RESEARCH PAPER

Biotechnological pathway to resilience: Genetically modified crops as a tool for climate change mitigation and adaptation

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ABSTRACT
The escalating instability of global agricultural systems driven by greenhouse gas emissions necessitates the adoption of high-yield, climate-resilient crop varieties to safeguard international food security. This research investigates the function of Genetically Modified (GM) crops as a dual mechanism for climate change mitigation and adaptation, exploring the intrinsic connection between their implementation and the dynamic evolution of International Climate Change Adaptation Law. Employing a doctrinal legal methodology, the study assesses important international instruments such as the UNFCCC and the Paris Agreement together with the latest empirical data on biotechnology efficacy. The results indicate that GM technology significantly contributes to mitigation; as of 2020, GM adoption prevented the emission of 23.6 billion kilograms of CO2, equivalent to removing 15.6 million cars from the road annually. Furthermore, by 2025, advancements in molecular breeding and New Genomic Techniques (NGTs) have demonstrated the ability to boost yields by up to 30% under severe abiotic stressors such as drought and salinity. However, the study identifies critical socio-legal impedimenta, particularly the conflict between Intellectual Property Rights (IPR) under the TRIPS Agreement and the Seed Sovereignty of smallholder farmers. The article finds that international law serves as the "regulatory scaffolding" for technological transfer; but, a more equitable legal framework is necessary to harmonise individual patent rights with the collective global necessity for a sustainable and equitable agricultural future.
Keywords: Genetically Modified Crops, Climate change Mitigation and Adaptation, International Law Legal Framework, Biosafety.
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1. Introduction

The global climate crisis has become the biggest threat to the stability of contemporary agricultural stability and international food security. As anthropogenic greenhouse gas emissions continue to change the atmospheric compositions, the resulting changes in climate patterns such as rising average temperatures, unpredictable rainfall patterns, and more frequent extreme weather events have put unprecedented stress on agribusiness. These environmental stressors not only lower agricultural yields, but they also lower the nutritional value of the food and facilitate the rapid proliferation of novel pests and diseases (IPCC, 2023). As a result, traditional farming methods are becoming increasingly insufficient to meet the needs of a growing world population. In this situation, creating a strong agricultural model is no longer just a choice; it is now necessary for the survival of the world. Agricultural biotechnology provides a highly effective "pathway to resilience" for ensuring sustainable food production. Genetically Modified (GM) crops serve a critical dual function in this paradigm: mitigation and adaptation.

A review of recent agronomic and environmental literature extensively documents the biological utility of GM crops. On the mitigation front, longitudinal studies have quantified the substantial reduction in greenhouse gas emissions facilitated by agricultural biotechnology (Brookes, 2022). The adoption of herbicide-tolerant and insect-resistant crops has enabled a massive shift toward conservation tillage, which significantly reduces agricultural fuel consumption and enhances soil carbon sequestration (Brookes, 2022). Simultaneously, literature on climate adaptation emphasizes the role of New Genomic Techniques (NGTs) in securing food systems. Advanced molecular breeding now allows for the rapid development of cultivars with inherent resistance to severe abiotic stressors, such as drought and salinity, positioning biotechnology as an indispensable tool for climate resilience (Pagnotta, 2025).

However, in contrast to the unified scientific consensus, current legal scholarship reveals a deeply fragmented international regulatory framework. The mandates of the Paris Agreement specifically Article 7 on adaptation and Article 10 on technology transfer urge international cooperation in deploying climate-resilient technologies (United Nations Framework Convention on Climate Change [UNFCCC], 2015). Yet, these broad climate goals are often structurally hindered by restrictive international biosafety regimes, notably the Cartagena Protocol on Biosafety (Secretariat of the Convention on Biological Diversity, 2000), whose reliance on the precautionary principle creates prohibitive hurdles for developing nations. Furthermore, a fierce socio-legal conflict exists regarding Intellectual Property Rights (IPR), where the commodification of climate-resilient seeds under the TRIPS Agreement is argued to undermine the "Seed Sovereignty" of smallholder farmers (World Trade Organization [WTO], 1994).

