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Meta Research

Evaluating the safety of genetically modified crops: Findings from toxicological meta-research

Mohammed Bashir Tijjani[1], Adamkolo Mohammed Ibrahim[2]
mtijjani@unimaid.edu.ng, adamkolo@unimaid.edu.ng

[1]University of Maiduguri, Faculty of Veterinary Medicine, Department of Veterinary Pharmacology and Toxicology, 1069 Bama Road, Maiduguri, Borno State, 600104, Nigeria

[2]University of Maiduguri, Faculty of Communication and Media Studies, Department of Mass Communication, 1069 Bama Road, Maiduguri, Borno State, 600104, Nigeria

ORCID:
M. B. Tijjani https://orcid.org/0000-0003-2149-5279
A. M. Ibrahim https://orcid.org/0000-0003-1662-7054

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TMB: Conceptualization; Project administration; Investigation; Data curation; Writing — original draft.
IAM: Methodology; Investigation; Data curation; Formal analysis; Writing — review & editing.

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This meta-analysis examined the safety of genetically modified (GM) crops by collating findings from controlled animal feeding trials and human observational studies published between 2017 and 2025. The investigation critically assessed acute and chronic toxicity, allergenicity, metabolic disturbances and carcinogenic endpoints, focusing on research from Nigeria, Africa and Western regions (Europe and the USA). Advanced statistical methods, including random-effects modelling, subgroup analyses and meta-regression, were employed to quantify heterogeneity and evaluate the robustness of the evidence. The findings are presented in percentage terms to facilitate a clear summary of the safety profile of GM crops. The analysis indicates that genetically modified foods are not acutely toxic while some studies reported minor metabolic and immunological changes on chronic or prolonged exposure. Discrepancies in chronic toxicity findings were largely due to variations in experimental model, study design and sample size. Therefore, overall evidence supports the general safety of GM crops under current testing protocols; however, some uncertainties persist regarding long-term effects. Hence, the paper concluded that safety depends on the type of modifications made. Insect-resistant and pesticide-tolerant modifications are more associated with safety concerns than any other type, like biofortified modification.

Key words: genetically modified crops, toxicological safety, meta-research, crop-vigilance, risk assessment

Introduction

Evaluating the safety of genetically modified (GM) crops has spanned scientific, ethical and socio-political domains for more than three decades. Following the first field trials in the early 1990s, most notably for insect-resistant *Bacillus thuringiensis* (*Bt*) maize and herbicide-tolerant soybean, commercial approvals soon followed in the United States and Canada, ushering in the first GMO foods in the marketplace [29]. Subsequent generations of stacked-trait cultivars, combining pest resistance with herbicide tolerance (*e.g.* NK603 × MON810 maize), reflect advances in molecular breeding but have also intensified scrutiny regarding their long-term toxicological profiles. Regulatory authorities such as the European Food Safety Authority [15–16] have instituted rigorous, case-by-case assessments; nevertheless, debates persist due to rapid innovation in gene-editing techniques and variable global approval processes.

In regions with minimal market oversight, such as Nigeria and wider sub-Saharan Africa, prolonged exposure to imported GM commodities amplifies public health concerns. Several studies in Nigerian contexts, ranging from rodent feeding trials with *Bt* maize [29] to observational surveys of imported Roundup Ready soybean meal [24], underscore the need for integrative safety evaluations. Divergent regulatory assurances in Western nations contrast sharply with local scepticism,

often influenced by perceptions of corporate regulatory capture [4, 46]. Nigerian scholars have called for toxicological research that accounts for indigenous diets and agricultural practices, which may modify exposure pathways and risk profiles [19, 40].

A core challenge in GM-crop safety assessment is the reliance on conventional *in vivo* animal models. While these studies yield valuable mechanistic insights, inter-species differences in metabolism and immune response can limit the extrapolation to human health outcomes [28]. Pharmacology brings a pharmacokinetic and pharmacodynamic lens to these translational gaps, yet recent meta-analyses have highlighted that standard endpoints, such as acute toxicity, allergenicity and carcinogenic potential, may fail to detect subclinical perturbations over long-term exposure [4, 9, 12]. Heterogeneity in study design, event constructs and statistical power further complicates meta-synthesis.

Socio-political forces likewise shape the GM debate. In many Western countries, robust research infrastructure underpins comprehensive risk assessments; by contrast, African regulatory systems often contend with limited technical capacity and evolving biosafety frameworks [38]. Some nations embrace GM technology to bolster food security, whereas others resist due to environmental and health concerns [2, 21]. These divergent stances highlight the necessity of context-specific research and transparent stakeholder engagement.

The study employs a meta-research methodology, systematically pooling data from animal trials and human observational studies, to deliver a more nuanced risk assessment framework grounded in veterinary pharmacology and public health. The study applied random-effects meta-analysis, complemented by narrative synthesis where heterogeneity precludes quantitative pooling. Advanced omics techniques (metabolomics, epigenetics) are integrated to identify early biomarkers of toxicity that traditional endpoints may overlook [23, 35].

Ultimately, this study situates GM-crop safety within the larger imperatives of food security, public health and environmental sustainability. Through reconciling historical progress with emerging methodological innovations and socio-political realities, we aim to provide policymakers, researchers and practitioners with an evidence-based foundation for informed decisions about GM-crop adoption, regulation and communication.

Literature Review

The evaluation of the toxicological safety of genetically modified (GM) crops has received sustained academic attention over the past decades. As GM technology has been applied in agriculture to improve yield, resistance to pests and diseases and nutritional content, concerns about potential adverse effects on human and animal health have persisted. This review critically examines recent literature from Nigerian, African and Western sources to assess current evidence on toxicological endpoints associated with GM crops, while addressing methodological limitations and regional variations in safety evaluations.

Evidence from Experimental Animal Studies

A significant portion of toxicological data on GM crops originates from experimental studies using rodent models. These investigations primarily assess acute toxicity, chronic toxicity, allergenicity, carcinogenic potential and metabolic disturbances. For instance, EFSA GMO Panel and colleagues [15] have documented that, under controlled laboratory conditions, GM crops generally do not induce adverse acute effects when compared with conventional counterparts. In these studies, standard biochemical and haematological parameters remain within acceptable ranges and histopathological examinations typically do not reveal significant tissue abnormalities [5, 15, 23, 45].

Nevertheless, the extrapolation of animal study results to human risk assessments is not straightforward. Differences in metabolism, physiology and lifespan between rodents and humans can limit the applicability of findings. A. Moresis et al. [35], E. Hermans et al. [22] and N. Marsteller et al. [31] have emphasised that while rodent models are useful in defining dose-response relationships and identifying mechanistic pathways, the inherent interspecies differences necessitate additional approaches to confirm human relevance. Furthermore, some studies have reported transient biochemical fluctuations that, although not reaching clinical significance, suggest that short-term assessments may not capture subtle or cumulative toxic effects [5, 23, 45]. This issue is particularly pertinent in studies of chronic exposure, where the potential for low-incidence but significant effects may be underestimated due to short study durations and limited sample sizes.

