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The Ameliorative Effect of Foliar Applied Salicylic Acid on Zinc Toxicity in Diverse Maize Genotypes

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ABSTRACT

This review examines the ameliorative results of foliar-applied salicylic acid (SA) on zinc (Zn) toxicity in numerous maize genotypes. While Zn is a crucial micronutrient for plant growth, immoderate ranges can lead to widespread physiological and morphological limitations, including stunted growth and reduced photosynthesis. This study highlights the multiple functions of Zn in plant health and its poisonous effects when present in high concentrations. SA, a plant hormone recognized for improving stress tolerance, is proposed as a feasible technique to mitigate the unfavorable effects of Zn toxicity. The evaluation synthesizes modern-day studies on how foliar application of SA can improve physiological and biochemical responses in maize under Zn pressure. The methods through which SA reduces oxidative stress in response to excessive Zn are discussed. These methods include improving antioxidant defenses, modulating gene expression, and retaining nutritional homeostasis. This article elucidates the impact of genetic heterogeneity among maize genotypes on their response to treatment toxicity with SA and Zn. To generate highly resilient maize genotypes that could flourish in conditions with alternating Zn levels, breeding applications should be used to offer this genotypic variability. The capability of SAs as a biostimulant in agriculture is emphasized throughout the paper, which helps their application in controlling Zn toxicity and raising maize yields in harsh environmental conditions. This study offers valuable insights into sustainable farming methods that can enhance crop productivity in light of emerging soil contamination issues.

Keywords: Maize zinc toxicity, Salicylic acid stress mitigation, Plant growth regulators, Foliar application, Maize genotypic variation

Introduction

Maize is a vital global cereal crop, serving as a primary food source for many human beings. However, its cultivation faces demanding situations from non-biological elements like zinc (Zn) toxicity, which disrupts plant morphology and decreases yields. Simultaneously, Zn is crucial for plant growth and enzymatic roles, but excessive amounts can negatively influence biological processes, leading to the cessation of development and jeopardizing food security in areas reliant on maize. Plant growth regulators (PGRs) and salicylic acid (SA) can be useful in mitigating the consequences of Zn toxicity and enhancing crop yields. SA acts as a signaling molecule that enhances pressure tolerance in flora, potentially improving their ability to manipulate Zn levels and assisting standard health when applied to maize.[1]

Salicylic acid (SA) , a plant hormone, has the potential to revolutionize agriculture by helping plants adapt to various environmental stresses, including heavy metal toxicity. Studies have shown that foliar application of SA enhances physiological and biochemical processes, enabling plants to effectively cope with stressors like soil contamination. This treatment can lead to improved yield, increased biomass, and better maintenance of essential physiological functions, ultimately enhancing plant performance in challenging conditions.[2,3]

Research has delved into the effect of exogenous Zn nutritional supplements on maize growth and physiological structure, focusing on increasing parameters like plant material and biomass, as well as physiological measures including photosynthesis and nutrient uptake. Zn is a vital micronutrient that enhances plant growth, but excessive Zn can lead to stunted morphological features, chlorosis, and reduced photosynthesis. Certain maize genotypes exhibit diverse tolerances to Zn toxicity,[4] underscoring the importance of understanding these responses for breeding more resilient genotypes. This aspect of the research can engage and interest the scientific community in the study of genetic variability in plant responses.

We aimed to synthesize modern knowledge on the beneficial effects of foliar-applied SA in alleviating Zn toxicity across various maize genotypes. Our assessment will explore the physiological, biochemical, and agronomic changes induced by SA under Zn-toxic conditions, emphasizing the differing responses among maize genotypes. Analyzing different genotypes' responses to Zn stress will provide valuable insights for developing strategies to mitigate the adverse effects of Zn toxicity.[4,5]

SA is crucial for plants to be more resilient to abiotic situations like warmth, salinity, and drought. It improves resistance to environmental stressors with the help of SA, which acts as a signaling molecule that initiates morphological and physiological reactions. One significant mechanism by which SA operates is through the regulation of reactive oxygen species and the enhancement of the antioxidant defense system, thereby mitigating oxidative damage via the utilization of antioxidant enzymes.[6]

