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Sustainable Water Purification Using Green-Synthesized Nanoparticles: A Comparison Between Mono- and Bimetallic Nanoparticle Systems

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ABSTRACT

This review explores recent advancements in using environmentally benign monometallic nanoparticles (MMNPs) and bimetallic nanoparticles (BMNPs) for photocatalytic water purification, addressing the urgent need for sustainable solutions to global water scarcity. This study systematically analyzes how key photocatalysis variables, including nanocatalyst concentration, dye selection, and pollutant concentration, influence dye degradation outcomes. Standardized experimental conditions utilizing UV irradiation, 10 ppm, methylene blue (MB), and green synthesis routes were employed for comparative assessment. Results indicate that BMNPs, particularly Ag-Cu BMNPs composites, consistently outperform their MMNPs, achieving degradation rates between 90% and 99%, compared to 70%–85% for MMNPs. This superior performance is attributed to synergistic effects between the constituent metals. The review further highlights the advantages of plant-based synthesis methods, which offer a safer, more economical, and stable alternative to conventional chemical methods. By critically evaluating the potential of these NPs under controlled scenarios, this work underscores the transformative potential of engineering BMNPs in advancing next-generation water treatment technologies.

1 | Introduction

The global water crisis, intensified by population growth and industrialization, poses unprecedented challenges in securing safe water resources, particularly in developing regions. Among various contaminants, synthetic dyes from textile industries constitute a class of recalcitrant pollutants that resist conventional degradation methods. Semiconductor photocatalysis has emerged as a powerful solution to these challenges, harnessing light energy to generate reactive oxygen species (ROS) that completely mineralize organic pollutants without generating secondary waste [1–5]. This technology holds promise for water-stressed regions where energy-efficient, solar-driven purification technologies are urgently needed [6]. The development of advanced nanocatalysts with tailored properties has further enhanced the efficiency and practicality of photocatalytic water

treatment, positioning this technology as a key innovation in addressing global water security challenges [7].

Agricultural activities account for nearly 70% of global freshwater withdrawals, with resulting wastewater often containing elevated levels of organic pollutants, pathogens [8], and agrochemical residues [6, 9]. This interconnection between water scarcity and contamination necessitates innovative treatment approaches capable of addressing diverse water quality challenges across various settings [3, 10]. Metal oxide nanoparticles photocatalysis has emerged as a sustainable technology that utilizes ultraviolet, solar, or visible radiation to initiate redox reactions capable of degrading organic pollutants [9, 11]. Through the generation of ROS [12], this process effectively breaks down complex pollutants, including pesticides [13], pharmaceutical compounds, and industrial chemicals [14]. Recent studies suggest that incorporating metal nanoparticles as catalysts and their composite structures, such as plasmonic metals or carbon-based composites, have substantially improved photocatalytic efficiency under a broader light spectrum. These advancements have positioned photocatalytic systems as viable solutions for decentralized water treatment applications, particularly in regions with limited infrastructure but abundant solar resources. Consequently, the versatility of photocatalytic technology demonstrates significant potential for addressing a wide range of water quality challenges beyond agricultural applications.

The efficacy of photocatalytic systems extends to addressing water quality issues across diverse socioeconomic contexts [15]. Unlike conventional methods that often fail to eliminate emerging contaminants, photocatalytic metal nanoparticles can achieve complete mineralization of pharmaceuticals and endocrine-disrupting compounds through advanced oxidation reactions. In agricultural settings, nanoparticle-based photocatalysis enables safe wastewater reuse by effectively removing organic pollutants [16], and heavy metals that would otherwise accumulate in crops and soils [17]. Integration of photocatalytic nanomaterials into irrigation systems provides sustainable water purification while reducing pressure on freshwater resources [18]. These applications address critical challenges in both water-scarce regions and agricultural economies and support broader sustainable development objectives through advanced material solutions [19]. While demonstrating broad applicability, current water treatment strategies face limitations regarding consumption, scalability, and effectiveness against persistent pollutants.

Conventional water purification strategies face significant limitations in addressing complex contaminants from industrial effluents. Although conventional physical, biological, and chemical treatment methods provide partial solutions, they frequently encounter challenges including high energy consumption, chemical dependence, and limited efficacy against persistent pollutants [20]. Semiconductor nanoparticle-based photocatalysis has emerged as a transformative approach that utilizes sustainable solar energy to completely mineralize organic contaminants by utilizing sustainable solar energy for contaminant mineralization [21–23]. Green-synthesized metallic nanoparticles are particularly effective photocatalysts, offering advantages in operational stability and, for bimetallic compositions, powerful synergistic effects that enhance catalytic activity.