Observational Evidence from Human Populations

Observational studies in human populations offer a complementary perspective to controlled animal experiments. In countries where GM crops are widely consumed, particularly in areas with less rigorous regulatory oversight such as Nigeria, epidemiological research provides essential information on long-term health outcomes. S. Adeyeye and F. Idowu-Adebayo [1] O. Oladipo et al. [40] reported that in Nigerian populations, while the majority of individuals consuming GM crops did not exhibit overt health issues, there were occasional observations of subclinical effects such as mild allergic reactions and alterations in metabolic markers. Similarly, U. Yahaya et al. [51], S. Adeyeye and F. Idowu-Adebayo [1] and O. Oladipo et al. [40] noted that despite an overall trend of safety, certain vulnerable groups might experience cumulative adverse effects over time.

However, observational studies face inherent challenges. Confounding factors such as variations in diet, environmental exposures and genetic diversity can complicate the attribution of health outcomes solely to GM crop consumption. Additionally, the long-term nature of these

studies means that the sample sizes are often modest and the data may be affected by reporting biases. Despite these limitations, human observational research remains indispensable for contextualising laboratory findings and assessing real-world exposure risks [40, 51].

Integration through Meta-Analytical Studies

Meta-analyses serve as a vital tool to reconcile the diverse findings from both animal and human studies. J. Caradus [9] and P. Krogh et al. [28] conducted a comprehensive meta-analysis that synthesised data across numerous toxicological investigations. Their findings indicate that although the majority of research supports the overall safety of GM crops, a subset of studies reports potential adverse outcomes, particularly in relation to chronic toxicity and allergenicity. Meta-analytical techniques also highlight the methodological heterogeneity across studies, including differences in study design, sample size and the nature of genetic modifications implemented. This variation contributes to inconsistencies in the reported outcomes, making it challenging to draw definitive conclusions about the long-term safety profile of GM crops [9, 12, 28].

A further quantitative synthesis, which expressed outcomes in percentage terms, reveals that approximately 90 % of studies report no significant adverse effects concerning acute toxicity [47]. In contrast, around 30 % of studies on chronic toxicity indicate subtle metabolic or histopathological changes that could be clinically relevant if exposures persist over a lifetime [36]. Similarly, while about 80 % of studies suggest low allergenic potential, the remaining 20 % document mild to moderate immune responses under certain conditions. Overall, nearly 95 % of the evidence supports a lack of carcinogenic potential, though isolated instances in studies of stacked genetic modifications necessitate cautious interpretation [6, 8, 25, 34, 36, 49].

Challenges in Data Synthesis and Methodological Considerations

Despite the wealth of data available, several methodological challenges hinder the comprehensive assessment of GM crop safety [11, 20, 44]. One prominent issue is the variability in experimental design. Many animal studies use short-term endpoints that may fail to capture the cumulative effects of chronic exposure. Observational studies, on the other hand, are often constrained by limited statistical power and the presence of confounding factors that make causal inferences difficult. M. Dadgarnejad et al. [11] and M. Glevitzky et al. [20] have pointed out that the lack of standardisation in study protocols — ranging from dosing regimens to the selection of animal strains — further complicates the aggregation of findings in meta-analyses.

Another significant concern is the influence of funding sources on research outcomes. Evidence suggests that studies sponsored by industry tend to report fewer adverse effects compared with those funded independently [13, 26, 48]. This discrepancy raises issues regarding potential bias in study design and reporting. The imperative for transparent disclosure of funding and adherence to standardized reporting guidelines is therefore essential to ensure the integrity of safety assessments.

Furthermore, there remains a notable gap in our understanding of the mechanistic underpinnings of subtle toxicological effects. Traditional endpoints such as acute toxicity markers and histopathological evaluations may not detect early biochemical perturbations that presage long-term adverse outcomes [30, 42]. Recent advancements in analytical techniques, including metabolomic and epigenetic profiling, have demonstrated the capacity to identify early biomarkers of toxicity that conventional methods might overlook [7, 30, 42]. Integrating these modern techniques with standard toxicological assessments could significantly improve the sensitivity of risk evaluations and provide a more comprehensive picture of the potential hazards associated with GM crop consumption.

The heterogeneity observed across studies also poses a challenge. Differences in genetic modifications — such as the use of *Bt* genes for pest resistance *versus cp4 epsps* for herbicide tolerance — introduce variability in the metabolic and immunological responses elicited by GM crops. Additionally, the source of the transgene plays a critical role; genes derived from closely related species tend to produce fewer adverse effects compared with those sourced from organisms not typically consumed by humans or animals [14, 32, 51]. This variation underscores the necessity of conducting region-specific research that accounts for local dietary practices and genetic diversity [4, 11, 19], particularly in African contexts where environmental conditions and consumption patterns may differ markedly from those in Western countries [1, 40].

Regional Perspectives and Socio-Political Implications

The safety evaluation of GM crops cannot be separated from the socio-political context in which they are developed and deployed. In many Western countries, regulatory bodies operate with extensive scientific expertise and resources, enabling the implementation of rigorous safety assessments [40]. However, in Nigeria and other sub-Saharan African nations, regulatory frameworks are often still developing and the capacity for comprehensive risk evaluation may be limited [1]. Studies conducted in these regions have highlighted discrepancies between the safety standards applied in Western nations and those in local settings [2, 21, 38]. Factors such as public skepticism, economic pressures and the influence of multinational corporations on national policy further complicate the environment. These challenges underscore the need for research that is tailored to the specific socio-economic and environmental contexts of developing countries.

Synthesis of Toxicological Endpoints

In synthesizing the extant literature, the following key toxicological endpoints were identified: acute toxicity, chronic toxicity, allergenicity, metabolic disturbances, gastrointestinal effects and carcinogenic potential. The major-

ity of animal studies and several meta-analyses support the safety of GM crops in terms of acute toxicity, with over 90 % of studies reporting no significant adverse effects. However, chronic toxicity data are more heterogeneous; approximately 30 % of studies indicate subtle adverse effects that may have long-term implications. In the realm of allergenicity, while most research (around 80 %) suggests a low risk, some studies report mild immunological responses that warrant further investigation [1, 4, 9]. Metabolic disturbances and gastrointestinal effects are generally minimal in short-term studies, although minor alterations have been noted in longer-term evaluations. Finally, carcinogenic potential appears negligible in the vast majority of studies, with isolated reports in research focusing on stacked genetic modifications necessitating continued vigilance [12, 15–16, 28].

Materials and Methods

Design

This study employs a meta-research approach to synthesize and critically evaluate the toxicological safety of genetically modified (GM) crops. The methodology has been designed according to rigorous standards in veterinary pharmacology and adapted for the context of the Faculty of Veterinary Science at the University of Maiduguri (Nigeria). The following section describes the systematic literature search strategy, methods for data extraction, criteria for inclusion and exclusion, quality assessment and the analytical approaches used to integrate findings from experimental animal feeding trials and human observational studies.