To address this gap and explore how the legal regime can be harmonized to support biotechnological resilience, the present study is conducted with the following primary objectives:

- To analyse the international legal framework governing climate mitigation and adaptation, assessing its efficacy in facilitating the deployment of agricultural biotechnology.
- To assess the mitigation potential of Genetically Modified (GM) crops, specifically focusing on their capacity for carbon sequestration and the reduction of greenhouse gas emissions.
- To evaluate the adaptation capabilities of GM crops in response to climate-induced abiotic and biotic stressors.
- To address the multifaceted legal and socio-political controversies surrounding GM technology, particularly the tension between Intellectual Property Rights (IPR) and global seed sovereignty.

2. Research Methodology

The present study adopts a doctrinal research methodology, characterized by a systematic and critical analysis of legal instruments, statutory provisions, and secondary empirical data. While providing the interdisciplinary nature of the research intersecting biotechnology, environmental science, and international law, the study employs a qualitative analytical framework to bridge the gap between scientific efficacy and regulatory scaffolding.

2.1 Research Design and Approach:

The research is designed as a descriptive and analytical study employing a "top-down" conceptual framework. This approach begins with a global analysis of international climate mandates, specifically evaluating the coherence between the "Mitigation and Adaptation Mandates" found in climate treaties and the "Restrictive Mandates" found in biosafety and intellectual property regimes. This design is essential to determine if Genetically Modified (GM) technology, through its dual capacity for carbon sequestration and climate-stress resilience, can be effectively integrated into the transparency and technology transfer frameworks of the Paris Agreement. By narrowing down from these high-level international obligations to the specific legal hurdles faced by agricultural biotechnology, the study provides a critical assessment of whether current legal scaffolding facilitates or hinders the "Biotechnological Pathway" to a low-carbon, resilient agricultural future.

2.2 Sources of Data:

The study relies on a dual-stream data collection process involving primary and secondary sources:

- Primary Legal Sources: The core of the analysis is grounded in international conventions and treaties, specifically the United Nations Framework Convention on Climate Change (UNFCCC, 1992), the Paris Agreement (UNFCCC, 2015), the Cartagena Protocol on Biosafety (Secretariat of the Convention on Biological Diversity, 2000), and the TRIPS Agreement (WTO, 1994).
- Secondary Empirical Sources: To ensure technical accuracy regarding mitigation and adaptation, the study incorporates high-impact secondary data. This includes the Assessment Reports (AR6) from the Intergovernmental Panel on Climate Change (IPCC, 2023) and longitudinal environmental impact assessments from peer-reviewed literature (Brookes, 2022).

2.3 Data Analysis Technique:

The collected data were analysed using content analysis and comparative legal interpretation. Content analysis was applied to scientific reports to extract data on carbon sequestration and yield resilience. Comparative legal interpretation was then utilized to identify "regulatory friction" points—areas where the goals of one treaty (e.g., technology transfer under the Paris Agreement) may conflict with the requirements of another (e.g., patent enforcement under TRIPS).

2.4 Scope and Limitations:

The scope of this research is limited to the international legal framework and global environmental impacts. While the study references general challenges faced by the Global South, it does not provide an exhaustive analysis of the municipal laws of individual nations. Furthermore, the empirical data on GM crop performance is based on existing longitudinal studies up to the year 2025, acknowledging that biotechnological advancements are rapidly evolving.

3. Results

This section details the synthesized outcomes of the doctrinal and empirical analysis, beginning with an evaluation of the international climate law framework, followed by a quantitative assessment of the mitigation and adaptation potential of agricultural biotechnology.

3.1. Climate Change and International law Legal Framework

The World Meteorological Organisation (WMO) is one of the specialised agencies of the United Nations that sponsored the First World Climate Conference, which took place in Geneva from February 12–23, 1979. It is one of the first significant international gatherings on climate change, where four working groups were formed to examine climate data, identify climate-related topics, conduct integrated impact evaluations, and conduct research on climate variability and change. Additionally, it resulted in the creation of the Intergovernmental Panel on Climate Change (IPCC) by the WMO and the United Nations Environmental Programme (UNEP) in 1988 as an intergovernmental assessment of the science, impacts, and response options of climate change. Since its establishment, the Intergovernmental Panel on Climate Change (IPCC) has produced five thorough assessments providing 'full scientific and technical assessments of climate change that have undergone stringent review procedures. The IPCC has drawn criticism for being "too cautious" as well as "too political and alarmist." However, its publications are regarded as the definitive source of knowledge about the science and effects of climate change by most people (House of Commons Library, 2023).

