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Phytoremediation Technique for Pesticide-Contaminated Environments as a Green and Eco-Friendly Approach: A Review

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ABSTRACT

Phytoremediation or bioremediation is the use of plants and their rhizosphere's microorganisms to contain, remove, transform, or detoxify pollutants in soil, water, or air. This eco-friendly method has become a very effective strategy for addressing pesticide contamination, one of the major global environmental issues, and has even been proven in scientific circles. The review's main purpose is to present phytoremediation in detail to the world as a sustainable, environmentally friendly technology for the cleanup of pesticide-contaminated soils. The review integrates the latest information on bio-remediating plants and, at the same time, emphasizes recent developments in different plant species proficient at accumulating or degrading pesticide residues. Among the major phytoremediation mechanisms are phytoextraction, wherein the contaminants are taken up and stored in the plant parts that can be easily collected; phytodegradation, which is the process of breaking down the pollutants by plants and their associated microorganisms''' metabolic activities; phytostabilization, preventing the contamination spread and the toxins being taken up by living organisms in soils and sediments; phytovolatilization, the conversion of the less toxic forms of the pollutants and their release into the atmosphere; and rhizofiltration, the practice whereby the roots of the plants act as filters to remove contaminants from the water supplying them. Together, the above-stated mechanisms play a significant role in reducing the toxicity of pesticides and their persistence in the environment. The review points out the pros and cons of efficiency between phytoremediation and conventional methods, the latter often being very expensive, energy-intensive, and environmentally damaging. In conclusion, phytoremediation is a cost-effective, environmentally friendly option for large-scale pesticide cleanup, helping nature recover and protecting the environment for the long term.

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1. INTRODUCTION

Agro-ecosystems, urban and peri-urban settings as well as industrial activities have led to the pollution of the environment by chemical pesticides, which in turn disrupts the ecological systems that depend on soil, water and air due to the misuse or overuse of synthetic pesticides. [1]. These chemicals serve for pest elimination or control purposes however their use may backfire resulting in non-target organisms, beneficial insects/ pollinators, wildlife and human being are affected [2]. Pesticides are capable of persisting in the environment for a long period leaching into groundwater or running off into water bodies thus causing long-term ecological problems if they are not managed properly [3]. The accumulation of those poisonous substances along the food chain is also a major risk for biodiversity with negative health effects on wildlife and human beings alike [4]. These chemical products are used in agriculture, a primary means through which pests and diseases of plants are overcome resulting in high crop yields and food security [5]. However, the use of these chemicals is very worrying because they pose many threats to human health and the safety of our environment [6]. Pesticides exposure can be through; direct contact, inhalation or consumption and have been associated with various health disorders [2].

Short term effects include irritation on the skin, nausea and dizziness as well as pulmonary issues while long term effects may result to some chronic diseases like cancer, neurological disorders such as Parkinson's disease or Alzheimer's disease, endocrine disrupters, and reproductive system conditions [6]. Agricultural workers, farm residents and those who live near farms face a greater risk due to prolonged exposure [5].

Pesticides have an impact on biodiversity by affecting non-targeted organisms, such as beneficial fauna in the form of bees and butterflies, which ensure pollination. Excess water drainage from cultivated lands is entering into water bodies and polluting them, causing a threat to aquatic life as well as disturbing the entire ecosystems [4]. Moreover, pesticide residues accumulate in the soil and interfere with microbial communities and over time reduce soil fertility [7]. The toxic effects of the bioaccumulation of pesticides in higher organisms (up to humans) can have a cascading effect in the food chain, where direct and indirect losses are not uncommon [8]. To counteract these disadvantages, environmentally safe to use bio-pesticides, such as integrated pest management (IPM), organic farming and eco-friendly biopesticide are recommended strategies to adopt in lieu of chemical-based toxic pesticides [4].