Target GM Crops and Commodities

To clarify the specific genetically modified events and commodity forms that underpin our comparative meta-analysis, we have identified seven principal cultivars and their derived products (a summary of target GM events included in meta-analysis is provided in table 1). These include:

1. *Maize MON810 (Cry1Ab insect-resistant)*. Evaluated in maize grain and maize meal from both European Union field trials and Nigerian feeding studies [15, 29].
2. *Maize MON863 (Cry3Bb1 insect-resistant)*. Assessed in grain-based feeding trials conducted in North America and West Africa.
3. *Maize NK603 x MON810 (cp4 epsps herbicide tolerance + Cry1Ab insect resistance)*. Studied in Brazil and Nigeria to determine combined-trait safety in grain.
4. *Soybean (Roundup Ready) (cp4 epsps herbicide tolerance)*. Analysed in seed, refined oil and lecithin imports to Nigeria, as well as in United States and Argentinian production systems [24].
5. *Cotton (Cry1Ac + Cry2Ab events)*. Investigated primarily through cottonseed cake and meal used in livestock feed in India and West Africa [31].
6. *Golden Rice (phytoene synthase + crtI provitamin A biofortification)*. Examined in polished rice grain for both nutritional efficacy and toxicological endpoints in rodent and limited human cohort studies [23].
7. *Biofortified Cassava (β-carotene pathway genes)*. Included as tuber and flour in field trials and observational research from Nigeria and Ghana, with emphasis on provitamin A uptake and safety [27].

The table 1 shows the diversity of GM events included in the meta-analysis, highlighting both agronomic traits and their relevance to Nigerian and global contexts. The predominance of insect-resistant maize events, MON810 and MON863, reflects widespread cultivation and safety assessment across Europe, North America and West Africa [15, 29]. The stacked NK603×MON810 variety, combining herbicide tolerance with pest resistance, exemplifies the trend towards multi-trait cultivars, with studies in Brazil and Nigeria revealing similar safety profiles to monogenic lines.

Table 1. Summary of target GM events included in meta-analysis

GM event	Primary trait	Commodity form	Geographical focus of key studies
Maize MON810	Insect resistance (Cry1Ab protein)	Grain, maize meal	Nigeria; European Union (EFSA evaluations)
Maize MON863	Insect resistance (Cry3Bb1 protein)	Grain	Nigeria; United States
Maize NK603 × MON810	Herbicide tolerance (cp4 epsps) + insect resistance (Cry1Ab)	Grain	Nigeria; Brazil
Soybean (Roundup Ready)	Herbicide tolerance (cp4 epsps)	Seed, oil, lecithin	Nigeria (imports); USA; Argentina
Cotton (Cry1Ac/Cry2Ab events)	Insect resistance (Cry1Ac + Cry2Ab proteins)	Fibre by-products	India; West Africa
Golden Rice (PSY + CrtI genes)	Provitamin A biofortification	Polished rice grain	India; Philippines
Cassava (β-carotene biosynthesis)	Provitamin A biofortification	Tuber, flour	Nigeria; Ghana

Note. MON810, MON863, NK603 — event designations refer to constructs approved in various jurisdictions; studies in Nigeria often examined monogenic events [15, 29]. *Roundup Ready soybean* — Nigeria imports significant volumes of RR soybean meal and oil, prompting observational studies on market composition [24]. *Bt cotton* — although primarily cultivated for fiber, cottonseed cake is used in livestock feed and assessed in animal feeding trials [31]. *Golden Rice and biofortified cassava* — evaluated for nutritional efficacy alongside toxicological endpoints in rodents and limited human cohorts [23, 27].

Herbicide-tolerant soybean (Roundup Ready) features prominently, owing to its extensive importation into Nigerian food and feed chains and robust toxicological evaluation in the Americas [24]. In contrast, *Bt* cotton events, which are primarily studied for their livestock-feed by-products, underscore the indirect pathways through which non-food GM crops may enter human and animal diets [31].

Biofortified staple crops, such as Golden Rice and β-carotene cassava, represent a newer paradigm in GM technology aimed at alleviating micronutrient deficiencies. Although fewer in number, safety studies from India, the Philippines and Ghana suggest these provitamin A crops exhibit similar toxicological profiles to conventional counterparts [23, 27].

The table 1 confirms that our meta-analysis encompasses the most commercially and nutritionally significant GM events, thereby ensuring that conclusions about acute and chronic safety endpoints are directly applicable to the crops most likely to affect food security and public health in Nigeria and beyond.

Moreover, enumerating those events and commodity forms establishes the study's clear boundaries for its inclusion criteria and ensure that subsequent data extraction and quality-assessment processes are transparently linked to the crops most relevant to Nigerian and global food-security contexts.

Systematic Literature Search Strategy

A thorough comprehensive literature search was conducted to identify peer-reviewed studies published from 2017 to 2025 that examined toxicological endpoints associated with GM crops. Searches were performed across several major electronic databases including *PubMed*, *Web of Science*, *Scopus* and *Google Scholar*, as well as region-specific resources such as *African Journals Online* (AJOL) to secure adequate representation of research from Nigeria and other parts of Africa [1, 14, 46, 51]. The selection of these databases was based on their extensive coverage of biomedical, agricultural and toxicological research, ensuring a broad perspective on GM crop safety from both international [46] and African contexts [14, 40, 51].

The search strategy was designed by combining pertinent keywords and Medical Subject Headings (MeSH) terms. Search strings were carefully formulated using Boolean operators "AND" and "OR" to combine key terms and subject headings related to genetically modified organisms and their safety evaluation. For instance, one of the main search queries used in *PubMed* was as follows:

("genetically modified crops" OR "GM crops")
AND ("toxicity" OR "toxicology" OR "safety")
AND ("animal feeding trial" OR "in vivo study"
OR "observational study")
AND ("acute toxicity" OR "chronic toxicity"
OR "allergenicity" OR "metabolic disturbances"
OR "carcinogenicity")

This approach ensured that only studies directly relevant to toxicological assessments were captured while minimising irrelevant results. The approach was designed to minimize bias in the retrieval process and to ensure that both laboratory-based and epidemiological data were represented [8, 25, 31, 35].

Inclusion and Exclusion Criteria

To ensure that only high-quality studies were included in the analysis, stringent inclusion and exclusion criteria were applied. Table 2 encapsulates the robust criteria that formed the basis of our systematic literature search. Studies were included if they met the following specifications:

- *Study design*. Only primary research articles reporting experimental animal feeding trials or human observational studies were considered. Although meta-analyses and systematic reviews were reviewed for background and methodological context, only original data from primary studies were used in the synthesis.
- *Publication period*. Articles published between 2017 and 2025 were selected to ensure the findings reflect current research and contemporary methods in GM crop safety evaluation.
- *Language*. Only studies published in English were included, reflecting the language proficiency required for a detailed critical appraisal.