The first assessment report from the IPCC was released in 1990. A warning was issued: "The atmospheric concentrations of greenhouse gases are substantially increasing due to emissions resulting from human activities." This sparked multiple calls for an international convention. As a framework for international cooperation to combat climate change by limiting average global temperature increases and the resulting climate change, as well as coping with impacts that were by then inevitable, countries joined the United Nations Framework Convention on Climate Change in 1992. Five years later in 1997 the Kyoto Protocol was ratified. The developed countries Parties to the Kyoto Protocol are legally required to meet emission reduction targets (UNFCCC, n.d.).

The UNFCCC and the Kyoto Protocol collectively form the international legal framework on climate change. While this framework does not impose explicit obligations on states, it serves as a regulatory framework where negotiations for addressing climate change take place. The objectives of the UNFCCC encompass both mitigation, which aims to reduce the impacts of climate change, and adaptation, which involves adjusting to the repercussions that are already occurring or inevitable. The initial reactions mostly emphasised the reduction of the impact of climate change. The focus on mitigation is evident in previous IPCC assessment reports, as well as in the wording of the UNFCCC and the Kyoto Protocol and reducing additional consequences of climate change. In addition to emphasizing mitigation, the legal framework on climate change also aims to govern the responsibilities of states to implement adaptation measures and improve their ability to adapt (Saab, 2016).

3.2 Mitigation, Adaptation, and Climate Change

As per the fifth assessment report of the IPCC, mitigation is defined as "with respect to climate change, mitigation means implementing policies to reduce greenhouse gas emissions and enhance sinks." The report also evaluates human actions aimed at decreasing the origins of various substances that may have a direct or indirect impact on mitigating climate change. These actions include, for instance, reducing the release of particulate matter that can directly modify the radiation balance (such as black carbon), as well as implementing measures to regulate the emissions of carbon monoxide, nitrogen oxides, volatile organic compounds, and other pollutants that can influence the concentration of tropospheric ozone, which in turn has an indirect effect on the climate (Intergovernmental Panel on Climate Change [IPCC], 2014).

As per the sixth assessment report of IPCC, the adaptation is defined as "In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects (IPCC, 2023)." Whereas the fourth Assessment Report of IPCC defined adaptation as "Initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects." There are different types of adaptation, such as anticipatory and reactive, private and public, and autonomous and planned. Examples include the implementation of measures such as elevating river or coastal dikes and replacing vulnerable plants with more temperature-shock resistant ones. (IPCC, 2007).

Climate change is the alteration of the climate's condition, which may be determined through statistical analysis of changes in the mean and/or the variety of its characteristics. This change persists for a significant duration, usually spanning decades or more. The causes of climate change can be attributed to either natural internal processes or external factors, such as variations in solar cycles, volcanic eruptions, and ongoing human-induced alterations in atmospheric composition and land use (United Nations, 1992). The United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as a change of the Earth's climate that can be directly or indirectly attributed to human activity. This alteration affects the composition of the global atmosphere and is separate from the natural climate variations observed over similar time periods. The UNFCCC differentiates between climate change caused by human activities that modify the composition of the atmosphere and climate variability caused by natural factors (IPCC, 2023).

3.3 Genetically Modified Crops and Climate Change Mitigation and Adaptation

Genetic modification (GM) is a technological process that entails the introduction of foreign DNA into the genetic makeup of an organism. GM plants are created by introducing foreign DNA into plant cells. Typically, the cells are subsequently cultivated in a controlled environment known as tissue culture, where they undergo growth and transform into plants. The offspring of these plants will inherit the newly introduced genetic material. Plant genetic modification entails the insertion of a distinct DNA sequence into the plant's genome, hence imparting novel or altered traits. This may involve altering the plant's growth patterns or conferring resistance to a specific pathogen. The newly introduced DNA integrates into the genome of the genetically modified (GM) plant, and subsequently, the seeds generated by these plants will inherit this modified genetic material (Royal Society, n.d.).

