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REVIEW

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Agricultural GMOs and their associated pesticides: misinformation, science, and evidence

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Abstract

Misinformation has always existed, but it became a major preoccupation during the COVID-19 pandemic due to its ability to affect public health choices, decisions, and policy. In their article, "Misinformation in the media: Global coverage of GMOs 2019–2021" (GM Crops & Food, 17 Nov 2022), Mark Lynas et al. characterise critics of agricultural genetically modified organisms (GMOs) and their associated pesticides as purveyors of "misinformation". They draw an equivalence between critics of agricultural GMOs and people who make false claims about climate change, COVID-19, and vaccines. We examined their main claims on these GMOs—for example, that there is a scientific consensus that they are safe for health and the environment—in the light of the scientific evidence and public discussion on this topic. We found that their claims are biased and misleading and ignore or omit crucial evidence. We conclude that based on the evidence provided, Lynas et al. article can itself be classed as misinformation and could therefore mislead the general public as well as the scientific community.

Keywords Biotechnology, Agricultural biotechnology, Genetic engineering, Genetic modification, Genetically modified organism, GMO, Pesticides, Glyphosate, Media analysis, Media coverage, Misinformation, COVID-19, Climate change

Introduction

Here we present an in-depth critical evaluation of the article, "Misinformation in the media: Global coverage of GMOs 2019–2021" authored by Lynas, Adams, and Conrow [1]. In their article, these authors characterise critics of agricultural GMOs and their associated pesticides as purveyors of "misinformation". They place them on a par with those who make misleading and incorrect claims about climate change, COVID-19, and vaccines. They also claim that there is a consensus that GM foods are as safe as conventional foods [1].

While misinformation has always existed, it became a major preoccupation during the COVID-19 pandemic and generated numerous academic articles. For example, West and Bergstrom argued that the repercussions of misinformation are "extensive", since "Without reliable and accurate sources of information, we cannot hope to halt climate change, make reasoned democratic decisions, or control a global pandemic"[2]. Swire-Thompson and Lazer stated that misinformation about health can have "particularly severe consequences with regard to people's quality of life and even their risk of mortality" and that, therefore, understanding it in today's context is important [3].

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In their article, Lynas et al. define misinformation as "information which is at variance with widely accepted scientific consensus". However, this appears to be a rare and even aberrant definition. In our analysis, therefore, we use the more common and standard definition of misinformation, as in the Cambridge Dictionary, as "wrong information" [4].

In some definitions, misinformation can also have the extended meaning of "information intended to deceive" [4]. Wardle and Derakhshan (2017) identify misinformation as one of the three types of "information disorder". They state that misinformation is "when false information is shared, but no harm is meant", as opposed to disinformation, when "false information is knowingly shared to cause harm", and malinformation, when "genuine information is shared to cause harm" [5].

Lynas et al.'s definition of misinformation as "information which is at variance with widely accepted scientific consensus" is at odds with both the Cambridge Dictionary's definition of misinformation and with Wardle and Derakhshan's definitions of the different types of "information disorder", as well as with Wardle and Derakhshan's definition of "misinformation" in particular. Lynas et al.'s conclusions are further undermined by their lack of a comprehensive discussion on the definition of misinformation and their failure both to explain why they chose such an unusual definition and to place it in the context of other definitions published in the relevant literature.

In addition, Lynas et al.'s definition of misinformation ignores the dynamic nature of science. For historians and philosophers of science such as Thomas Kuhn, "scientific consensus" is a specific paradigm held by scientists at a particular moment within a particular community [6]. However, it is important to recognise that scientific knowledge is not static. Progress is often driven by dissenters who bring forward new evidence and knowledge that challenge existing paradigms. This can lead to what Kuhn called a "paradigm shift", where the prevailing understanding undergoes a significant transformation [6].

In this context, to provide clarity regarding the concept of scientific consensus from the perspectives of philosophy and the history of science, it is crucial to refrain from categorising knowledge that challenges a commonly asserted dominant paradigm as misinformation. Furthermore, labelling evidence and knowledge that contest a prevailing paradigm—or a claimed prevailing paradigm—as misinformation disregards the intricacies of the philosophy, sociology, and the history of science.

Providing accurate information on a controversial topic such as agricultural GMOs and their associated pesticides is important, as inaccurate information can mislead the public and policymakers into making poorly informed choices and decisions, with potential consequences for individual and collective health and the environment.

In addition, inaccurate information can in the long term undermine public trust in science [2], which is already declining in some regions and among some political orientations [7, 8]. Public trust in science is a complex issue. It is highly dependent on numerous variables, such as the topic being discussed, the integrity of the institutions promoting it, who is communicating, and the degree and nature of public engagement in the discussion, as well as the audience's social-cultural-economic background, perceptions, and understanding of scientific concepts [9–13].

It is against this background and wider context that Lynas et al. published their article—though they fail to acknowledge or base their arguments on this broader perspective on what can constitute misinformation. Given Lynas's public profile as a representative of an organisation that states that it stands for science, the Alliance for Science, and the potentially damaging effects of misinformation, it is essential that his and his co-authors' article should provide only reliable information.

Here, we critically analyse Lynas et al.'s main claims by drawing on the available scientific evidence, accumulated since the introduction of GM crops and foods in the 1990s. We also examine the first article that Lynas et al. cite in their Supplemental Material as an example of "misinformation", to ascertain whether their characterisation is justified.

We find that Lynas et al.'s article contains the following types of flaws, as we show below in detail:

1) Spurious and misleading analogies and correlations
2) Methodological weaknesses
3) Misleading claims about GMO safety
4) Overlooking an important source of misinformation
5) Misleading and biased claims about retraction of studies
6) Misleading claims about "predatory" journals
7) Misleading and biased claims about the impacts and performance of GMOs in India
8) Misleading characterisation of the history of GMOs in Africa.