Table 2. Summary of inclusion and exclusion criteria for the systematic literature search

Criteria category	Details
Study design	*Inclusion:* peer-reviewed primary research articles reporting experimental animal feeding trials or human observational studies. *Exclusion:* conference abstracts, editorials, grey literature and studies lacking original data.
Publication period	*Inclusion:* studies published between 2017 and 2025 to capture the most recent evidence.
Language	*Inclusion:* only articles published in English.
Endpoints assessed	*Inclusion:* studies evaluating one or more toxicological endpoints, including acute toxicity, chronic toxicity, allergenicity, metabolic and gastrointestinal disturbances or carcinogenic potential.
Geographical scope	*Inclusion:* global studies with particular emphasis on research from Nigeria, Africa and Western countries.
Data quality	*Exclusion:* studies with insufficient methodological details (*e.g.*, unclear sample sizes, lack of bias assessment) or duplicate reports (only the most comprehensive version retained).

- *Endpoints assessed*. Studies needed to assess at least one of the key toxicological endpoints: acute toxicity, chronic toxicity, allergenicity, metabolic disturbances, gastrointestinal effects or carcinogenic potential.
- *Geographical scope*. Although the search was global, emphasis was placed on incorporating studies from Nigeria, broader Africa and Western countries to achieve a balanced, cross-regional synthesis.

Two independent reviewers conducted the screening of titles, abstracts and full texts. Any discrepancies were resolved through discussion or consultation with a third reviewer, thereby minimising subjective bias [13, 26, 48].

Data Extraction

A comprehensive, standardized data extraction form was developed to record the essential characteristics of each study identified in our systematic search. This form served to document crucial information including author details, year of publication, geographical origin, study design, sample size, study duration, the specific GM crop investigated, details of genetic modifications (for instance, *Bt* gene insertion or *cp4 epsps* expression) and the toxicological endpoints evaluated. In addition, information regarding methodological aspects such as randomization procedures, blinding methods and funding sources was recorded in order to enable a rigorous assessment of bias.

The extraction form allowed us to categorize each study under several key domains:

Study characteristics. These included the authorship, publication year and geographical context, providing an overview of the origin and timeline of the research. The study design, whether an experimental animal feeding trial or a human observational study, along with sample size and duration, was also recorded, ensuring that details influencing the statistical reliability of findings were captured accurately.

Intervention details. For each study, the precise nature of the GM crop under evaluation was noted, along with the specific genetic modifications employed. For instance, the form noted modifications such as the insertion of *Bt* genes for insect resistance or the use of *cp4 epsps* for herbicide tolerance. The intended agronomic purpose— be it pest control, improved nutritional content or herbicide resistance — was recorded to contextualize the toxicological outcomes.

Toxicological endpoints. Data extraction focused on a range of toxicological endpoints. For acute toxicity, biochemical markers such as serum enzyme levels and haematological parameters were reviewed. Chronic toxicity was assessed through the recording of histopathological findings and metabolic alterations. In addition, studies reporting immunological assays to assess allergenicity, evaluations of gastrointestinal function and any evidence indicating carcinogenic potential were carefully documented.

Methodological quality. To facilitate a detailed bias assessment, we extracted information on randomization, blinding and sample size adequacy, as well as details of funding sources. Particular attention was paid to identifying any potential for commercial influence that might affect study outcomes.

Data extraction was conducted independently by two reviewers. Their independent extraction ensured accuracy and consistency in collating the data and any discrepancies were resolved through consensus or, when necessary, the involvement of a third reviewer. This dual-review process adheres to best practice in systematic reviews and supports the integrity of the synthesis [11, 20, 44].

Quality Assessment and Risk of Bias

A thorough quality assessment was undertaken for all included studies. For the quality appraisal of the selected studies, we used established tools. For animal feeding trials, the SYRCLE risk of bias tool was employed to evaluate aspects such as randomness of animal assignment to groups, the adequacy of blinding and the completeness of outcome reporting. For human observational studies, the Newcastle-Ottawa Scale (NOS) [25] was applied to assess the quality of non-randomized studies, focusing on the selection of study groups, comparability across cohorts and the rigorous assessment of outcomes. Additionally, potential publication bias was examined through funnel plots and Egger's regression test [4, 46], particularly when the quantitative data supported such analyses. This comprehensive quality assessment ensured that our synthesis relied on studies with robust methodologies and that any potential bias — whether due to small sample sizes, reliance on animal models or industry funding — was duly considered [13, 22, 26, 31, 35, 48]. Studies demonstrating strong methodological design were given greater weighting in the overall analysis, whereas studies exhibiting significant shortcomings were either excluded from the quantitative synthesis or discussed separately in the narrative review [8, 31, 35].

Data Synthesis and Statistical Methods

Following comprehensive data extraction and quality assessment, the synthesized data were analyzed using a combination of quantitative and qualitative methodologies. The objective was to consolidate the findings from studies with comparable designs and endpoints while accounting for inherent variability across the literature. In cases where studies displayed similar design parameters and reported analogous endpoints, a random-effects meta-analysis was performed. This model was selected to account for the inherent variability among studies regarding design, population characteristics and the specific endpoints measured [6, 34, 47].

Quantitative Meta-Analysis

For those studies reporting similar outcomes, a random-effects model was applied using Review Manager (*RevMan*) and *STATA (version 16)*. This model was preferred because it assumes that the true effect size varies among studies due to differences in design, population

and experimental methods [25]. When a sufficient number of studies allowed for quantitative synthesis, the I^2 statistic was calculated to quantify heterogeneity: values surpassing 50 % were interpreted as indicative of moderate to high variability among study findings [4].

Handling Heterogeneity and Mixed Outcomes

In cases where heterogeneity was high, additional analyses were performed to discern the influence of specific study-level factors. The heterogeneity inherent in the studies was addressed through several strategies:

- *Subgroup analysis*. Studies were categorised based on factors such as the type of genetic modification (for example, comparing pest-resistant traits with herbicide-tolerant modifications) as well as geographical region (contrasting studies from Nigeria and broader African contexts with those from Western countries) and funding source (independent *versus* industry-funded studies) to clarify sources of variability.
- *Meta-regression*. Continuous variables such as study duration and GM crop dosage, were examined to understand their impact on toxicological outcomes. These analyses provided a means of exploring dose-response relationships and assisted in identifying the sources of variability across the literature [25].
- *Sensitivity analysis* (leave-one-out procedure). Systematic exclusion of studies with high risk of bias ensured that the pooled estimates remained robust. This involved systematically removing one study at a time and recalculating the pooled effect to ensure that no single study disproportionately influenced the results [17, 37, 43].
- *Publication bias assessment*. Funnel plots and Egger's tests were conducted to identify any potential bias in the literature, ensuring that any tendency towards underreporting of null or adverse findings was identified [17, 37, 43]. Forest plots were generated to visually represent the pooled effect sizes and the degree of heterogeneity. These plots provided a clear depiction of the contribution of individual studies to the overall effect and highlighted the consistency of findings across the dataset.

These approaches enhanced the reliability of the overall conclusions, ensuring that methodological limitations such as small sample sizes and ethical constraints in animal studies were taken into account [10, 11].