Moreover, SA coordinates pressure tolerance pathways by interacting with other hormones and influencing the expression of genes connected to strain responses.[7,8] Improved physiological characteristics, which might be essential for plant development under pressure, including stomatal conductance, photosynthetic costs, and root structure, were related to the usage of exogenous SA.[6,7] Furthermore, it helps with osmotic balance for the duration of water deficiencies via contributing to glycine betaine production and proline metabolism.[6,8] Through growing photosynthetic efficiency and stabilizing mobile membranes during heat pressure, foliar application of SA has been proven to improve vegetation thermotolerance, including grapes and cucumbers.[6]

Further, SA promotes the production of secondary metabolites, which are crucial for resistance to hyperthermia, such as cardenolides and antioxidants.[6,7] Its diverse abilities in regulating plant responses to abiotic stressors underscore its potential as a biostimulant in agriculture, enhancing crop resilience under adverse environmental changes.[7,8] This aspect of SA's role in agriculture can inspire and motivate the scientific community to adopt sustainable farming practices.

The interactive consequences of foliar-applied SA and Zn toxicity in various maize genotypes have been investigated. The differential responses of cold-tolerant and cold-sensitive maize genotypes to SA during hypothermic conditions were investigated.[9] Furthermore, the relief function of lysine-chelated Zn on maize flowers grown in tannery wastewater has been discussed.[10]

Methodology

The technique involves a scientific evaluation of peer-reviewed articles, experimental research, and meta-analyses published in respectable journals. Applicable studies were identified using PubMed, Google Scholar, Scopus, and Web of Science databases. Zn poisoning causes physiological disturbances in maize, which results in decreased photosynthesis and stunted development. Plant hormone SA has effectively reduced those impacts by regulating gene expression, boosting antioxidant defenses, and maintaining dietary balance. A foliar spray of SA decreases oxidative stress and encourages the synthesis of phytochelatins and other metal-binding compounds, which restrict the bioavailability of Zn. SA controls metal transporter proteins to protect further cellular integrity, ensuring suitable Zn distribution in flowers.

The effectiveness of SA varies among maize genotypes due to genetic range. Cold-tolerant genotypes exhibit stronger responses to SA under stress compared to sensitive ones. Environmental factors, including soil contamination, also impact the severity of Zn toxicity. Research highlights SA's capability to improve photosynthesis, stabilize membranes, and enhance stress tolerance through hormonal interactions and osmotic changes. These findings underscore SA's capability as a biostimulant for enhancing maize resilience towards Zn toxicity while emphasizing the importance of genotype-specific techniques.

Zn Toxicity in Maize

Zn is an important mineral nutrient that substantially influences numerous physiological processes in crops, including protein synthesis, photosynthesis, and enzymatic activities.[11]

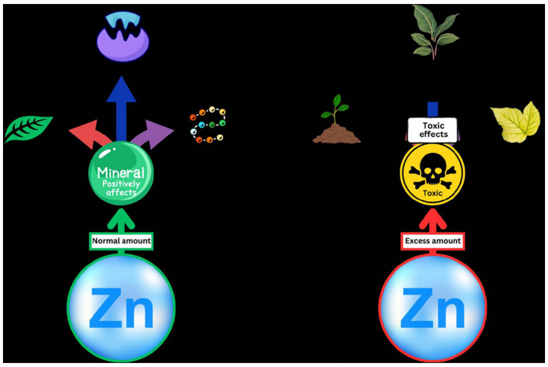

Fig 1 | Effect of Zinc on plants when applied in normal and excess amount.

Figure 1 presents the positive role of Zn when applied significantly and shows that immoderate Zn ranges can cause toxicity, resulting in stunted morphological activities, chlorosis, and diminished biomass in maize (*Zea mays* L.). SA, a plant hormone, has emerged as a functional agent to mitigate Zn toxicity in maize through enhancing the plant's safety mechanisms and lowering the dangerous effects of excessive Zn. The present study consolidates the current information regarding the protective effects of foliar-spray of SA closer to Zn toxicity throughout maize genotypes. Initially, we examined physiological and biochemical responses of maize to Zn toxicity, focusing on its effects on nutrient uptake, photosynthetic performance, and antioxidant protection systems. Finally, we checked the location of SA in assuaging the bad influences of Zn toxicity, emphasizing its functionality to modulate gene expression, raise antioxidant properties, and preserve nutrient homeostasis. Furthermore, we analyzed the range of diverse maize genotypes to Zn toxicity and SA utility, underscoring the importance of genetic variety in devising powerful management techniques.[12]