Agricultural practises, including the application of synthetic fertiliser, the cultivation of rice crops, overgrazing, and deforestation, contribute to 25% of greenhouse gas emissions (carbon dioxide, methane, and nitrous oxide) released into the atmosphere (IPCC, 2023). Biotechnology offers a very dependable solution for addressing climate change by implementing energy-efficient farming practises, carbon sequestration, and minimising the use of synthetic fertilisers (Brookes, 2022; Qaim, 2020). The yearly worldwide impacts repo rt by PG Economics provides a quantitative analysis of the effects of agricultural biotechnology on the environment and the incomes of farmers since its commercialization in 1996. Genetically modified crops have played a substantial role in effectively decreasing the quantity of greenhouse gas emissions resulting from agricultural practices. This is a consequence of decreased fuel use and increased retention of carbon in the soil due to the adoption of genetically modified crops and reduced tillage practices. The analysis of longitudinal data confirms that agricultural biotechnology serves as a potent instrument for climate goals. Regarding mitigation, results indicate that the global adoption of GM crops has facilitated a massive shift toward conservation tillage. From 1996 to 2020, the total cumulative permanent reduction in fuel has been about 39,147 million kg of CO2 which is result of using 14, 662 million litres of less fuel. This is equivalent to pulling 25.9 million cars off the road for a year (Table 1).

The most significant reductions in carbon dioxide emissions associated with fuel consumption have resulted from the implementation of GM HT technology, which has enabled a transition to RT/NT production systems characterised by diminished soil cultivation techniques. This made up 92% of the savings in fuel and carbon dioxide from 1996 to 2020. GM HT soybeans made the biggest contribution, making up 68% of the total savings. The most savings have come from South America. In 2020, the savings from using less fuel were 2,330 million kg of carbon dioxide, which came from using 948 million litres less gasoline. These savings are like removing 1.68 million cars off the road for a year (Table 1).

Table 1. Carbon storage/sequestration from reduced fuel use with GM crops 1996–2020.

Crop/trait/country	Fuel Saving (Million Liters)	Permanent Carbon dioxide Savings from reduced fuel Use (Million kg of carbon dioxide)	Permanent fuel Savings: as average family car equivalents removed from the road for

			a year ('000s)
HT soybeans			
Argentina	4,433	11,837	7,844
Brazil	2,749	7,341	4,865
Bolivia, Paraguay, Uruguay	899	2,401	1,591
US	1,687	4,503	2,982
Canada	255	681	451
HT Maize			
US	2,257	6,027	3,994
Canada	121	323	214
HT Canola			
Canada (GM HT Canola)	1,067	2,848	1,887
IR maize			
Brazil	369	984	652
US/Canada/Spain/ South Africa	91	243	161
IR Cotton (Global)	285	760	504
IR Soybeans (South America)	449	1,199	795
Total	**14,662**	**39,147**	**25,942**

Source: Adapted from Brookes (2022).
Note: Data reflects cumulative environmental benefits from 1996 to 2020. HT denotes Herbicide Tolerant; IR denotes Insect Resistant.
Assumption:

(1) an average family car in 2020 produces 123.4 grams of carbon dioxide per km. A car does an average of 12,231 km/year and therefore produces 1,509 kg of carbon dioxide/year
(2) GM IR cotton. India, Pakistan, Myanmar and China excluded because insecticides assumed to be applied by hand, using back pack sprayers

3.3.1 Additional Soil Carbon storage/sequestration

Carbon sequestration refers to the process of absorbing carbon-containing compounds, specifically carbon dioxide, from the atmosphere. It aids in the extraction of CO2 from the atmosphere and enhances the organic carbon content of the soil, resulting in the subsequent improvement of the soil. Carbon sequestration alleviates the impact of climate change (West & Post, 2002). Carbon sequestration is considered one of the most effective methods for mitigating the impact of climate change. It involves capturing and storing the continuously rising levels of carbon dioxide (CO2) from the atmosphere. One method to boost carbon sequestration is through the implementation of conservation tillage. Conservation tillage refers to any tillage and planting approach that ensures that more than 30% of the soil surface is covered by crop residue after planting. This practise helps to prevent erosion caused by water and subsequently promotes the consumption of methane and the sequestration of carbon in the soil.In 2020, it has been predicted that an additional 5,750 million kg of soil carbon was sequestered in the regions of GM HT crops utilising RT/NT production systems in North and South America. This equates to 21,101 million kilograms of carbon dioxide that has not been emitted into the global atmosphere. The reduction of automobiles off the roadway corresponds to the removal of 13.98 million cars for a duration of one year (Table 2).