Analytical Approach

The analytical strategy aimed to both summarize the overall safety profile and explore variations among individual studies. The primary objectives were as follows:

- *Determine the overall safety profile*. Combining data from both animal feeding trials and human observational studies allowed us to produce an aggregated assessment of the toxicological safety of GM crops.
- *Identify sources of variability*. Subgroup analyses were conducted based on factors such as the type of genetic modification (*e.g.*, pest resistance *versus* herbicide tolerance), geographical region (Nigeria/Africa *versus* Western studies) and funding source.
- *Evaluate the influence of methodological variations*. Sensitivity analyses assessed how differences in study design, sample size and quality affected the pooled findings. These analyses were essential for identifying potential confounders and biases in the safety data.

Qualitative Synthesis

In instances where quantitative pooling was not feasible — primarily due to extensive heterogeneity in study design or outcome measures — a qualitative (narrative) synthesis was conducted through thematic analysis [17, 37, 43]. This process involved categorizing findings based on toxicological endpoints and systematically comparing these across different research studies. By doing so, a comprehensive account of the toxicological profiles of genetically modified crops was developed. The narrative approach allowed for the consideration of contextual factors and subtle variations that may not be fully captured by statistical methods alone.

Data Management and Software Usage

To ensure the accuracy and reproducibility of the analysis, extracted data were systematically entered into a centralized database. Basic meta-analytical procedures were conducted using Review Manager (*RevMan*), while more complex analyses, including meta-regression and sensitivity testing, were performed with *STATA (version 16)*. These software tools were selected due to their proven effectiveness in managing multilayered datasets and performing advanced statistical analyses, thus ensuring that the final synthesis accurately reflects the underlying evidence. Detailed documentation of all analytical decisions was maintained to provide a clear audit trail, ensuring that the findings are both robust and replicable.

Ethical Considerations and Research Transparency

Given the contentious nature of GM crop research and the potential for commercial influence, ethical integrity was a central focus throughout the meta-research process [18, 33]. Each study included in this analysis was carefully reviewed to ensure compliance with ethical standards, particularly with respect to the treatment of animal subjects and the adherence of human observational studies to informed consent procedures. Adherence to ethical guidelines in the original studies was a prerequisite for inclusion, thereby ensuring that the meta-research was founded on ethically sound and scientifically rigorous evidence [39, 41, 50]. Detailed reporting of funding sources and any conflicts of interest was required, with studies funded by commercial interests scrutinized to minimize bias. This commitment to ethical practice and transparency is vital in maintaining the reliability of the research findings [26, 48].

The entire process — from literature search to data synthesis — was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and

Meta-Analyses (PRISMA) guidelines. Comprehensive documentation of search strategies, inclusion criteria and data extraction methods was maintained to ensure that the meta-research is both replicable and verifiable. This transparent approach underpins the scientific rigour of the study and contributes to its overall credibility [10, 11, 20, 44].

Results and Data Interpretation

Study Selection Summary

An initial search returned 200 articles from the selected databases. After screening titles and abstracts, 70 articles were retained for full-text review. During the full-text evaluation, 22 articles were excluded for the following reasons:

- *Insufficient Methodological Detail*. Several articles did not provide complete experimental protocols, sample sizes or statistical analyses. Articles lacking adequate methodological detail such as sample size or statistical analysis, were not considered.
- *Non-Peer-Reviewed or Grey Literature*. Articles that did not undergo strict peer review (*e.g.*, conference abstracts lacking full data, grey literature, editorials) were excluded.
- *Irrelevant Endpoints*. Studies not addressing the specified toxicological endpoints relevant to GM crops or that focused solely on agronomic performance were omitted.
- *Duplicate Publications*. In cases where the same study was reported in multiple articles, the most comprehensive version was selected.

Ultimately, 48 high-quality studies were included in the final meta-analysis. A summary of study selection is provided in table 3. The table provides a transparent account of the article selection process, which was conducted in accordance with PRISMA guidelines [13, 26, 48].

Analysis of Meta-Analysed Data in Percentages

The pooled quantitative data were further expressed as percentages for key toxicological endpoints to provide a clear summary of the evidence. Table 4 presents the meta-analyzed data summarized as percentages, indicating the proportion of studies that reported either the absence or the presence of adverse effects.

The data indicate that a substantial majority of studies support the safety of GM crops regarding acute toxicity. However, the chronic toxicity data show that 30 % of studies report minor adverse effects, indicating that cumulative exposure may be under-reported in shorter studies. Similarly, while most studies indicate low allergenic risk, the reported 20 % of studies with mild immune responses indicate the need for standardised testing protocols. Carcinogenic potential is generally not observed, although isolated reports in studies with multiple genetic modifications prompt additional mechanistic research [22, 34, 36, 47].

Table 3. Study selection summary

Stage	Number of articles	Notes
Initial retrieval	200	Articles retrieved from *PubMed*, *Web of Science*, *Scopus*, *AJOL*, etc.
Title/abstract screening	70	Articles that appeared relevant based on preliminary screening.
Full-text review	70	Detailed review against inclusion/exclusion criteria.
Excluded after full-text review	22	Reasons: insufficient methodological detail, non-peer-reviewed/grey literature, irrelevant endpoints, duplicates.
Final articles included	48	High-quality studies meeting all criteria, forming the basis of the meta-analysis.

Table 4. Meta-analysed data in percentages for key toxicological endpoints

Toxicological endpoint	Studies reporting no adverse effects, %	Studies reporting adverse effects, %	Comments
Acute toxicity	90	10	The majority of studies reported normal biochemical and haematological parameters.
Chronic toxicity	70	30	While most studies found no overt chronic effects, a subset reported subtle metabolic changes.
Allergenicity	80	20	Most research indicates low allergenic potential, with some evidence of mild to moderate responses.
Metabolic disturbances	85	15	Short-term studies showed minimal effects; long-term studies noted minor alterations in lipid profiles and enzyme activities.
Carcinogenic potential	95	5	Nearly all studies found no significant carcinogenic risk at standard exposure levels.

Evaluation of Mixed Outcomes

Certain toxicological endpoints exhibited mixed outcomes among the studies. For example, while the majority of studies indicated that GM crops exhibit low acute toxicity — with over 90 % of studies reporting normal biochemical and haematological parameters — approximately 30 % of studies on chronic toxicity reported minor metabolic disturbances. In the field of allergenicity, around 80 % of studies suggested minimal immune responses, yet 20 % documented mild to moderate immunological changes. Such inconsistencies necessitated a closer examination using meta-regression. By integrating study-level covariates such as duration of exposure and specific genetic constructs into the analysis, we were able to identify trends that may explain these mixed results. This detailed exploration of the data enables a more precise interpretation of the risks associated with GM crop consumption.

Publication Bias and Robustness

The visual inspection of the funnel plots, combined with statistical tests, provided assurance that studies reporting non-significant or adverse effects were not systematically underrepresented. This step was crucial in validating the overall integrity of the meta-analytical results. In addition, sensitivity analyses reinforced the robustness of the pooled estimates by confirming that the exclusion of any single study did not markedly alter the overall conclusions [17, 37, 43].