Despite being one of the most challenging problems, pollution can be divided into categories like air pollution, water pollution, soil pollution and environmental degradation [9]. Pollution is a growing issue caused by the increase in industrial waste, chemical pollutants and greenhouse gas emissions that result to severe environmental destructions, loss of biological diversity and health risks [7,8]. Pollution prevention requires means that will not harm the environment while promoting the economic and social well-being of people [9,5]. Sustainable solutions become a general approach due to their critical importance for nature protection, public health; sustainable development as well as social and economic wealth creation process [10]. It is common to find that traditional pollution control measures are relief oriented but may not achieve zero discharge level in future time [11]. Thus, sustainable solutions that include renewable energy forms, waste reduction measures and environmentally friendly technologies guarantee continuous ecosystem protection [9]. Pollution causes many diseases such as respiratory diseases lead by air pollution, and waterborne illnesses [12]. Consequently, application of sustainable waste management practices, cleaner production approaches including air filters significantly mitigates these health dangers [10,13]. Circular Economy value chain models require green solutions because they promote resource efficiency job creation plus economic resilience consequently protecting planetary ecosystems [9].

Phytoremediation as an eco-friendly approach is a bio-remediation process that is cost effective and uses plants to extract, degrade, or immobilize contaminants from soil, water, and air [14]. This technique makes use of the innate capacity of certain plants to uptake, translocate, accumulate or metabolize pollutants hence it can be regarded as a green remediation technology in contrast to the chemical and mechanical approaches [15]. Phytoremediation proves to be an effective sustainable solution as it is environmentally safe. For this reason, its cost is low it promotes soil and water restoration as well as supports biodiversity protection [14]. The key phytoremediation uses are heavy metal remediation , pesticide degradation , oil spill cleanup , air purification [15].

2. MECHANISMS OF PHYTOREMEDIATION

Phytoremediation is an eco-friendly and sustainable approach that makes use of plants in removing, breaking down or containing pesticide pollutants in soil and water [10,9]. Several plant species have the ability to uptake, metabolize and detoxify pollutants so phytoremediation is a more eco-friendly way to clean polluted land than using chemicals alone [15]. Phytoremediation of pesticides is based on a variety of mechanisms which complement each other and these are determined by physiological characteristics of the plant species, root–microbe interactive association as well as environmental factors [16]. Moreover, *Helianthus annuus* L. Has demonstrated a high in-vitro phytoremediation capacity of 40-70% for persistent organic pollutants, indicating its potential as a green technique for removing organic contaminants from contaminated environments. The species was also found to have substantial accumulation of the contaminants in both its roots and shoots. [17] , some studies have shown that Helianthus annuus could have a strong phytoremediation and bioremediation ability by taking in more than 50% of heavy metals from the contaminated soils and transforming them into the soil through rhizosphere. It also showed that the removal efficiency of heavy metals can be as high as 50-70% in soils with moderate contamination levels, making Helianthus annuus a suitable plant for sustainable soil management [18]. In *Brassica juncea* exposed to chlorpyrifos toxicity, 24-epibrassinolide (EBL) combined with PGPR significantly reduced oxidative damage, resulting in 60.8% and 51.5% decreases in malondialdehyde and electrolyte leakage, the treatment also enhanced the antioxidative defense responses such as superoxide dismutase and glutathione peroxidase up to 3.25 fold, 2.66 fold during stress respectively. Also, the nitrate reductase and nitric oxide levels increased by 4.21 and 2.76 fold during stress, which suggest a strong positive signal for stress mitigation [19,20]; rhizodegradation then follows whereby root exudates stimulate microbial communities within rhizosphere for enhanced breakdown of pesticides [21,22].

In addition, phytovolatilization promotes conversion and release of volatile pesticide residues into atmosphere while phytostabilization decreased pesticide mobility because it retains them within rhizosphere [23,24]. An integrated understanding of those pathways influences on practical design of phytoremediation treatment programs since different agrochemicals as well as environmental conditions exhibit specific modes of action depending on environmental conditions [16].

Table 1. Mechanisms of Phytoremediation of Pesticides

Mechanism	Pesticides addressed	Plant species	Description	Reference
Phytoextraction	Organochlorines, herbicides	*Helianthus annuus* (Sunflower)	Root uptake and accumulation in tissues	[17]
Phytodegradation	Organophosphates, carbamates	*Brassica juncea (Indian mustard)*	Enzymatic breakdown inside plant tissues	[19,20]
Rhizodegradation	Atrazine, glyphosate	*Salix spp., Lolium perenne*	Microbial degradation enhanced by root exudates	[21,25]
Phytovolatilization	Volatile organophosphates	*Populus spp. (Poplar trees)*	Uptake, conversion, and release into the air	[23]
Phytostabilization	Persistent herbicides (e.g., diuron)	*Phragmites australis (Reeds)*	Immobilization in soil/rhizosphere	[26]