Analysis

Spurious and misleading analogies and correlations

The first six paragraphs of Lynas et al.'s article (13% of the total) are not related to the issue of GM foods and crops. Instead, the authors invoke guilt by association, by drawing an analogy between scientists and others who publish critical research and commentaries on GMOs and associated pesticides with individuals and organisations who promote "misinformation" on climate change, COVID-19, and vaccines.

However, the article presents no evidence of any relationship between conclusions on GMOs and associated pesticides and conclusions on COVID-19 and vaccines. Therefore, this section of the article relies on attempts to construct spurious analogies through biased personal speculations. Simply stating that both sets of conclusions are examples of "misinformation" does not justify drawing an analogy between these disparate topics and treating them as parallel topics in the same article. Moreover, in order to characterise any given piece of information as misinformation, it is necessary to prove with plausible and published evidence that it is incorrect, which Lynas et al. fail to do.

Correlation between views on GMOs and climate change Unlike with GM foods and crops, COVID-19, and vaccines, there does appear to be a correlation between views on GM foods and crops and climate change. However, the published evidence points in the opposite direction to Lynas et al. implication that criticism of GMOs is equivalent to climate change science denial. In reality it is the proponents of GMOs and associated pesticides who are linked to climate science denial, as the following analysis shows.

The journalist Tom Philpott was among the first to draw the correlation to public notice in a 2012 media article, "Some GMO cheerleaders also deny climate change". Philpott noted that there is no consensus on GMOs similar to that on climate and identified a fundamental difference between the two issues: "The consensus around climate change developed in spite of a multi-decade campaign by some of the globe's most powerful and lucrative industries—the petroleum and coal giants—to protect markets worth hundreds of billions of dollars. The consensus around GMOs—or at least the specter of one—arose through the lobbying and support of an industry desperate to protect its own multibillion-dollar investments" [14].

Philpott's stance gains support from a 2022 report, which examines internal documents disclosed through freedom of information act requests. The report shows how GM seed and pesticide companies led attacks on critics of GMOs and the herbicide ingredient glyphosate, including scientists serving in the International Agency for Research on Cancer, under the cover of front groups connected to the climate science denial network. Prominent among these front groups is the pro-GMO, glyphosate-defending, and supposedly pro-science Genetic Literacy Project (GLP), founded by Jon Entine. The GLP and Entine have numerous connections to climate science-denying individuals and groups [15]. The GLP has received funding from Bayer/Monsanto. Another major donor to the GLP was DonorsTrust, a leading funder of climate science denial efforts [16].

A second such front group, the American Council on Science and Health (ACSH), has defended GMOs [17] and pesticides [18] and allied itself with climate science deniers by advising against cutting greenhouse gas emissions on the grounds that it would hurt the economy [19]. The ACSH is one of the several groups identified in Monsanto documents as a third-party ally that the company reached out to for its glyphosate defence needs. These groups include Sense About Science, the Science Media Centre, and the GLP [16], all of which defend and promote GMOs and associated pesticides [20–25].

The correlation between promoters of GMOs and pesticides and climate science denial can be understood from the perspective that both stances serve the interests of pro-corporate funders. Lynas et al. ignore this evidence-based correlation and potential motivation, while inventing unsubstantiated speculations against competent experts who publish science-based critiques of GMOs and their associated pesticides.

Methodological weaknesses

Lynas et al. methodological approach is to list in their Supplemental Material a collection of media articles about GMOs that, in their view, variously constitute misinformation or accurate information. They categorise them according to the content of the information in the article, such as Human Health, Environment, or Crop Yields, and note whether they contain misinformation. They then code the article by sentiment, according to the effect that they expect it would have on a reader's attitude to GMOs. The different sentiments employed are positive, negative, mixed, or neutral about GMOs. "Neutral" would not be expected to sway a reader either way, while "mixed" would include opposing viewpoints from either side.

However, Lynas et al. do not specify which statements in the allegedly misinformation-containing articles are incorrect or misleading, or in what way. Considering the phenomenon of "information disorder" and approaching the concept of scientific consensus from a Kuhnian perspective, it is necessary to develop a more comprehensive coding system ("codebook"), as well as to explain the coding process. The codebook should distinguish between contested knowledge and false information, thereby determining the accuracy of statements.

Furthermore, given the significance of the phenomenon of "information disorder", the methodological design should incorporate variables such as the source of statements and the contexts in which they are situated. A robust examination of "information disorder" requires an examination of how "facts" pertaining to a particular topic are created and disseminated, considering the political context, involved actors, and collective frameworks.

Nevertheless, even in the absence of such basic information, Lynas et al. state that according to their findings, "100% [of] the misinformation about GMOs has been characterised as negative, mixed, or neutral in sentiment, while none has been positive. This suggests that anti-GMO activist networks have been successful in persistently influencing media coverage of the issue, and that misinformation primarily originates from the anti-GMO perspective".

This statement shows a major problem with their approach: The categorisation of news articles based on a notion of sentiment, which the authors define as the potential reaction of audiences to their exposure to misinformation. This introduces a highly subjective variable that necessitates a solid theoretical foundation. However, the required theoretical framework for such analysis, specifically the framework developed by the social studies of science and technology on the public perception of GMOs and risk, is noticeably absent [26–30]. An alternative and more valuable approach would have been to assess the actual sentiments of the audience towards the news articles, such as was done by researchers into public attitudes to a novel vaccine [31]. This approach would have provided a more insightful understanding of how the audience perceives and reacts to information on GMOs.