Zn is imperative to numerous metabolic abilities, including RNA and ribosomal synthesis, carbohydrate and protein production, and the biosynthesis of auxin precursors.[13] A Zn deficiency can result in physiological strain by disrupting those essential metabolic pathways.[14] SA has been placed to alleviate Zn toxicity in maize, commonly by enhancing antioxidant defenses, modulating gene expression, and maintaining nutrient balance.[13]

Furthermore, foliar application of SA has confirmed an increase in plant biomass, chlorophyll stages, and reductions in oxidative stress in rice crops subjected to quinclorac herbicide strain. This shows a similar capacity for mitigating Zn toxicity in maize.[15]

Elements like genetic history, growth degree, and environmental conditions can affect the efficacy of SA in mitigating Zn toxicity. Metal toxicity is a massive threat to the environment and agriculture and has been extensively studied in plant research.[16]

Zn holds a very particular region in some of the widespread heavy metals. The mechanisms via which SA reduces Zn toxicity in flora are complex and incorporate numerous interrelated pathways. This phytohormone is utilized in various physiological and biochemical strategies to counteract the terrible consequences of immoderate Zn buildup, demonstrating the complexities of plant stress responses and SAs versatility as a stress-protective molecule.[16,17]

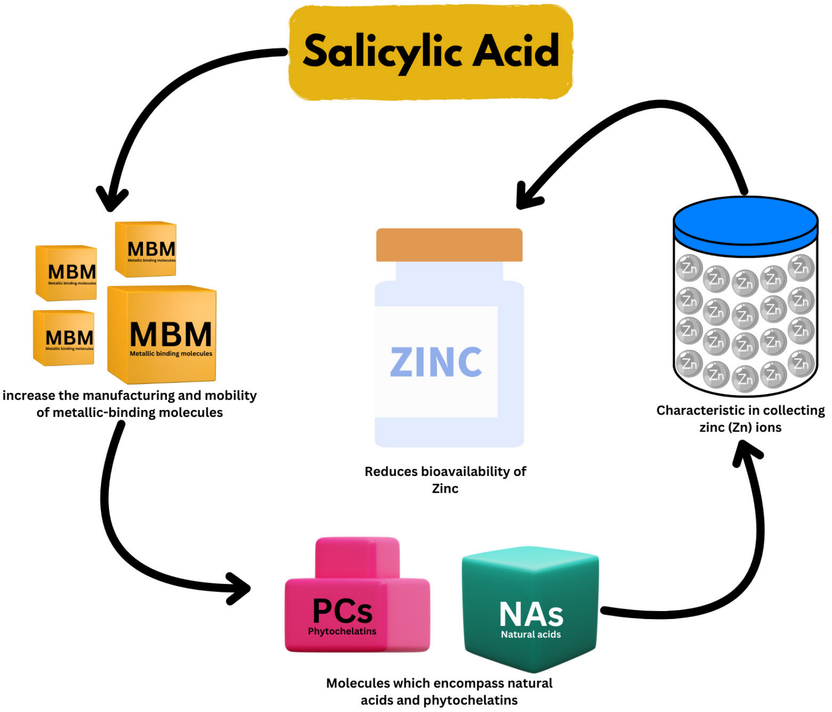

Fig 2 | Effect of Salicylic Acid.

SA can increase the manufacturing and mobility of metal-binding molecules inside plants. These molecules embody natural acids and phytochelatins and play a critical role in accumulating Zn ions. This notably reduces the bioavailability of Zn within the plant. This technique is a critical protection method for plants, permitting them to adjust possibly dangerous Zn degrees while retaining cellular homeostasis (Figure 2).[17,18]

Furthermore, SA has been verified to considerably impact the production and features of metal transporter proteins. This modulation is crucial for controlling the depletion, transportation, and distribution of Zn in vegetation. SA regulates those proteins to ensure that Zn is correctly absorbed from the soil, transported to regions of the plant, and properly compartmentalized inside cellular systems. This complete law mechanism is vital for ensuring Zn status, which is required for physiological activities and common plant health.[16,18]

