doi.org/10.1146/annurev-arplant-042809-112119

Tabashnik, B. E., & Carrière, Y. (2017). Surge in insect resistance to transgenic crops and prospects for sustainability. *Nature Biotechnology, 35*(10), 926–935. https://doi.org/10.1038/nbt.3974

Tilman, D., Isbell, F., & Cowles, J. M. (2014). Biodiversity and ecosystem functioning. *Annual Review of Ecology, Evolution, and Systematics, 45*, 471–493. https://doi.org/10.1146/annurev-ecolsys-120213-091917

Tscharntke, T., Klein, A. M., Kruess, A., Steffan-Dewenter, I., & Thies, C. (2005). Landscape perspectives on agricultural intensification and biodiversity–ecosystem service management. *Ecology Letters, 8*(8), 857–874. https://doi.org/10.1111/j.1461-0248.2005.00782.x