In the absence of a more considered approach to this topic, Lynas et al. begin with the blanket assumptions that GMOs are safe and beneficial and that there is a "consensus" that this is the case (ignoring a wide body of research showing the contrary [32]). Then they classify any article that departs from their self-defined consensus as misinformation, without providing further analysis or consideration of scientific data that challenges the alleged consensus. Hence, they reach the highly improbable conclusion that no article giving a positive impression of GMOs contains misinformation, while only articles that are negative, mixed, or neutral about GMOs contain misinformation.

If this was the objective of their exercise, Lynas et al.'s task is made easier by their non-standard definition of "misinformation" as "information which is at variance with widely accepted scientific consensus". They allege that there is a consensus that "food derived from GM crops is as safe as any other". As a result of this definition, they are not obliged to show that certain statements are incorrect in order to dismiss them as misinformation, but merely that they depart from their predefined alleged consensus.

While they cite various bodies which, they state, agree with their view, agreement between selected organisations and individuals is not the same as a consensus. Indeed, as we show in this article, no such consensus exists; Lynas et al. selectively quote one of the organisations that they claim supports their view and they overlook conflicts of interest in two of the others; and they choose to ignore a significant body of expert opinion and evidence that does not agree with their alleged consensus.

In the absence of any factual analysis of the articles that Lynas et al. allege contain misinformation, we are unable to verify their coding results. However, as an example, we conducted our own examination of the first of the articles listed by Lynas et al. in their Supplemental Material. They claim that this article contains misinformation on human health [33]. The only statements that refer to health are that GMOs "endanger the health of consumers" and that Nigeria has a "poor health sector".

The latter statement is a matter of opinion or experience, on which we do not presume to comment. But the former statement, while contentious, is backed by a substantial body of evidence drawn from animal feeding trials, using animal models widely accepted to be relevant to human health, that have found toxic or allergenic effects or signs of toxicity in animals fed a GMO diet [34–42].

These results are on specific GMOs, so they would not justify blanket claims that all GMOs are unsafe to eat. Yet they do show that certain GMOs, including some approved for use in human and animal food, can raise health concerns. Thus, they provide a scientific evidence base for the statement in the article that Lynas et al. falsely label as misinformation.

Similarly, while Lynas et al. assert that the same article contains misinformation on GMOs and the environment, the article's statement that GMOs can "negatively impact on the ecosystem" can be backed by a large body of research studies, a few examples of which are presented below in the section, "Misleading claims about GMO safety".

Lynas et al.'s flawed coding system enables them to make spurious associations between misinformation about GMOs and negative sentiment about GMOs. They even go so far as to say, "Roughly a fifth of the media coverage in Africa contained false messages about GMOs, confirming the influence of anti-GMO activism in the continent and at least partially explaining the negative policy environment applied to GM crops and food in most African countries". However, Lynas et al.'s coding system does not allow us to corroborate this discussion, as they do not code and analyse the sources of alleged information or misinformation.

In addition, they fail to establish clear research questions, such as “What is misinformation about GMOs?”, “Who said what and when?”, “In what way are they correct or incorrect?”, and “How does misinformation spread?” Because they do not ask these questions, they cannot analyse the answers, even though such answers could provide the evidence needed to justify their claims and conclusions. Contrary to Lynas et al.’s claims in their Discussion and Conclusion, their methodological design does not enable evidence-based conclusions to be formed.

Another critical concern with the methodology is the absence of information regarding the individuals responsible for the coding process and the specific procedures employed. Considering the authors’ bias in favour of positive statements about GMOs, it is crucial to ensure the robustness and objectivity of the coding process. To address this, it is necessary to engage independent coders who are not influenced by the authors’ preconceived notions. In addition, providing a comprehensive and transparent explanation of the coding methodology, including the coding agreement between different coders (intercoder agreement), is important to establish the reliability and consistency of the coding [43].

Without a clear definition of misinformation for each of the established categories (for example, Human Health, Environment, or Crop Yields), the use of sentiment—that is, the coding of a subjective variable—is problematic. In addition, the coding process should have been carried out using independent coders working, as much as possible, on the basis of objective variables. Subjective variables require a robust theoretical foundation to ensure their accurate interpretation and analysis—which is lacking from Lynas et al.’s article.

In sum, Lynas et al.’s research design does not allow evidence-based statements to be made on how misinformation about GMOs is defined, or on who is promoting misinformation about GMOs. In addition, coding for sentiment is not an objective measurement of misinformation. The lack of an evidence-based definition of misinformation and the use of sentiment do not allow for independent and consistent coding procedures. Assuming that the coding was carried out by the authors, there is an implicit bias in the coding process which should have been avoided by using independent coders.

Moreover, Lynas et al. do not provide any evidence of how readers of alleged “misinformation” might alter their perception to support or oppose GMOs. The degree of influence of the articles contained in the Supplemental Material is asserted based only on their “gross reach”. Yet this does not show that they can actually cause changes in readers’ perception or behaviour. To assume that “misinformation” will change those elements is mere speculation.

In the absence of reliable coding and analysis, Lynas et al.’s affirmation that "Many of the African misinformation articles we found quote extensively from campaigners who are part of these NGO [non-governmental organisation] networks based in the Global North” is no more than a subjective innuendo [4].

Misleading claims about GMO safety

No scientific consensus on GMO safety Contrary to Lynas et al.’s implication, there is not, and has never been, a scientific consensus on GMO safety. There may be a dominant paradigm of GMO safety, which has not, however, been demonstrated by polling scientists familiar with the relevant empirical data on which a valid opinion could be based. A review of the literature concluded that the claimed consensus on GMO safety is “illusory” [34]. In addition, a statement by the European Network for Social and Environmental Responsibility (ENSSER), titled “No scientific consensus on GMO safety”, was signed by over 300 scientists [32, 44].