The efficacy of SA in decreasing Zn toxicity is considerably dependent on multiple factors, including genetic differences amongst plant species or cultivars. This genotypic variety, collectively with unique elements, could adversely affect how efficiently SA capabilities mitigate the dangerous outcomes of high Zn on plant life.[17,19]

The SA reaction, which is known to help in plant stress management, may interact with these intrinsic tolerance mechanisms. In some plant genotypes, the interaction of those genetic predispositions with SA-mediated responses can result in more potent protection against heavy metal toxicity.[19]

SA and Stress Mitigation in Maize

SA is an important plant hormone that notably influences numerous physiological and biochemical strategies among flora. It is critical for regulating plant growth and development, apart from the plant's response to biotic (dwelling) and abiotic stresses.[7] Abiotic stresses interact with environmental factors that could negatively impact plant growth and agricultural productivity. Key examples of those stresses encompass salinity, drought, and immoderate temperatures (both hyper and hypothermic). Those stresses will have profound and damaging consequences on crop yields. Research indicates that they will impact 70% of the manufacturing of staple meal plants. This implies the crops we depend on for meals could face environmental challenges. The consequences of abiotic stresses are vital for developing strategies to mitigate their effects and ensure crops are protected in alternating environmental conditions.[20,21]

Previous studies emphasized the essential function of SA in assuaging pressure in maize, especially under drought and salinity situations. SA enhances diverse physiological and biochemical developments, enhancing morphology and yield. For example, its utilization in drought stress drastically expanded chlorophyll content, general soluble protein, and free amino acids, resulting in a grain yield rise to 9451.7 kg/ha.[22]

SA treatment significantly enhanced seed germination rates and seedling vigor under salinity stress, with germination probabilities rising by 43–69% and shoot and root lengths increasing by 24–56% and 13–37%, respectively. These improvements are associated with higher stages of chlorophyll and relative water content (RWC), each crucial for photosynthetic performance.[23]

Moreover, foliar applications of SA have been proven to improve the antioxidant systems of maize, especially during saline conditions where oxidative stress can hinder growth. SA mitigates the unfavorable results of salinity on morphological and physiological tendencies, advocating better water balance and nutrient uptake.[24]

Furthermore, under excessive salinity, a synergistic effect between SA and useful rhizobacteria has been stated, ensuring high-quality morphological enhancements, such as shoot and root dry weights, relative water content, and grain production. This implies that combining SA with microbial treatments will effectively multiply crop tolerance in opposition to environmental challenges.[25]

SA improves stress tolerance in maize by many physiological and biochemical processes, which are probably intricately related. Controlling antioxidant enzymes is one essential component that protects plants from oxidative strain imposed by environmental conditions. Moreover, SA encourages the synthesis of appropriate solutes, probably small molecules that assist osmotic balance, safety, and cell structural stability in challenging environments. Also, SA impacts gene expression, which activates genes that respond to stress and could increase the resilience of the plant. As these mechanisms work together, they produce a holistic response that makes maize more resilient to adversity and, in the end, improves yield and development in changing climates.[26]

The complete stress reaction of plants relies upon the interaction of SA with numerous plant hormones, particularly ethylene and abscisic acid. This interaction is critical as it affects how plants respond to distinctive environmental stresses like infections, drought, and environmental problems. In addition to its function in protection mechanisms, SA collaborates with abscisic acid, which controls stomatal closure and water loss in drought-affected areas. Hormonal crosstalk plays a vital role in plant resilience, as a complex network of interconnected hormones helps plants to effectively regulate changes in their surroundings.[21]

The efficiency of SA in decreasing abiotic stress in maize is a multi-dimensional phenomenon that may be drastically altered by using some critical parameters. Among these, the maize genotype is important for its exceptional genetic contribution and may respond in a specific manner to SA treatment. Furthermore, the timing of treatment is vital; for instance, administering SA throughout various developmental levels may additionally result in a better growth rate than in others. Moreover, the use of SA should be controlled carefully, as both under- and over-application may also produce suboptimal consequences. Subsequently, the appropriate abiotic pressure conditions, which include drought, salt, or temperature extremes, determine how efficiently SA can lessen stress. These variables engage in a complicated manner to decide the general impact of SA.[26]