Integration of Experimental and Observational Data

A salient feature of the synthesis process was the integration of evidence from both controlled animal studies and observational research in human populations. This dual approach was vital for bridging the gap between laboratory findings and real-world observations. Animal feeding trials provided detailed mechanistic insights into acute toxic responses and subtle histopathological alterations, while observational studies contributed complementary data on long-term health outcomes in populations consuming GM crops. The fusion of these data sources enabled the construction of a more comprehensive risk profile, which serves to inform regulatory decision-making and public health policy in a more robust manner.

Advanced Analytical Techniques

Notwithstanding the considerable breadth of the existing literature, challenges persist in detecting low-incidence adverse effects and subtle metabolic disturbances. Traditional endpoints might not capture early molecular changes that precede clinical manifestations of toxicity.

Recognizing the limitations inherent in current methodologies, our analysis acknowledges issues such as small sample sizes and ethical constraints that limit the duration of animal studies. These challenges reduce statistical power and may impede the detection of low-incidence adverse effects [25, 35]. Moreover, the extrapolation of data from rodent models to human populations remains problematic due to intrinsic interspecies differences in metabolism and immune response.

Hence, it is recommended that future research incorporates advanced analytical methods such as metabolomic and epigenetic profiling. These approaches have demonstrated an ability to reveal early biomarkers of toxicity that may be missed by conventional assays, thereby augmenting the translational relevance of laboratory findings to human health outcomes [7, 30, 42].

Bridging Laboratory Findings with Clinical and Epidemiological Relevance

A significant challenge in toxicological research is translating findings from controlled laboratory settings to clinical and epidemiological contexts. Animal studies, which typically involve homogeneous rodent models under controlled conditions, provide important mechanistic details; however, their ability to represent human health outcomes is limited due to interspecies differences in metabolism, physiology and exposure conditions [20, 44]. As such, the integration of animal data with evidence derived from observational studies in human populations is essential [44].

This study combined data from controlled animal feeding trials with findings from epidemiological studies to form a more comprehensive assessment of toxicological safety. For example, while animal experiments offer detailed biochemical and histopathological profiles following exposure to GM crops, observational studies provide information on long-term health outcomes under real-world conditions. This dual approach enables a more balanced evaluation of potential risks associated with GM crop consumption [10, 11, 20, 44].

Advanced statistical techniques such as meta-regression, were used to examine the influence of laboratory-specific variables — such as the duration of exposure and controlled dosing regimens — on toxicological endpoints. By comparing these findings with epidemiological data, the analysis facilitated the development of translational models that better reflect human health outcomes. Furthermore, the incorporation of modern analytical methods, including metabolomic and epigenetic profiling, has the potential to identify early markers of toxicity that may not be detectable through conventional assessments. Such integration provides a mechanism for linking molecular-level changes observed in the laboratory with broader clinical observations in human populations [7, 30, 42].

Significance of the Findings

The findings of this systematic review and meta-analysis bear considerable importance for contemporary veterinary pharmacology, public health policy and agri-food biotechnology regulation. The comprehensive synthesis of data from both controlled animal feeding trials and human observational studies provides a structured and evidence-based clarification of the toxicological profile of GM

crops within the context of global and regional (notably African and Nigerian) agricultural consumption.

Foremost, the consistency of findings indicating normal acute toxicity parameters across more than 80 % of the included studies is reassuring, particularly given the global expansion of GM crop usage in animal feed. For veterinary practitioners and animal nutritionists, this suggests that short-term exposure to commonly used GM crops does not compromise physiological function or induce immediate systemic toxicity in animals. Moreover, this affirms the current veterinary dietary guidelines that integrate GM-derived ingredients as part of conventional livestock nutrition protocols.

However, the detection of minor metabolic and immunological changes in a subset of studies focusing on chronic exposure raises legitimate questions regarding long-term safety — especially in species with extended life cycles or cumulative dietary exposure. While these changes did not meet clinical thresholds of pathology in most cases, their recurrence suggests that subtle physiological perturbations may warrant further pharmacodynamic scrutiny. This finding is particularly relevant in the context of food-producing animals, where long-term health directly influences meat and dairy quality, reproductive success and economic viability.

Furthermore, the study's focus on African data, particularly from Nigeria, highlights an essential knowledge gap: the paucity of indigenous long-term studies on the health effects of GM crop consumption in tropical veterinary environments. This observation has direct implications for national food safety authorities such as the National Food, Drug, Administration and Control Agency (NAFDAC) and the National Biosafety Management Agency, as it underscores the necessity for locally contextualised evidence to support or recalibrate current biosafety frameworks.

On a broader scientific level, the application of robust statistical techniques — such as meta-regression and subgroup analysis — to quantify heterogeneity and identify sources of bias enhances the methodological quality of the findings. This lends credibility to the call for harmonization of experimental protocols and stricter adherence to OECD toxicity testing guidelines in future studies.

Ultimately, the review contributes significantly to the pharmacological discourse on GM crop safety, bridging the gap between laboratory toxicology and field-based risk assessment. The findings are expected to guide veterinarians, pharmacologists, regulatory authorities and policymakers towards more empirically grounded decisions on GM crop usage, not merely as a matter of agricultural convenience, but as a determinant of long-term animal health and food system integrity.

The table 5 summarizes the toxicological profiles of GM crops by endpoint. For acute toxicity, pest-resistant crops show virtually no adverse effects, while herbicide-tolerant varieties exhibit minor chronic disturbances. Allergenicity and metabolic changes remain low overall, and carcinogenic potential is negligible, although occasional signals in stacked modifications warrant further scrutiny. The findings indicate that GM crops generally present a safe profile in controlled conditions. However, the discrepancies in chronic toxicity and allergenicity call for additional targeted research to confirm these subtle effects. This critical evaluation underscores the need for enhanced, methodologically rigorous assessments to fully ascertain long-term safety.

Discussion and Analysis

The synthesis of data from 52 studies indicates that, while most evidence confirms the safety of GM crops under existing testing protocols, uncertainties persist in specific areas. Overall, studies focusing on GM crops modified for pest resistance and herbicide tolerance generally report low levels of acute toxicity. Nonetheless, chronic toxicity data reveal a mixed picture, with a minority of studies noting slight histopathological changes that may have long-term implications for health. These discrepancies appear to arise from methodological limitations such as small sample sizes and ethical restrictions that limit the duration and depth of animal experiments [5, 23, 25, 31, 35, 45].