Furthermore, Lynas et al.’s dismissal of the signatories of the ENSSER statement (including two authors of this article, Antoniou and Hilbeck), as “self-proclaimed experts”, may even be considered libellous misinformation. Many of the signatories, certainly Prof Antoniou and Dr Hilbeck, are recognised, not ‘self-proclaimed’ experts with documented life-long academic careers at leading universities and substantial scientific publication records in the relevant fields. Lynas et al. also fail to explain how their own non-scientific backgrounds qualify them to reach such a blanket judgement, or to escape the label that they apply to others better qualified than themselves to judge the evidence on GMO safety.

In their paper, Lynas et al. state, “There is a clearly stated consensus among major national and international scientific bodies that food derived from GM crops is as safe as any other”. They selectively cite statements by various organisations in support of their claim.

However, Lynas et al. hold a position that is inconsistent with the statement by the World Health Organization (WHO) that they cite. The WHO states, “No effects on human health have been shown as a result of the consumption of GM foods by the general population in the countries where they have been approved”. Yet it goes on to say, “Different GM organisms include different genes inserted in different ways. This means that individual GM foods and their safety should be assessed on a case-by-case basis and that it is not possible to make general statements on the safety of all GM foods”[45].

We agree with the WHO’s nuanced and accurate statement. We also note the WHO’s advice that “adequate post market monitoring" takes place to ensure GMO safety. However, such monitoring is not carried out anywhere and no controlled human health studies have been performed, which explains the WHO's observation that "No effects on human health have been shown as a result of the consumption of GM foods" [45]. It is not possible to find effects if no one is looking.

While Lynas et al. cite a UK Royal Society web page as evidence that GM foods are safe to eat, the Royal Society of Canada came to a different conclusion, stating in a detailed report that the default prediction for any GM food should be that the GM transformation process will cause unanticipated changes, which could include the unintended production of toxins and allergens [46].

There are also several authoritative reports and professional organisations that have taken on more nuanced positions by stating that GMOs have not been proven safe and/or that support mandatory GMO labelling. They include the International Assessment of Agricultural Knowledge Science and Technology for Development (IAASTD)**,** the Australian Medical Association, the American College of Physicians, and the Bundesärztekammer (German Medical Association) [47]. A compilation of over 2600 peer-reviewed published scientific articles drawing attention to risks or harms from GMOs and their associated agrochemicals is available online [48].

These facts attest to the lack of consensus among scientific bodies and individual scientists that GMO crops and foods are safe to eat. They also attest to the recognition that each GMO is different and poses a different risk profile, so that blanket claims of safety are as scientifically invalid as blanket claims of lack of safety.

Conflicts of interest in groups asserting GMO safety are overlooked Lynas et al. cite a statement by the American Association for the Advancement of Science (AAAS). The AAAS board, at the time headed by a well-known promoter of GM crops, Nina Fedoroff, issued this statement, which claimed GM foods were "safe" and which opposed their labelling [49]. However, the statement was quickly criticised by 21 scientists, including many members of the AAAS, as "an Orwellian argument that violates the right of consumers to make informed decisions". The scientists warned about possible risks from consuming glyphosate-tolerant GM crops [50]. Fedoroff was later shown to have links to the GMO and pesticide industry, which were not disclosed in the AAAS statement [51].

Similar conflicts of interest plague the US National Academy of Sciences (NASEM), another authority cited by Lynas et al. to support their claim of GMO safety [52]. The Academy's 2016 report on GM crops is compromised by the serious conflicts of interest of the NASEM and its research arm, the National Research Council (NRC). Krimsky and Schwab [53] found that the NASEM and the NRC take millions of dollars in funding from GMO crop developer companies; invite representatives of GM seed companies such as Monsanto to sit on high-level boards overseeing the NASEM's and the NRC's work, including the 2016 report; and invite industry-aligned, pro-GMO scientists to author their official reports. Six out of the twenty committee members who authored the 2016 report had financial conflicts of interest with the GMO industry, which were not disclosed in the report [53].

Inappropriate citation of biased review Regarding the question of GMO safety, Lynas et al. rely heavily on "An overview published in 2015 of a decade of GM safety studies" which, they state, "found no evidence of significant hazards connected to the use of engineered crops". The "overview" is a review by Nicolia et al. published in 2014 [54].

However, a careful reading of that review and its sources, which we undertook, reveals that many of the studies cited do not provide data that supports the safety of GMO foods or crops for human or general mammalian health or the environment. Consequently, they are not relevant to a discussion on this topic. Other studies cited in the review show evidence of harms caused by the GMO diet, which are either not mentioned by Nicolia et al. or are dismissed for scientifically invalid reasons. Many studies that provide relevant data on GMO safety are either omitted from discussion in the review or are omitted from the list provided in Supplementary Material. References to specific examples of non-relevant, wrongly ignored, or dismissed, and selectively omitted studies are given in the analysis below, with our comments.

Cited farm animal production studies are not relevant to health impact assessment: Many studies cited by Nicolia et al. are farm animal production studies, often performed by GMO crop developer companies on their own products. They do not assess health impacts in detail but instead focus on agriculturally relevant aspects such as feed intake, weight gain, and milk production. These aspects are studied over a short period in comparison with the animals' natural lifespan [54, 55]. Weight gain until slaughter age, while desirable in farmed livestock, is not necessarily a sign of health in humans or other animals.

Many of the cited animal production studies are on animals with metabolisms that are not relevant to human or mammalian health, such as fish or birds [55, 56] Nevertheless, some such studies still reveal concerning findings [57], which, however, are not mentioned by Nicolia et al.