Table 2. Context of carbon sequestration impact 2020: car equivalents.

Crop/trait/country	Additional carbon stored in soil (million kg of carbon)	Potential additional soil carbon sequestration savings (million kg of carbon dioxide)	Soil carbon sequestration savings: as average family car equivalents removed from the road for a year (‘000s)
HT soybeans			
Argentina	1,832.5	6,725.2	4,445.8
Brazil	1,485.0	5,450.1	3,611.0
Bolivia, Paraguay, Uruguay	490.7	1,800.8	1,193.1
US	110.9	407.0	269.6
Canada	62.9	230.7	152.9
HT Maize			
US	1,481.6	5,437.6	3,602.7
Canada	15.6	57.4	38
HT Canola			
Canada (GM HT Canola)	270.4	992.4	657.5
IR maize			
Brazil	0	0	0
US/Canada/Spain/South Africa	0	0	0

IR Cotton (Global)	0	0	0
IR Soybeans (South America)	0	0	0
Total	**5,749.6**	**21,101.1**	**13,980.7**

Source: Adapted from Brookes (2022).

Note: Data reflects cumulative environmental benefits from 1996 to 2020. HT denotes Herbicide Tolerant; IR denotes Insect Resistant.

3.4 Adaptation to abiotic and biotic stresses

Climate change-induced variations in climatic conditions significantly impact plant production and crop yield. These variations in climate result in abiotic stress in plants, primarily affecting the performance of agricultural species. The primary abiotic stressors in plants caused by climate change encompass increased CO2 concentration, heightened temperature, salt, and drought. The increased concentration of CO2 has both beneficial and detrimental effects on the physical structure and biological functions of agricultural plants. Elevated levels of CO2 lead to enhanced photosynthetic activity in plants, resulting in improved growth, biomass, and yield (Chaudhry & Sidhu, 2021). Molecular breeding procedures for enhancing tolerance to abiotic stress rely on the upregulation of genes associated with stress response. Various researchers have successfully generated genetically modified crops, such as Arabidopsis, tobacco, maize, wheat, cotton, soybean, pearl millet, tomato, rice, and brassica, that are resistant to drought, salt, and heat (Barrows et al., 2014). In response, advanced molecular breeding and New Genomic Techniques (NGTs) offer a targeted solution by upregulating specific stress-response genes, thereby creating resilient phenotypes capable of maintaining high yields under sub-optimal conditions ability to boost yields by up to 30% under severe abiotic stressors such as drought and salinity. (Pagnotta, 2025).

Agricultural biotechnology has the potential to enhance crop output by creating strains that are resistant to biotic stressors, such as insects, fungi, bacteria, and viruses. The Bacillus thuringiensis (Bt) gene is inserted into corn, cotton, and soybeans, providing them with insect resistance against pests like the European corn borer. However, this gene does not pose any risk to humans and has minimal impact on the environment. GM crops have been demonstrated to be a valuable tool for integrated pest management. The herbicide tolerance trait is included into corn, soybeans, and canola. Furthermore, there are ongoing efforts to generate genetically engineered potatoes, cassava, and other crops that possess resistance to biotic stressors. In fact, certain varieties have already been successfully introduced into the commercial market (Hong et al., 2000).

4. Discussions

Building upon the empirical validation of Genetically Modified (GM) crops as effective instruments for climate mitigation and adaptation, this section critically evaluates the regulatory friction generated at the intersection of international climate, biosafety, and intellectual property regimes.