Green-synthesized metallic nanoparticles demonstrate exceptional photocatalytic performance due to their tunable band structures, enhanced surface-to-volume ratios, and unique optoelectronic properties [24, 25]. Monometallic nanoparticles (MMNPs), including TiO_2, ZnO, and AgNPs, demonstrate significant photocatalytic activity for organic pollutants. However, bimetallic nanoparticles (BMNPs) [26] exhibit superior performance through electronic and geometric synergistic effects between metal components, achieving 90%–99% degradation efficiency under optimized conditions while reducing reliance on precious metals [27]. The integration of plant-mediated synthesis further enhances metal nanoparticle stability and catalytic activity while minimizing environmental impact. This review systematically evaluates the comparative performance of MMNPs and BMNPs for the sustainable photocatalysis process.

Focusing on methylene blue (MB) as a model pollutant, this review assesses photocatalytic degradation under standardized conditions (10 ppm concentration, UV light exposure, and green synthesis protocols). Comparative analysis seeks to establish structure–activity relationships to guide optimal nanoparticle design, and the findings provide critical insights for developing efficient photocatalytic systems for sustainable water purification applications.

2 | Physicochemical Properties of Metal Nanoparticles

Biosynthesized metal nanoparticles (MNPs) possess important physicochemical properties that enhance their efficacy in sustainable water purification through photocatalytic processes under UV and visible light. The basic green synthesis process is shown in Figure 1. The photocatalytic efficacy is governed by a spectrum of physicochemical properties. Key factors such as particle size, morphological shape, surface charge, elemental composition, and environmental pH collectively dictate light harvesting efficiency and the dynamics of photogenerated charge carriers. To illustrate, a reduction in particle size (10–50 nm) maximizes the surface area–to-volume ratio, thereby promoting the generation of free radicals and increasing the density of active sites. Concurrently, a spherical morphology proves beneficial by enhancing light scattering within the material and improving the separation efficiency of electron–hole pairs [28, 29]. Optical bandgap energy determines visible light responsiveness, enabling efficient utilization of irradiation of light for different pollutant degradation. Surface functionalization or modification via plant-based phytochemicals and bioactive components stabilizes MNPs, prevents aggregation, and facilitates pollutant adsorption. Crystallinity and composition further improve catalytic mechanisms through the photocatalysis process [20]. Additionally, the magnetic properties of iron-based MNPs allow for easy recovery and reuse, enhancing sustainability [30]. Higher pH values during synthesis can enhance morphology and photocatalytic activity [31]. The pH values modulate surface charge and pollutant adsorption; acidic conditions favor the adsorption of anionic pollutants on positively charged catalysts [32]. Mono/bi/multimetal nanoparticles leverage synergistic effects to improve dye degradation in a shorter period with effective MNPs catalysts via the photocatalysis process. Surface charge, influenced by pH and functional

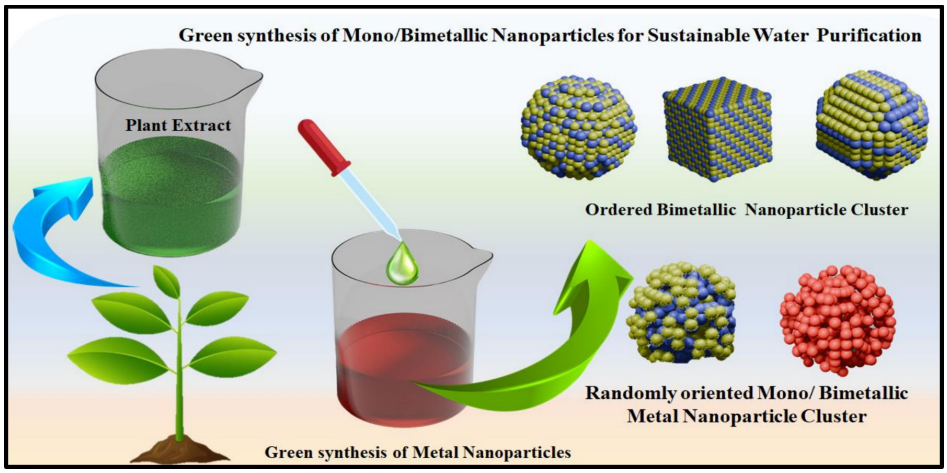

FIGURE 1 | Schematic of green synthesis of MNPs.