3. PLANTS USED IN PHYTOREMEDIATION

Many plants are effective phytoremediators for pesticide polluted surroundings. For example, sunflowers (*Helianthus annuus*) have been utilized extensively because of their high biomass production capacity and the ability to sequester and metabolize an assortment of pesticides residues [17]. Willow trees (*Salix* spp.) have a wide-ranging root systems and do not simply take up pesticides, but they also promote the microbial degradation in the rhizosphere [27]. Indian mustard (*Brassica juncea*) displayed high tolerance to and accumulation of herbicides and organophosphate residues, hence qualifying it for use in agricultural field soils [28,29]. Likewise, phragmites (*Phragmites australis*) are highly versatile in engineered wetlands and provide excellent adsorption for the depuration of pesticides from polluted water sources [30,31]. These cases demonstrate the feasibility of mixing plant species designed for local conditions to improve the overall effectiveness of remediation.

Table 2. Abilities of Different Plants in Pesticide Phytoremediation

Plant species	Pesticide type removed	Key traits contributing to efficiency	Main mechanism (Absorption vs. Degradation)	References
Helianthus annuus (Sunflower)	Organochlorines, herbicides, mixed residues	High biomass, broad-spectrum uptake	Direct absorption & accumulation	[17,32]
Salix spp. (Willow trees)	Insecticides, herbicides	Deep roots, rhizosphere microbial stimulation	Rhizosphere microbial stimulation > accumulation	[27,33]
Brassica juncea (Indian mustard)	Organophosphates, herbicides	High tolerance, fast growth, strong uptake	Direct uptake & partial degradation	[28,29]
Phragmites australis (Reed)	Carbamates, organophosphates, herbicides	Wetland adaptability, large root network	Combination of uptake & rhizodegradation	[30,34,31]

4. FACTORS AFFECTING PHYTOREMEDIATION EFFICIENCY

4.1. Concentration of pesticide

The efficiency of phytoremediation strongly depends on the type and concentration of pesticides in the polluted medium. Hydrophilic pesticides such as atrazine, simazine are highly bioavailable and easily absorbed by plants, in contrast hydrophobic extremely persistent compounds like DDT, endosulfan do have a restricted uptake and require longer remediation periods [35,36].

But not just that, pesticide concentration is also a two-edged sword: low to moderate levels tend to promote the detoxification capacities of plants and rhizosphere microorganisms, thus their activity, while too high concentrations usually induce phytotoxicity that results in inhibition of plant growth and consequently impaired remediation efficiency (or even loss) not to mention a complete loss of efficiency [35].Zeb et al. have shown that pollutant uptake from the soil environment varies greatly between species and organic pollutants, with an accumulation factor, known as a Plant Concentration Factor PCF, of > 10 for hydrophobic pesticides in root tissues and -58 in shoots. Indicating the preference of the compounds to locate into the plants' underground organs, the study also highlights that bioconcentration factors (BCFs) for certain persistent organic pollutants often exceed 1.5–3.2 in leafy crops, reflecting significant translocation potential [37]. Recently, it has also been reported that the appropriate selection of plant species, along with bioaugmentation and soil amendments, can prevent these problems and improve the degradation rate for various classes of pesticides [37,38,39]. These studies found soil bacterial strains capable of degrading chlorpyrifos while also promoting plant growth, with some bacteria shown to degrade 65-78% of chlorpyrifos within 7 days under optimal conditions.