Different Maize Genotypes May Exhibit Varying Degrees of Responsiveness to Foliar-Applied SA Under Zn Toxicity

Corn manufacturing is specifically tough in temperate climate zones because of its enhanced susceptibility to various biological and environmental stresses. These stressors are temperature, droughts, heavy precipitation, pest infestations, and inadequate soil nutrients. They should substantially impact maize vegetation, affecting flowering patterns and crop yield. As a result, farmers and agricultural researchers have observed that damaging effects could result in huge drops in total grain production, which can have a poor impact on the economy and raise questions regarding food safety in areas where maize is a primary crop. Because maize is susceptible to many stresses in temperate climates, it is mandatory to create resilient genotypes and use adaptive control strategies to reduce yield decreases and maintain sustainable maize production in the face of climate change. Scientists have advocated foliar application of Zn supplementation as a short and powerful way to address Zn deficiency in corn plants. This method has previously shown promising effects in wheat and several crop species, indicating that it can be useful in various agricultural settings. Farmers are capable of enhancing the dietary content in their maize harvests, which could result in higher yields and regular plant growth, through the foliar spray of Zn on the leaves and stems of the plants (Figure 3).[27]

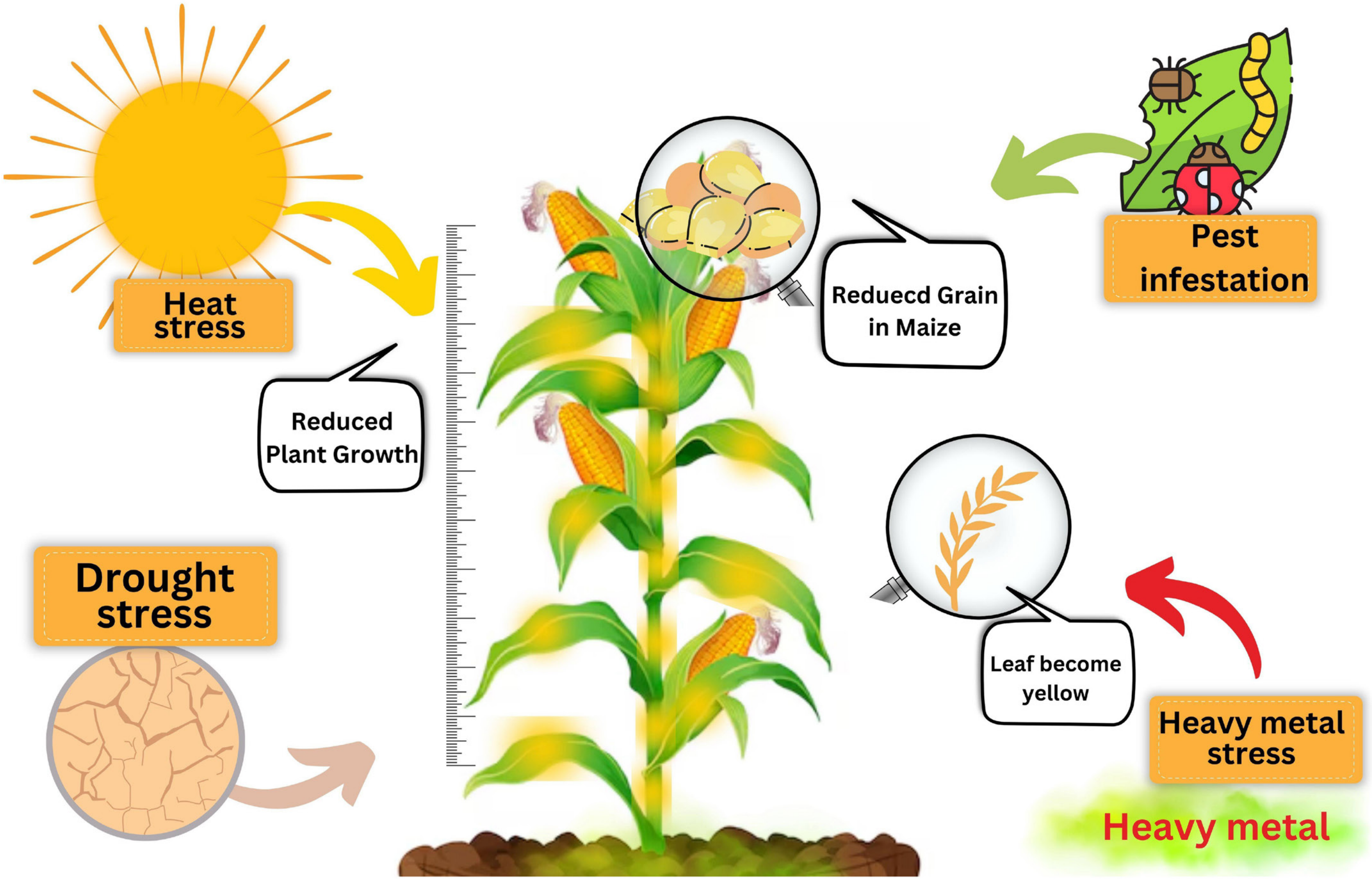

Fig 3 | Effect of different stresses on the maize plant

Controlling Zn toxicity in maize manufacturing is a big problem and prevents Zn scarcity. For instance, it has been observed that salt has a considerable effect on the morphological features of maize and its development, and every osmotic stress and many ion toxicities increase the problem.[5] In this case, using SA topically in the leaves of maize plants is a possible way to reduce the harmful effects of Zn toxicity. SA is useful for numerous plant genotypes and developmental stages, as it has been proven to improve plant growth and tolerance to various types of heavy metal toxicity. Thus, even during severe environmental situations, agricultural productivity may be improved with an SA application.[28]

More research is required to understand better the variations among the responses of maize cultivars to foliar SA spray in Zn toxicity instances. This review aims to understand better how genetic heterogeneity inside maize populations can also impact the effectiveness of SA in mitigating the adverse effects of Zn stress. By analyzing the genotype-specific reactions and developing extra-focused and efficient strategies, scientists can enhance maize's resistance to Zn toxicity in various agricultural practices.

Future Directions and Policy Implications