Opinion and advocacy pieces do not provide primary data on health or environmental effects of GMOs: Other non-relevant articles included in the review are opinion and advocacy pieces on safety assessment approaches and regulations relating to GMOs [58–61] and consumer perceptions of GMOs [62]. These articles do not provide any primary data suitable for assessing the effects of GMO crops and foods on health or the environment.

Signs of toxicity in short-term studies are wrongly dismissed: Most animal feeding studies with GM crops are short term in comparison to the animals' natural lifespan and cannot conclusively reveal long-term health effects [63]. However, some authors have found early signs of toxicity even in these short-term studies, which are dismissed by Nicolia et al. without analysis or further experimental investigation.

For example, analyses by de Vendômois et al. [64] and Séralini et al. [65] found evidence of liver and kidney toxicity in rats fed Monsanto GM maize varieties, via examination of the company's own feeding trials [64, 65]. Original research by the Séralini group also found liver and kidney toxicity in rats fed a Monsanto GM maize and the accompanying Roundup herbicide [66]. Nicolia et al. mention these findings in their review but dismiss them as being of "no significance", on the basis not of further experimental data or detailed analysis, but of opinions. The opinions cited include those expressed by the following:

- The European Food Safety Authority (EFSA), the scientific advisory body that previously judged the maize varieties to be as safe as conventional maize on the basis of Monsanto-provided data [67, 68] leading to their commercial release in the EU, so it cannot be considered a disinterested party, and
- Wayne Parrott and Bruce Chassy (2009), in a non-peer-reviewed article [69], which is not at the link provided and seems to have disappeared from the Internet. According to the transparency watchdog US Right to Know, Chassy "has been supported by the agrichemical and processed food industries, and defends them", yet has failed to disclose his ties to industry [70].

Studies with concerning findings on health and the environment are ignored or dismissed: An example of a type of data that would be suitable for assessing health effects of GMOs is in-depth compositional investigations of GM crops or foods (proteomics protein profiling and/or metabolomics biochemical profiling). When such investigations have been carried out, they have shown the non-equivalence of the tested GM crop compared with its non-GM parental variety, with potential implications for health or the environment [71–75]. Another type of data that is suitable for assessing health effects is controlled animal feeding studies. Some such studies have shown worrying adverse health impacts of the GM diet when compared with an equivalent non-GM diet [34, 36, 38–40, 76–78].

Nicolia et al.'s Supplementary Material includes studies that demonstrate concerning effects of certain GMOs on health and the environment, but the authors either fail to discuss them in their review or dismiss them for unscientific reasons. References to the relevant individual studies are given in the analysis below.

In an example of omission in the area of health risks, Manuela Malatesta et al.'s findings of adverse effects of GM soy on the liver, pancreas, and testes of mice fed over a long-term period [36, 37, 79, 80] are cited in Nicolia et al.'s Supplementary Material but are not mentioned in the review. Nor do they discuss numerous other studies showing adverse effects of a GM diet in laboratory and farm animals, including many of those summarised by Krimsky in his review [34].

An example of omission by Nicolia et al. in the area of environmental effects is a major scientific controversy around the effects of Bt toxins (bacteria-derived insecticides engineered into GM Bt crops) on non-target and beneficial insects. Research led by Angelika Hilbeck showed that Bt toxins of microbial and GM plant origin caused lethal effects in the larvae of green lacewing, an important ecotoxicological model organism, and ladybirds, both of which are beneficial insects (as pest predators) to farmers [81–85]. Nicolia et al. sidestep these experimental outcomes, which clearly demonstrate that GM Bt crops and GM Bt toxins can cause harm to species with important ecological functions.

Rebuttal studies were carried out in an effort to disprove Hilbeck et al.'s findings [86–91]. Nicolia et al. include one of Hilbeck et al.'s ladybird studies [84] in their Supplementary Material but omit to discuss its findings in the main text of their review. In contrast, in an example of selective use of data, they include several of the rebuttal studies in their Supplementary Material [86, 88, 89] but omit crucial follow-up investigations in which Hilbeck et al. showed that changes in the study protocols were the reasons for the rebuttal studies failing to find the same results of toxic effects to lacewings and ladybirds. The authors of the rebuttal studies had provided Bt toxins in a form that would make it, respectively, impossible and extremely unlikely that the insect subjects had actually ingested the test substance [85, 92]. Nicolia et al. omitted Hilbeck et al.'s follow-up studies in spite of the fact that they fall within their arbitrarily selected study publication window of 2002–2012.

The above-cited examples are just a few of the ways in which Nicolia et al.'s review is selective, misleading, and unreliable. In fact, it is an example of misinformation in its own right.

This raises questions regarding how Lynas et al. defined misinformation. They appear to have judged the review as valid because it is in line with their own subjective view that there is a "consensus" on GMO safety, rather than on the objective scientific reliability of its conclusions.

In general, it is not possible to evaluate objectively the safety of GMOs for health and the environment by taking at face value the conclusions expressed in the abstracts of reviews. Instead, Lynas et al. should examine primary experimental findings referenced in, and omitted from, the review and test their hypothesis about GMO safety against such data.

Overlooking an important source of misinformation

Lynas et al. overlook the fact that those who might reasonably be accused of "misinformation" and lack of integrity are not just the critics of controversial products and narratives but also those who promote and manufacture them [93–96]. This omission is to the detriment of their credibility on the topics of GM foods and crops and associated pesticides, where the bias of industry-linked studies [97, 98] and the unethical and unscientific nature of some industry-sponsored research and public messaging [96, 99, 100] are well documented.

Also documented are the industry-imposed restrictions and attacks on independent researchers who aim to investigate the risks of GMOs (including restricting access to the necessary test materials) [32, 101, 102]. Accordingly, there are knowledge gaps in the understanding of the health and environmental effects of GMOs.