Table 3. Influence of Pesticide Type and Concentration on Phytoremediation Efficiency

Pesticide Type	Concentration Range	Observed Effect on Plants	Phytoremediation Efficiency	References
Atrazine (herbicide)	Low–moderate (≤5 mg/kg)	Enhanced root uptake and rhizosphere degradation	High (rapid removal in crops like maize)	[36]
Atrazine (herbicide)	High (>20 mg/kg)	Phytotoxicity, reduced biomass	Low (limited plant survival)	[35]
Chlorpyrifos (insecticide)	Moderate (1–10 mg/kg)	Stimulates microbial degradation in the rhizosphere	Moderate to high (when plants + microbes)	[38]
DDT (organochlorine)	Trace–moderate (<10 mg/kg)	Very slow uptake, accumulates in roots	Low (requires decades without amendments)	[37]
Endosulfan (insecticide)	Moderate (2–15 mg/kg)	Causes oxidative stress and growth inhibition at higher doses	Moderate (improved with biochar addition)	[39]

4.2. Soil and water properties

Physicochemical properties of soil and water are considered important factors that determine the success of phytoremediation in pesticide-contaminated environments. Soil pH, cation exchange capacity (CEC), texture, and organic matter content play a significant role in pesticide leachability from the root zone to the soil and in pesticide uptake by plant roots [40,41]. For instance, higher pH levels (alkaline conditions) reduce herbicide solubility, thereby reducing uptake of certain herbicides. In some organic-poor soils, hydrophobic pesticides can adsorb, making them unavailable for phytoremediation applications [42]. Likewise, in constructed wetlands, water pH, dissolved oxygen, and nutrient levels influence pesticide persistence and the growth of aquatic or semi-aquatic plants [35]. Salinity and poor aeration also limit plant metabolism and microbial activity, reducing pesticide degradation [22]. To overcome these limitations, various studies advocate applying biochar, compost, and surfactants to enhance soil properties and improve pesticide desorption. In contrast, plant species tolerant to abiotic stresses, site-constricted water, and growing media are selected [22,41].

Soil and water properties are the most important factors to consider when using phytoremediation for pesticide-contaminated sites. For instance, soil pH, texture, organic matter content and redox potential can influence adsorption, degradation, uptake, and translocation of pesticides in plants [43]. Hydrophobic pesticides are prone to strong adsorption onto organic matter-rich or clay soils, thereby reducing their availability, whereas acidic or neutral soils have higher mobility than alkaline soils [40].

Also, the quality of the water, including pH, dissolved oxygen, salinity, nutrients, among others, will affect the persistence of pesticides and the growth performance of plants in aquatic environments or wetlands [41]. For example, at high salinity or under low oxygen concentration, root metabolism and microbial activity may be sloweddown, resulting in a decrease in pesticide degradation. It was recently discovered that biochar, as well as organic materials and surfactants drastically improve soil and water conditions for greater desorption of contaminants into the plants in diverse environmental scenarios [35].

4.3. Types of plants (tolerance and adaptability)

The choice of the plant species used in phytoremediation is an important factor in increasing the efficiency of pesticide gaining removal. Plants with greater tolerance, adaptation to stress, and rapid growth rates are known to be more efficient in the accumulation of pesticides into their system, metabolism of or rhizosphere-mediated degradation of pesticides [43],[42]. For instance, grasses such as *Vetiveria zizanioides* and *Lolium perenne* are commonly employed due to their deep root systems and ability to tolerate contamination, whereas aquatic macrophytes including *Eichhornia crassipes* (water hyacinth) and *Lemna minor* (duckweed) exhibited great potential of removal in water-based systems [41]. In addition, native flora adapted to local soil and climate usually succeed over exotics since they have better developed interactions with indigenous (microbes) which enhance pesticide degradation ability [44]. Some recent studies indicate the importance of plant screening and genetic improvement to improve stress tolerance achieving higher survival and remediation efficiency in pesticide-contaminated environment [45,46].

Table 4. Examples of Plant Species Used in Pesticide Phytoremediation and Their Characteristics

Plant species	Pesticide type removed	Key traits	References
Vetiveria zizanioides	Organochlorines, organophosphates	Deep roots, high tolerance to toxins	[43]
Lolium perenne	Herbicides (atrazine, glyphosate)	Fast growth, adaptable to temperate soils	[41]
Eichhornia crassipes	Carbamates, organophosphates	Aquatic adaptability, rapid biomass production	[44]
Lemna minor	Insecticides, herbicides	Small size, high surface-area-to-volume ratio	[46]
Helianthus annuus	Multiple pesticide residues	High biomass, tolerance to varying soil pH	[45]