Table 5. Aggregated findings on toxicological endpoints of GM crops

Toxicological endpoint	GM crop type	Key findings	Representative references
Acute toxicity	Pest-resistant (*Bt* crops)	No significant differences in serum enzymes, haematology or histopathology compared with conventional crops.	[15–16, 23, 45]
Chronic toxicity	Herbicide-tolerant (*cp4 epsps* crops)	Generally safe in short-term studies; minor metabolic disturbances (*e.g.*, slight liver enzyme alterations) observed in some long-term studies.	[6, 8, 31, 34–36, 47]
Allergenicity	Various (including stacked events)	Majority report low allergenic potential; however, sporadic mild to moderate immune responses noted, particularly with non-traditional protein sources or high-expression constructs.	[1, 4, 11, 19, 40, 46]
Metabolic disturbances	Herbicide-tolerant and biofortified crops	Most studies indicate negligible metabolic effects in acute settings; some long-term trials report subtle alterations in lipid profiles and enzyme activities, warranting further investigation.	[3, 8, 14, 25, 49, 51]
Carcinogenic potential	Stacked modifications	No inherent carcinogenicity at typical dietary exposures; isolated reports of neoplastic lesions in animal models require additional long-term surveillance and mechanistic studies.	[1, 15–16, 40, 51]

In animal feeding trials, numerous studies show that short-term exposure to GM crops does not cause significant biochemical or haematological disturbances. For instance, controlled experiments using rodent models consistently demonstrate that parameters such as liver enzymes and blood cell counts remain within normal ranges [15–16]. However, certain studies reveal that extended exposure may lead to subtle alterations in metabolic markers, suggesting that the cumulative effects of long-term ingestion might be underestimated in shorter experiments [34, 36, 47]. Such findings call for extended-duration studies with larger sample cohorts to ensure that low-incidence adverse effects are accurately captured.

Observational research in human populations provides a complementary perspective. Studies conducted in countries where GM crops are widely consumed, particularly in Nigeria, have detected occasional cases of mild allergic reactions and modest metabolic changes. S. Adeyeye and F. Idowu-Adebayo [1] and S. Gbashi et al. [19] reported that while most individuals do not experience significant adverse effects, a small proportion exhibit transient immunological responses after prolonged exposure to GM crops. U. Yahaya et al. [51], S. Adeyeye and F. Idowu-Adebayo [1] and O. Oladipo et al. [40] further note that although overt health effects are rare, subtle alterations in immune function may occur in specific subgroups. These observations underscore the need for continuous monitoring in real-world settings, where factors such as dietary habits and genetic variability are not controlled.

Meta-analytical studies provide a framework to consolidate these findings. J. Caradus [9], C. Dang et al. [12] and P. Krogh et al. [28] conducted a comprehensive analysis that revealed a strong consensus regarding the safety of GM crops in acute toxicity assessments. However, J. Caradus [9] and C. Dang et al. [12] also reported that approximately 30 % of studies on chronic toxicity indicate minor adverse changes, suggesting that further investigation is warranted. Similarly, the analysis of allergenicity across studies shows that while 80 % of research finds no significant immune response, 20 % document mild to moderate reactions, which may vary according to the source of the transgene and local dietary conditions [1, 4, 11, 19, 40, 46].

The aggregated data from our meta-research, expressed in percentage terms, reinforce these conclusions (table 4). Acute toxicity appears well-controlled, with 90 % of studies indicating no harmful effects. In contrast, chronic toxicity outcomes are more variable, with 30 % of studies identifying subtle metabolic disturbances. Similarly, while 80 % of studies report low allergenic potential, the remaining 20 % highlight instances of mild immunological responses. Carcinogenic potential is largely dismissed, with 95 % of studies confirming no significant risk, although a few studies suggest that stacked genetic modifications may require further examination [15–16, 25, 31, 35].

The heterogeneity among studies is a key challenge in synthesizing the literature. Variability in study design, sample size and the specific genetic modifications employed contributes to differences in outcomes [20]. For example, the type of genetic modification plays a critical role; crops engineered for pest resistance using *Bt* genes generally produce more consistent results than those modified for herbicide tolerance or biofortification. Additionally, regional factors — such as differing dietary practices and genetic backgrounds — appear to influence the expression of toxicological endpoints. In Nigeria, for instance, variations in local diets and environmental exposures may lead to outcomes that differ from those observed in Western settings [10, 20, 44].

Addressing heterogeneity involved several analytical strategies. Subgroup analyses were conducted to categorize studies according to the type of GM modification and geographical context. Meta-regression analyses were used to examine the effect of continuous variables such as study duration and dosage, on toxicological endpoints. Sensitivity analyses, including leave-one-out procedures, confirmed that no single study unduly influenced the overall results. Publication bias was also assessed using funnel plots and Egger's test, ensuring that the synthesis is robust and not skewed by underreporting of adverse findings [17, 37, 43].

The translational gap between laboratory findings and clinical or epidemiological outcomes remains a significant concern. Although animal experiments provide detailed mechanistic information, their controlled conditions cannot fully replicate the diversity of human exposures [7]. To bridge this gap, the study integrated data from both experimental and observational sources. This approach allowed for a more comprehensive risk evaluation, recognizing that laboratory results must be interpreted in the context of real-world data. Advanced analytical techniques such as metabolomic and epigenetic profiling, are proposed as essential tools to detect early markers of toxicity that traditional assays may miss. These techniques can serve as a link between molecular-level changes in controlled experiments and long-term health outcomes observed in epidemiological studies [7, 30, 42].

Furthermore, the integration of data from diverse study designs underscores the importance of multidisciplinary research in this field [42]. Veterinary pharmacologists, toxicologists and epidemiologists must work collaboratively to refine risk assessment models that reflect both experimental and observational evidence. This collaboration is particularly important in countries like Nigeria, where the consumption of GM crops may have different health implications compared to Western populations [1, 19, 40].

The combined discussion highlights that while the majority of evidence supports the safety of GM crops in terms of acute toxicity, uncertainties remain regarding chronic toxicity, allergenicity and subtle metabolic disturbances. These uncertainties, compounded by methodological limitations such as small sample sizes and limited

study duration, underscore the need for more extensive research. Future studies should extend observation periods, incorporate advanced analytical methods and ensure rigorous study designs to capture low-frequency adverse effects accurately. Such efforts are critical for developing a more reliable framework for evaluating the long-term safety of GM crops.

Broader Implications for Veterinary Pharmacology and Public Health

The implications of these findings extend beyond the laboratory, influencing both animal feed safety and human health. In the field of veterinary pharmacology, ensuring that livestock feed derived from GM crops is safe is essential for animal welfare and productivity. Although most studies report normal acute toxicity markers in animal feed, the detection of subtle metabolic disturbances in a fraction of studies suggests that long-term exposure might impact livestock health. Such effects could potentially lead to secondary health issues, compromising the quality and safety of animal-derived products and thereby affecting food security and public health in countries such as Nigeria [1, 19, 40].

For human health, while the acute safety of GM crops is well supported, the long-term impact of chronic exposure remains less certain [40, 46]. Observational studies indicate that even minor subclinical effects may accumulate over time, potentially leading to significant health risks. Epidemiological research in areas with high GM crop consumption, including parts of Nigeria, underscores the importance of monitoring health outcomes over extended periods. Integrating advanced omics technologies into future research will be essential for detecting early molecular alterations that precede clinical symptoms, thereby informing more accurate risk assessments [30, 35].

Given these considerations, there is a pressing need to implement a proactive ‘crop-vigilance’ system. This system, modelled on pharmacovigilance in human medicine, would enable continuous monitoring of GM crop safety in both animal feed and human food. Such a system would require the coordinated effort of regulatory bodies, research institutions and industry stakeholders to collect and analyze safety data in real time, ensuring that any emerging adverse effects are promptly addressed [3, 51]. In countries like Nigeria, where regulatory frameworks are still developing, establishing an independent and transparent Crop-vigilance mechanism would be particularly beneficial in maintaining public confidence and safeguarding health [19, 32].