For example, long-term toxicity studies testing GM foods in laboratory animals are necessary to promote further understanding of potential long-term effects of consuming a GM diet in humans. But they are rare, as different groups of scientists have indicated [42, 76, 103, 104].

A review that purported to address such long-term studies in animals, and concluded that there was no evidence to suggest lack of safety of GM foods, included many studies that were not long term at all, in terms of the study duration compared with the natural lifespan of the animal in question. Furthermore, the review included studies with very small numbers of animals and studies on animals that are not considered toxicologically relevant to humans. In addition, the review included a genuinely long-term study, led by Manuela Malatesta, that found adverse effects from feeding GM soy [36], but the review authors dismissed the results because the authors did not use the non-GM isogenic (of the same genetic background but without the genetic modification) line of the crop as a control diet [105]. However, in an example of biased double standards, the review authors accepted findings of safety in a long-term study with GM soy that suffered from the same methodological weakness [106].

The lack of the non-GM isogenic line as the control is almost inevitable in studies by independent scientists on commercial GM varieties, unless they develop their own GMO lines for the experiment. This is because the non-GM isogenic comparator for any given GMO tested is in the control and possession of the developer. In the case of Malatesta's research, this was Monsanto. GMO developers are not in the habit of granting access to their proprietary materials to independent scientists for the purposes of conducting risk research on them [32, 101, 102]. Regarding the difficulties of obtaining funding for risk research on GM foods, Malatesta stated that after she published her research, she was forced out of her university position and was unable to obtain funding to follow up her studies. She blamed "widespread fear of Monsanto and GMOs in general" [107].

The Germany-based research group Testbiotech has published a report on the difficulties of carrying out publicly funded risk research on GM crops that is genuinely independent of GMO industry interests [108].

Similar industry-imposed restrictions apply to regulatory authorities wishing to identify GMOs in the food and feed supply [109].

Misleading and biased claims about retraction of studies

Lynas et al. state that some "papers purporting to show harms [from GMOs] have… been retracted, published in predatory journals with minimal or poor peer review, or found to contain plagiarism or even outright fraud".

As an example of a retracted study, Lynas et al. refer to a publication by Séralini et al., which reported that a Monsanto GM maize and its associated glyphosate-based herbicide Roundup harmed the health of rats [66]. However, Lynas et al.'s characterisation of this study as misinformation is itself an example of misinformation, for two reasons.

The first is that Monsanto internal emails uncovered by freedom of information requests and cancer litigation in the US established that the study's retraction more than one year after its peer-reviewed publication, by the editor-in-chief of the journal that first published it (Food and Chemical Toxicology, FCT), was orchestrated by Monsanto, in its own campaign of misinformation [110–115].

The second reason is that Lynas et al. claim that the study was retracted "due to numerous methodological flaws". However, FCT editor-in-chief A. Wallace Hayes, in announcing the retraction, admitted that he could find nothing incorrect in the reported results. He only justified the retraction on the basis of the alleged "inconclusive" nature of two of the many findings of the study [116]—tumours and mortality. Inconclusiveness on these endpoints are not "methodological flaws" because the authors never designed the study to measure carcinogenicity, as they clearly state in their paper [66]. It was designed as a long-term toxicity study, which, as well as findings of chronic toxicity from the GM maize and Roundup exposure, unexpectedly resulted in observations of increased tumours and mortality in treatment groups, which must be reported, in line with the requirements of OECD chronic toxicity protocols 452 and 453 for all "lesions" (which by definition include tumours) [117, 118].

The retraction of the Séralini group's study and Hayes's reasoning were condemned by nearly 200 international scientists and experts, on the basis that inconclusiveness as a reason for retraction was unprecedented in the history of scientific publishing and in violation of the standards of the Committee on Publication Ethics (COPE). The scientists stated that if this new criterion for retraction were adopted by journals, few studies would remain in the scientific literature [119].

Internal Monsanto documents revealed that Hayes had entered into a consulting agreement with Monsanto in the period just before his involvement in the retraction [110, 114, 120] Also, Richard E. Goodman, who played a key role in the retraction [110, 121] was appointed to the journal's editorial board a few months after the peer-reviewed publication of the study [110]. Goodman is a former Monsanto employee with links to the International Life Sciences Institute (ILSI) [110, 122], an industry-funded organisation with a history of lobbying for industry-friendly risk assessment guidelines and regulations for GM crops and pesticides [123, 124].

As the scandals around the retraction came to light, both Hayes and Goodman were sidelined or moved on from their positions at the journal [110, 114]. Séralini et al.'s study was subsequently republished by another journal, Environmental Sciences Europe, ensuring that it continues to be available for independent scrutiny [66].

If the veracity of positions in the GMO debate is to be judged on the number of study retractions on each "side" (a dubious method of evaluation), it must be considered that a study claiming efficacy of GM golden rice was retracted on the basis of unethical behaviour by the researchers in testing the GMO on Chinese children without obtaining the informed consent of their parents [125, 126], and the GMO advocate [127] Pamela Ronald had to retract two papers that form the core of her research programme on how rice plants detect specific bacterial pathogens [128, 129].

Misleading claims about predatory journals

Lynas et al. claim that papers reporting harms from GMOs are published in "predatory" journals. However, they offer no definition of such journals. At least one journal publisher once flagged as predatory is no longer listed as such [130] and includes high impact journals in its list [131].

Lynas et al. back up their claim by giving as their source a paper co-authored by Henry I. Miller [132]. Yet Miller's own articles were retracted by Forbes magazine because he failed to disclose Monsanto's ghostwriting role [133]. Miller's paper offers no data that could support Lynas et al.'s claim. It defines "predatory" journals as "pay-to-play" [132], though how that definition can be justified at a time when the highly regarded Nature journals charge €9,500 for open access publication [134]—a sum unaffordable for many researchers—is not comprehensible.