5. CHALLENGES AND SOLUTIONS

5.1. Phytoremediation is slower than other methods

Phytoremediation sustainability in environments polluted by pesticides may be challenged by the slow process of removing pollutants that might take a long time compared to other methods like the use of chemical or mechanical approaches [41]. Technologies such as chemical oxidation, soil washing, and incineration can indeed remove pesticide residues in very short periods. However, these procedures are not only costly but also lead to high energy consumption and the generation of secondary pollution [22]. Although phytoremediation differs from these methods in being environmentally friendly and sustainable, it is inherent to the process that its duration is longer due to plant growth cycles, root-rhizosphere interactions [47]. In the past, the use of genetically engineered plants, biochar amendments, and plant-microbe synergy have increased the rate of degradation of persistent pesticides. This has also, in part, alleviated the problem of the time limit [48]. Even though it is slow, phytoremediation is still a long-term strategy for large-scale or old low-to-moderate-contaminated sites where other methods are not compatible.

5.2. Impact factors on plant efficiency

Environmental conditions are the primary factors that govern the effectiveness of using plants to clean up soils contaminated with pesticides [49]. Among others, soil characters like pH, texture, amount of organic carbon and water holding capacity play the most important role in determining the mobility and bioavailability of pesticides and, consequently, plant uptake [22]. Besides, temperature, light intensity, and seasonal changes continue to affect plant growth, root activity, and microbial interactions in the rhizosphere, as well as degradation rates [50].

In this sense, stress conditions induced by salinity, drought, or co-contamination with heavy metals have been reported to reduce the efficiency of phytoremediation by interfering with basic physiological processes of plants [51,52]. Recent studies raise the issue that utilizing soil amendments such as biochars, surfactants, beneficial microbes, and right crop species can help mitigate environmental constraints, thereby enhancing pesticide removal under diverse field conditions [53,54]. Characterization and enhancement of these interactions are pivotal for the upscaling of phytoremediation from simple experiments to practice.

5.3. Improve plants' efficiency

It is vital to improve plant efficiency for good performance of phytoremediation in pesticide-contaminated environments [41]. Several plant species show their inability or low capacity of uptake/degrading the high persistent pesticides indicating the need of such genetic manipulations that can boost metabolic pathways, increase root exudation, and augment tolerance towards toxic residues [22]. Genetic engineering technologies, including CRISPR/Cas9 and transgenics, have facilitated the generation of crops with improved detoxification enzymes (e.g., cytochrome P450s,glutathione-S-transferases) as well as rhizosphere interactions [55]. Alongside, there are various agro-techniques which can be modified, like the use of phytoremediation in crop rotation, intercropping, applying organic manures, and using plant growth-promoting rhizosphere bacteria and fungi having degrading activities towards chemicals. Symbiotically this practice of decontaminating soils is still one of the most efficient bioengineering techniques that integrates between gene engineering and classic/ sustainable agronomy [56].

6. PRACTICAL APPLICATIONS

6.1. Examples for successful phytoremediation

Numerous field phytoremediation applications have successfully demonstrated the use of plants to remediate pesticides in practice. For example, *Typha latifolia*- and Phragmites australis-planted constructed wetlands have shown efficacy in reducing organochlorine and organophosphate pesticide levels in agricultural drainage waters [57]. Similarly, sunflower Helianthus annuus and Indian mustard Brassica juncea are employed in pesticide-contaminated soils as alternatives to the herbicides atrazine and simazine under field conditions, and show significant uptake and degradation [28,50]. In China, vetiver grass *Chrysopogon zizanioides* is one of the vegetation species used on a large scale to remediate agricultural soils affected by several classes of pesticides, leading to improvements in soil quality and crop productivity simultaneously [58,20]. These cases highlight how carefully selected plant species, combined with appropriate site management strategies, can achieve measurable pesticide removal in real-world environments.

6.2. Phytoremediation Vs. traditional technologies

When we take into consideration the methods of pollution treatment specifically with pesticides, it is clear that there are now alternative methods other than; soil excavation, incineration, chemical oxidation, and advanced physicochemical methods and this is where phytoremediation comes in [50].These are usually intrusive to the environment as they make use of a lot of energy and are quite costly if compared to the phytoremediation method as the plants take care of the process gradually and their operational expenses are minimal [49]. Phytoremediation may take longer in general practice making it less effective for heavily contaminated pesticide areas but several benefits can be listed such as applications at an in situ level, incorporation into agricultural ecosystems and slow gradual contaminant removal using less expensive plant-based processes [59]. Moreover, the application of modern genetic engineering techniques in plants, biochar amendments and both have contributed towards more efficient and reliable uses of phytoremediation. As a result, now this performance is close to that of the conventional technologies only [60]. That being said, phytoremediation could be regarded as a supplementary or completely new solution, mostly desirable for the large sites with low–to–moderate pesticide contamination, where standard methods may be neither economically nor environmentally acceptable.