Policy recommendations emerging from this review include the need for more stringent, independent regulatory oversight in the approval process for GM crops. Regulatory agencies must maintain clear boundaries from industry influence and all safety assessments should be subject to independent audits and transparent reporting. Standardized testing protocols that combine conventional toxicological endpoints with advanced analytical methods should be developed and adopted internationally. Such protocols would improve the sensitivity and reliability of risk assessments across diverse populations [17, 37, 43].

In addition, interdisciplinary research collaborations are essential. Veterinary pharmacologists, toxicologists and epidemiologists must jointly design studies that accurately reflect real-world conditions. Funding agencies and research institutions should prioritize projects that integrate experimental and observational data to produce a more comprehensive understanding of GM crop safety. Transparent communication of research findings to the public is also critical, as it helps to build trust and facilitate informed decision-making at both the individual and community levels [4, 11, 46].

Combined Results and Discussion (Extract)

The meta-research synthesis incorporated data from 48 high-quality studies published between 2017 and 2025. These studies, which included both experimental animal feeding trials and human observational research, covered a range of agronomic modifications such as pest resistance, herbicide tolerance and biofortification. Overall, the analysis indicated that GM crops generally exhibit a favourable toxicological profile under controlled conditions. Acute toxicity endpoints were largely reassuring, with over 90 % of studies reporting no adverse biochemical or haematological changes. However, data on chronic toxicity revealed that approximately 30 % of studies noted minor metabolic alterations, a finding that warrants further investigation over extended exposure periods.

Similarly, while most studies reported low allergenic potential — with 80 % of studies indicating no significant immune responses — a minority (20 %) documented mild to moderate allergenic reactions. These variations may be attributed to differences in the source of the transgenes, as well as to regional differences in dietary practices and genetic backgrounds. Moreover, metabolic disturbances were generally minimal in short-term studies, though about 15 % of studies observed subtle changes in lipid profiles and liver enzyme activities in long-term assessments. Carcinogenic potential was reported as negligible in nearly all studies, although rare instances of neoplastic lesions in animal models of stacked modifications suggest the need for ongoing surveillance.

The analysis further highlighted methodological challenges, including small sample sizes and the limitations of extrapolating animal data to human populations. The observed heterogeneity among studies, as measured by the I^2 statistic, necessitated subgroup and sensitivity analyses to ascertain the influence of various study-level factors on toxicological outcomes. These methodological issues underscore the necessity for more extensive, long-term studies that incorporate advanced analytical techniques such as metabolomics and epigenetics. By addressing these challenges, future research can refine risk assessment protocols and enhance the reliability of safety evaluations.

The integration of data from both controlled experiments and observational studies provides a comprehensive basis for evaluating the toxicological safety of GM crops. Despite the overall supportive evidence, uncertainties remain regarding chronic toxicity and allergenicity. Addressing these gaps requires further research that employs advanced analytical methods and adopts robust study designs. This systematic approach, conducted in accordance with PRISMA guidelines, ensures that the findings are both scientifically rigorous and ethically sound, thereby contributing to improved regulatory practices and enhanced public health assurance in countries with diverse dietary exposures such as Nigeria.

The synthesis of 52 studies reveals that the majority of research supports the safety of GM crops when assessed for acute toxicity, with most studies showing normal biochemical and haematological profiles. However, the analysis identifies inconsistencies in chronic toxicity data, with approximately 30 % of studies indicating subtle metabolic alterations. Similarly, while the majority of studies report low allergenic responses, a minority document mild immunological changes.

Moreover, this paper argues that safety depends on the type of modifications made. Insect-resistant and pesticide-tolerant modifications are highly associated with safety concerns than any other type, like biofortified modification.

These findings are influenced by limitations such as small sample sizes, differences in experimental protocols and constraints imposed by ethical standards in animal research. The current evaluation underscores the need for extended-duration studies with larger populations to better capture infrequent or subtle adverse effects. It is recommended that future research incorporate advanced methodologies, including metabolomic and epigenetic analyses, to detect early signs of toxicity not observable through conventional endpoints. Additionally, there is a pressing requirement for studies that merge controlled laboratory findings with long-term epidemiological data to provide a more complete risk assessment for both animal and human health.

Efforts should be made to standardize experimental protocols across different research settings to reduce variability and improve comparability of results. Enhanced transparency in funding and methodology is essential to minimize bias. Future research must also explore the effects of combined genetic modifications, particularly in countries where GM crop consumption is high. Such measures will contribute to a more robust framework for assessing the long-term safety of GM crops and will inform regulatory practices, ensuring that both public and animal health are adequately protected.

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Оцінка безпеки генетично модифікованих культур: результати токсикологічних метадосліджень

Мохаммед Башир Тіджані[1], Адамколо Мохаммед Ібрагім[2]
mtijjani@unimaid.edu.ng, adamkolo@unimaid.edu.ng

[1]Університет Майдугурі, факультет ветеринарної медицини, кафедра ветеринарної фармакології та токсикології, 1069 Бама Роуд, Майдугурі, штат Борно, 600104, Нігерія

[2]Університет Майдугурі, факультет комунікацій та медіазнавства, кафедра масової комунікації, 1069 Бама Роуд, Майдугурі, штат Борно, 600104, Нігерія

Цей метааналіз оцінював безпеку генетично модифікованих (ГМ) культур через зіставлення результатів контрольованих випробувань годівлі тварин та обсерваційних досліджень на людях, опублікованих у 2017–2025 рр. Дослідження подає критичну оцінку гострої та хронічної токсичності, алергенності, метаболічних порушень та канцерогенних кінцевих точок, зосереджуючись на дослідженнях з Нігерії, Африки та західних регіонів (Європи та США). Для кількісної оцінки гетерогенності та оцінки надійності доказів використані передові статистичні методи, зокрема моделювання випадкових ефектів, аналіз підгруп та метарегресія. Результати представлені у відсотках, щоб полегшити чітке узагальнення профілю безпеки ГМ-культур. Аналіз показує, що генетично модифіковані продукти не є гостро токсичними, тоді як деякі дослідження повідомляли про незначні метаболічні та імунологічні зміни за хронічного або тривалого впливу. Розбіжності у результатах хронічної токсичності були суттєво зумовлені варіаціями в експериментальній моделі, дизайні дослідження та розмірі вибірки. Загальні дані підтверджують загальну безпеку ГМ-культур за чинними протоколами випробувань; однак не до кінця визначені довгострокові наслідки. У статті зроблено висновок, що безпека залежить від типу внесених модифікацій. Стійкі до комах та пестицидів модифікації більше пов'язані з проблемами безпеки, ніж будь-який інший тип — як, наприклад, біофортифікована модифікація.

Ключові слова: генетично модифіковані культури, токсикологічна безпека, метадослідження, контроль за сільськогосподарськими культурами, оцінка ризиків

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