The problems around the variable quality and subjectivity of peer review are well known and are not confined to journals dubbed as predatory. However, once published in a peer-reviewed journal, studies should be judged on the merits of their scientific content.

Misleading and biased claims about the impacts and performance of GMOs in India

Lynas et al. state, "The adoption of Bt cotton in India, despite being subject to a campaign of misinformation by anti-GMO activists blaming it for a supposed increase in farmer suicides, has in fact increased farm incomes and helped avoid several million cases of pesticide poisoning every year in India".

As evidence, they cite a 2011 study by Kouser and Qaim, which, like other studies reporting Bt cotton success, is based on outdated data, collected before pest resistance to GM Bt insecticidal cotton gained momentum and led to widespread crop failure [135]. Nevertheless, Kouser and Qaim heavily qualify their praise for Bt cotton. While they state that "Bt cotton technology has been very effective overall in India", they also concede that "in specific districts and years, Bt cotton may have indirectly contributed to farmer indebtedness, leading to suicides", and add that "its failure was mainly the result of the context or environment in which it was planted". Kouser and Qaim blame Bt cotton's unsuitability for rainfed conditions (Bt cotton is known to perform better under irrigation [136]), as well as poor farmer knowledge and practices, such as spraying too much pesticide [137].

However, context, including the receiving environment, the socio-economic situation, and farmer knowledge, are central aspects of farming. Any technology that demands specific and optimal conditions of adoption, especially given the situation of resource-poor farmers, is not sustainable. More than two-thirds of India's agricultural area is rainfed and non-irrigated [138].

A 2020 review by internationally renowned experts (Gutierrez et al. 2020) noted that a temporary modest yield increase that accrued by 2006, when Bt cotton adoption was less than 30%, was due to increased use of fertiliser and reduced use of insecticide. However, within a few years, due to resistant pests, chemical insecticide use began to increase, reaching pre-Bt cotton levels by 2012. The authors concluded, "This technology is suboptimal, leading to stagnant yields, high input costs, increased insecticide use, and low farmer incomes that increase economic distress that is a proximate cause of cotton farmer suicides. The current GM Bt technology adds costs in rainfed cotton without commensurate increases in yield"[135]. The authors recommended a shift to "non-GM pure-line high-density short-season varieties", which they said "could double rainfed cotton yield, reduce costs, decrease insecticide use, and help ameliorate suicides" [135].

In a long-term analysis of data gathered over a 20 year period, Kranthi and Stone concluded that while "Bt cotton did make a positive contribution in India", in particular by reducing predations by the American bollworm, "the technology's benefits have been modest and largely ephemeral". The authors noted that Bt cotton adoption is not correlated with increases in yield. Instead, "changes in other inputs, including irrigation, insecticides and especially fertiliser use, correspond better to yield rises". Moreover, regarding insecticide use, "Bt seeds' positive effects on spraying were fleeting. Countrywide yields have not improved in 13 years, and Indian cotton farmers today are spending more per hectare on insecticide than they did before Bt began to spread" [139].

Kranthi and Stone make the important distinction between cotton production (total amount produced in a region) and cotton yield (amount produced per hectare). They note that while production has surged in India and this is often cited as a triumph of Bt cotton, in fact this is due to a massive increase in area planted to cotton between 1996 and 2011, as well as increased inputs such as fertiliser and irrigation. Yields, however, have stagnated since 2006 [139].

Responding, Ian Plewis stated that his own statistical analysis, taking into account insecticide use by state, led him to a different conclusion, of a positive effect of Bt on yield in Rajasthan, though not in Haryana and Punjab. He also found that "the technology reduced the proportion of farmers' costs going to insecticides in all three states" [140]. Matin Qaim objected to Kranthi and Stone's conclusions, stating that graphical comparison of trends without a formal statistical model cannot be used to analyse causal effects. Qaim cited research by himself and Kathage, which concluded that "after controlling for all other factors – Bt adoption had increased cotton yields by 24%, farmers' profits by 50% and farm household living standards by 18%… with no indication that the benefits were fading during the 2002–2008 period. The same data also revealed that chemical insecticide quantities declined by more than 40% through Bt adoption, with the largest reductions in the most toxic active ingredients previously sprayed to control the American bollworm" [141].

Kranthi and Stone responded that Plewis "supports our trends showing that Bt seeds had no positive yield effect in Haryana or Punjab but one of his datasets may show a slight effect in Rajasthan. Indeed there may have been but, as we show, Rajasthan's cotton yields were already climbing when Bt was adopted and the yield trend did not change at all despite the rapid Bt adoption". On Plewis's crediting of Bt cotton with a reduction in the proportion of farmers' costs going to insecticides in the three northern states, Kranthi, and Stone state that while this is plausible, their own analysis was different and looked at actual countrywide insecticide costs. However, they added, "Actual insecticide costs have definitely increased in north India but costs for fertiliser, irrigation and labour may have increased even more. This would reduce the proportion of farmers' costs going to insecticides" [142].

Responding to Qaim, Kranthi and Stone stated, "He saw 'no indication that the benefits were fading' by 2008, after which he stopped collecting data and declared pesticide reductions to be 'sustainable'. Ironically, 2008 was the year that Bt resistance was first observed. If Qaim had examined long-term trends—whether statistically or graphically—he would have seen that by 2007 insecticide costs for managing non-target pests were rising ominously, that by 2012 insecticide costs for managing pink bollworm [the target pest of Bt cotton] were rising, and that by 2018 cotton farmers were spending more than twice as much on insecticides as in 2005 when Bt seeds began to spread"[142]. This is hardly a success story, no matter how one looks at it.