Progressive research guidelines for mitigating climatic disruption results on vegetation include developing genetically engineered crops with greater pressure tolerance trends, including advanced water-use performance and heat resistance. Experiments use biostimulants like SA to assess their efficacy in enhancing plant resilience towards abiotic stresses, particularly in vegetation liable to Zn toxicity. Moreover, organizing controlled environment research to assess the interactions between numerous stressors (e.g., drought, salinity, and heavy metal toxicity) on plant physiology could provide precious insights into adaptive mechanisms. Policymakers should prioritize grant funding projects that explore these progressive frameworks and advocate a combination of advanced breeding strategies in agricultural practices.

Actionable suggestions consist of imposing guidelines that incentivize adopting sustainable agricultural practices, including precision farming and the usage of biostimulants, to enhance crop resilience. Moreover, developing academic packages for farmers with the edge of genetic diversity and stress management strategies can facilitate the transition to more sustainable farming systems. Working with agricultural stakeholders to establish suggestions for useful nutrient control may also be critical in addressing soil contamination problems and ensuring food security.

Conclusion

This review emphasized the potential of SA as a biostimulant in agricultural practices and its essential role in lowering Zn toxicity in different maize genotypes whilst administered topically. Even though Zn is a vital mineral for maize, high concentrations can have terrible results on plant morphology, which includes lower photosynthesis and even stunted growth. The consequences highlight how SA improves antioxidant defenses and dietary homeostasis while strengthening the plant's physiological and biochemical reactions to Zn pressure.

The differential responses observed among various maize genotypes to SA application endorse that genetic range plays a vital role in the effectiveness of this intervention. By modulating gene expression and influencing stress response pathways, SA alleviates the adverse influences of Zn toxicity and promotes usual plant morphology and resilience during abiotic stress conditions. This article gives precious insights into the mechanisms that SA operates, such as its interplay with distinctive hormones and its position in improving photosynthetic performance.

Adding SA to maize farming techniques can also increase crop resistance to environmental stressors like Zn poisoning. Further to enhancing maize productivity and sustainability in Zn-affected regions, research should refine useful techniques and investigate the synergistic results of SA with extraordinary agronomic techniques. This approach may be vital in advocating food stability, particularly in areas where maize is a primary crop.

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