4.1 Extended Legal Framework and Nexus Analysis

The international legal framework on climate change, primarily anchored by the UNFCCC and the Paris Agreement, does not operate in institutional isolation. Instead, it exists at a complex nexus with other specialized regimes that govern the deployment of mitigation and adaptation technologies. While the Paris Agreement mandates the rapid transfer and scaling of "climate-resilient" technologies to meet the 1.5°C goal, the actual transboundary movement of these biotechnological tools is governed by the Cartagena Protocol on Biosafety (2000). This protocol introduces a "regulatory friction" through the application of the precautionary principle, which allows states to restrict the import of Genetically Modified (GM) crops based on perceived risks to biodiversity, even if such crops offer significant carbon sequestration benefits (Secretariat of the Convention on Biological Diversity, 2000).

Furthermore, a significant legal tension exists between the climate regime's goal of "equitable access" to technology and the protectionist mandates of the World Trade Organization's (WTO) Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS, 1994). Under Article 27.3(b) of TRIPS, biotechnological innovations are subject to stringent patent protections, which can create high cost-barriers for developing nations seeking to adopt high-mitigation cultivars (World Trade Organization, 1994). This creates a "monopolization of resilience," where the legal right to innovate under TRIPS potentially slows the collective obligation to mitigate under the Paris Agreement.

Finally, the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA, 2001) provides the essential "raw material" framework for this nexus. By governing the multilateral system of access and benefit-sharing for plant genetic resources, the ITPGRFA serves as the legal foundation for the molecular breeding of the very crops discussed in the

IPCC assessments (Food and Agriculture Organization [FAO], 2001). Consequently, the "Biotechnological Pathway" to mitigation is only achievable if a legal harmony is reached between the Mitigation Mandates (Paris Agreement), the Biosafety Hurdles (Cartagena Protocol), and the Proprietary Constraints (TRIPS).

5. Conclusion

This study demonstrates that agricultural biotechnology is not only an agronomic tool but also an essential instrument for attaining global climate resilience. The empirical evidence substantiates that Genetically Modified (GM) crops substantially enhance the mitigation and adaptation goals of the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement. Through the promotion of conservation tillage and a significant decrease in agricultural fuel usage, GM technology has already averted the release billions of kilograms of carbon dioxide, serving as a huge biological carbon sink. Advancements in molecular breeding offer essential adaptation strategies, enabling crucial food crops to sustain high yields despite increasing challenges from climate-induced drought, salinity, and biotic stresses.
Nonetheless, the doctrinal legal study uncovers significant structural fragmentation within international law that jeopardises these scientific advancements. The "Biotechnological Pathway" is presently hindered by significant regulatory obstacles at the intersection of global climate, trade, and environmental frameworks. The Paris Agreement urgently requires the global dissemination of climate-resilient technologies, although the implementation of these vital cultivars is significantly hindered by two conflicting frameworks. The monopolisation of resilient genetics under the patent protections of the TRIPS Agreement limits equitable access and directly undermines the traditional seed sovereignty of smallholder farmers in underdeveloped countries. The rigorous precautionary measures established by the Cartagena Protocol on Biosafety result in significant procedural delays that frequently conflict with the urgent timescale necessary for global decarbonisation.

To resolve this systemic dispute, the international community must transcend its currently fragmented approach to treaty enforcement by applying the legal principle of harmonious construction. Rather than viewing the intellectual property mandates of the TRIPS Agreement and the technology transfer obligations of the Paris Agreement as mutually exclusive, a cohesive, interdisciplinary framework is required. Policymakers must pursue a hybrid regulatory paradigm that effectively balances the commercial incentive to innovate with the global necessity for climate survival. Instead of dismantling patent protections entirely, a harmonious legal solution lies in operationalizing existing flexibilities within international trade law. This includes invoking public interest and environmental emergency provisions to facilitate the compulsory licensing of critical, climate-resilient germplasm. Furthermore, the establishment of a globally subsidized technology-transfer mechanism supported by international climate finance could fairly compensate private biotechnological innovators while legally classifying high-mitigation GM seeds as conditional global public goods. Ultimately, international law must evolve to ensure that the preservation of intellectual property rights does not supersede the fundamental global imperative of securing a climate-resilient agricultural future.

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