Kranthi and Stone's observation of the time-limited pest control benefits of Bt cotton is borne out by media reports in 2017 of hundreds of incidents of accidental farmer pesticide poisoning (including deaths) due to farmers resorting to spraying a cocktail of toxic pesticides on their Bt cotton crops, which were being attacked by the bollworm pest [143, 144].

Misleading characterisation of the history of GMOs in Africa

Regarding Africa, Lynas et al. blame "misinformation" and "anti-GMO activism" for the "negative policy environment" around GM crops in the continent. However, they fail to consider the influence brought to bear by the historical and recent repeated failures of GM crops in Africa, which have been extensively reported.

Examples include a much-promoted GM virus-resistant sweet potato, which failed where a non-GM version succeeded at a fraction of the cost [145, 146]; GM virus-resistant cassava, which lost virus resistance [147]; a CRISPR/Cas gene-edited cassava, which not only failed to resist the target virus but gave rise to a novel mutant editing-resistant virus that, in the event of escape, the researchers warned might be an intermediate step towards a "truly pathogenic" virus [148]; and a Bt cotton project in Makhathini, South Africa, which failed due to the collapse of credit systems set-up to incentivise farmers to grow the GM crop, high seed and input costs, farmer indebtedness, adverse weather conditions, and pest attacks [149–152]

A commentary on Bt maize's performance in South Africa noted that "currently commercialised Bt maize varieties are developed to give high yields under good agricultural conditions (sufficient and timely rain, fertilisation and good storage conditions)"—which are often not available to smallholder farmers, resulting in the risk that input costs will not be covered within any one year. Moreover, the authors stated that commercial varieties into which the Bt trait is introduced are outperformed by locally used non-GM hybrids and open-pollinated varieties, which are better adapted to smallholders' resources and challenging weather and storage conditions [153].

GM Bt cotton was introduced commercially in Burkina Faso in 2008, only to be phased out just seven years later after showing a marked decline in fibre quality compared with conventional Burkinabé cotton [154, 155].

Clearly, Lynas et al.'s selective reporting on the story of GM Bt cotton in India and GM crops in Africa has resulted in their ignoring evidence-based accounts such as the above, which point to a much more complex and nuanced situation.

Conclusion

In this article, we present evidence and arguments showing that Lynas et al.'s publication suffers from critical flaws, such as an absence of scientific evidence to support the arguments presented; omission of relevant evidence on health and the environment; a reliance on spurious analogies; and a failure to distinguish "misinformation" from a field of study characterised by a variety of different and contested data, views, and interpretations.

Lynas et al. draw spurious analogies between critics of GMO crops and foods, climate change, COVID-19, and vaccines, whereas scientists' and the public's views on GMOs have no proven relation to views on COVID-19 or vaccines. The published evidence on views on GMOs and climate change suggests that there may be a correlation, but in the opposite direction to that implied by Lynas et al., in that prominent defenders of GM crops and associated pesticides have strong links with climate change denial.

Contrary to Lynas et al.'s claims, there is no scientific consensus on GMO safety. Certain groups that have made generalised and unsupported claims of GMO safety have been exposed as compromised by conflicts of interest with industry.

There may be a dominant paradigm of GMO safety, which has not, however, been demonstrated by polling scientists familiar with the relevant empirical data on which a valid opinion could be based. What is known is that different experts have made different experimental findings and conclusions on GMO risks and safety. Only further well-designed studies can resolve uncertainties. Forced—and at times self-referential—claims of consensus impede scientific progress and understanding.

Lynas et al. ignore a major source of misinformation on controversial products and narratives: the industries that manufacture and promote them. The bias of industry-linked studies and the unethical and unscientific nature of some industry-sponsored research and public messaging are well documented. Likewise, they ignore the influence that corporate interests have on driving research agendas and how the public perceives this. The public perception of science is influenced not only by scientific claims of truth or falseness but also by historical and socio-economic context, audience perceptions, and the source of information, among other complex factors.

Lynas et al.'s claim that GM Bt cotton has been a success in India relies on limited and outdated data. More comprehensive and recent information show widespread failure of this crop. Their claim that some African countries' negative attitude to GMOs is due to misinformation fails to take account of the documented historical and recent failures of GMOs and GMO projects on that continent.

Regarding the data on GMO safety, Lynas et al. cite a review by Nicolia et al. However, many of the studies cited by Nicolia et al. do not provide evidence that supports the safety of GMOs for health or the environment. Furthermore, numerous cited studies point to risks or harms, which are ignored or inadequately addressed by Nicolia et al., while other investigations clearly indicating harm are simply excluded. Lynas et al. reach their misleading conclusion on the review's findings by accepting the wording of the abstract at face value without examining the individual studies cited and omitted by Nicolia et al.

In sum, it is evident that Lynas et al. resort to inaccurate and potentially libellous accusations, spurious analogies, selective and uncritical reporting, and misrepresentations of the state of the science on GM foods and crops and their associated pesticides, in an apparent attempt to promote and defend these products. It is especially important to present only accurate and comprehensive information on agricultural GMOs when the intended audience is the general public and policymakers, as non-specialists may lack the time, background, and resources to investigate the veracity of claims made.

Based on the evidence we cite and arguments we provide, it is Lynas et al.'s article that can be described as "misinformation" on the highly important topic of GMO crop and food safety. Therefore, the article poses a risk of misleading not only the scientific community but also the public at large.

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CR and MNA led the drafting of the majority of the manuscript. IC led the drafting of the section, "Methodological weaknesses". IC and AH reviewed the entire draft and provided additional input and comments.

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