7. FUTURE PERSPECTIVES

New possibilities have emerged for optimizing the phytoextraction efficiency of plants through modern achievements in genetic engineering. New technologies, such as CRISPR/Cas-based genome editing, are being used to enhance plant tolerance to pesticide-induced oxidative stress by reinforcing antioxidant defense mechanisms in plants, and high biomass and longer survival rate under pesticide contamination may be achieved [61]. Concomitantly, the transfer or overexpression of microbial degradative enzymes (e.g., organophosphate hydrolases, laccases) as well as detoxification genes (cytochrome P450s, GSTS), has also proved to enhance the degradation of pesticides in planta [62]. Furthermore, ongoing studies have focused on integrative approaches that combine genetically modified plants with beneficial microbes and soil amendments to reduce pesticide use by increasing uptake rates and the metabolism of applied pesticidal residues under natural field conditions [59]. Taken together, these methods illustrate the power of genetic modification to create robust, highly efficient phytoremediators for sustainable pesticide cleanup.

The deployment of phytoremediation and other technologies like biological and chemical treatments in their wake has made a new development recently, which helps to overcome the drawbacks of phytoremediation [63]. Phytoremediation and microbial bioaugmentation can be combined for better degradation of persistent pesticides. Rhizosphere activity growth can be enhanced by the use of soil amendments such as biochar, surfactant, or nanomaterials, which will increase biodegradation efficiency [64]. Also, when plants are used for AOPs or with low-dose chemical oxidants, it increases the decomposition of complex pesticide metabolites, which were recalcitrant before [65].These integrated strategies not only improve the removal efficiency but also improve the stability of remediation systems under in-situ conditions, suggesting a combined phyto-removal with bio/chemo methods may be a positive practice toward sustainable remediation for pesticide-contaminated soil [60].

In the last 10 years, the prospect of extending phytoremediation to a variety of environments has attracted more and more attention. Apart from agricultural soils, the application of phytoremediation is being investigated in aquatic sites (wetlands and rivers, wastewater), urban environment and industrial brownfields, where plants are used to remove not only pesticides but also co-contaminants such as heavy metals and hydrocarbons [60]. Progress in plant selection, genetic engineering and soil amendment has improved the potential tolerance and uptake efficiency of plants, broadening the application ranges to the particularly harsh conditions such as saline soils, contaminated solids or semi-arid lands [65]. In addition, combining phytoremediation with constructed wetlands and green infrastructure diversifies the range of applications for sustainable urban water and soil management [59]. These expansions highlight phytoremediation as a versatile, eco-friendly approach adaptable across multiple ecosystems.

8. CONCLUSION

Phytoremediation is a fashionable and nature-friendly method to detoxifying pesticides which has the advantages of being beneficial to the ecosystem, causing the environment the least possible harm while achieving optimum remediation of the soil water. The plant's uptake, degradation, and sequestration of pesticides is a solution and green remediation could be one part of that solution. However, this approach can't overcome these obstacles. Amongst them are plant resistance or environmental factors etc., not all of the pesticides can be degraded hope. The study indicates that it is the need to come up with new methods to enhance plants through genetic engineering, good farming practices, and the experience of chemical-biotechnology combined treatments. Political and regulatory incentives must be included in the proposed strategies that view phytoremediation as the main tool in the sustainable use of pesticides, if this technique is going to be used more widely with long-term success. These policy measures will help to ease the practical application and also create the chances for research and development, and the strengthening of phytoremediation as a green method in global environmental conservation.

CONFLICT OF INTERESTS

The author states that there is no conflict of interest regarding the publication of this review article. Opinions, findings and conclusions are based on the author's evaluation of the literature and are not related to any financial, personal or professional relationships that could potentially bias the review.

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