TABLE| 1 | Photocatalytic activity of MMNPs.

S. No	Name of nanoparticles	Name of the plant extract	Dye degradation %	Reference	Experimental constraints
1	SnO_2	Guava	40	[33]	UV light
2	ZnONPs	Hybanthus (Hyb)	70	[26]	10 PPM
3	WO3	Guava	75	[34]	120 min
4	AgNPs	*Alpinia officinarum* (AO)	80	[35]	MB dye
5	ZnONPs	*Phoenix dactylifera* (PD)	89.3	[36]	Green synthesis
6	TiO_2NPs	Mulberry (Mul)	96	[37]	
7	ZnONPs	*M. communis* (MCO)	99	[38]	

groups, governs pollutant adsorption and stability, with positively charged surfaces at low pH adsorbing anionic dyes more effectively. These factors collectively optimize photocatalytic efficacy, enabling efficient degradation of different pollutants under UV and visible light.

3 | Photocatalytic Properties of Metallic Nanoparticles

3.1 | Monometallic Nanoparticles

Monometallic nanoparticles (MMNPs), composed of a single-metal element, have been explored for their photocatalytic potential in water purification. These nanoparticles, often synthesized through environmentally friendly methods, have demonstrated promising results in degrading a variety of toxic dyes. For instance, silver (Ag), zinc (Zn), and titanium dioxide (TiO_2) nanoparticles are notable examples that have been widely studied for their photocatalytic activities against MB dye. By maintaining consistent conditions such as a fixed concentration of MB dye (10 ppm), degradation time (120 min), and UV light exposure, researchers have compared the dye degradation efficiencies of these MMNPs. The findings, summarized in Table 1, highlight the significant photocatalytic capabilities of these monometallic systems, underscoring their potential as effective tools in water treatment processes.

Among MMNPs, AgNPs and TiO_2NPs are prominent for their extensive application in sustainable water purification through dye degradation. These nanoparticles excel as catalysts by interacting with UV light to generate electron–hole pairs, which are a key factor for photocatalytic dye degradation activity. Notably, they exhibit reduced electron–hole recombination, enhancing their efficacy. AgNPs leverage their high surface plasmon resonance to improve photocatalytic performance. Additionally, zinc nanoparticles (ZnNPs) offer tunable optical bandgaps, allowing them to be tailored for specific applications. When ZnNPs are synthesized with different plant extracts, variations in dye degradation efficiency against MB were observed, even under consistent conditions. This variability is attributed to changes in surface charge due to the diverse phytochemicals present in the extracts, which modify the nanoparticles' interaction with the dye. Such modifications highlight the potential for optimizing photocatalytic performance by carefully selecting the synthesis conditions and plant extracts used.

Beyond silver (Ag) and titanium dioxide (TiO_2) nanoparticles, other MMNPs like nickel, cobalt, copper, and iron also exhibit notable photocatalytic properties against various dyes. However, their photocatalytic efficiencies often lag behind AgNPs and TiO_2 NPs [37]. Additionally, these MNPs may have certain limitations, such as lower stability or reactivity. To enhance their performance, researchers have explored combining these metals to different forms of metal nanoparticles such as

bimetallic, trimetallic, and multimetallic nanoparticles. This approach leverages synergistic effects to improve charge separation, increase surface area, and enhance overall photocatalytic activity. For instance, bimetallic systems, such as copper and silver bimetallic nanoparticles (Cu-Ag BMNPs), have shown improved efficiency compared to their monometallic counterparts, as observed in studies where copper nanoparticles outperformed AgNPs and ZnNPs in dye degradation. Such composite structures offer promising avenues for optimizing photocatalytic processes in water purification applications.

3.1.1 | Zinc Nanoparticles

Zinc oxide nanoparticles (ZnONPs) have emerged as promising photocatalysts due to their high photocatalytic activity and versatility in degrading organic pollutants. Their hexagonal wurtzite structure, which is the most stable form, contributes significantly to their photocatalytic efficiency by facilitating the generation of ROS. The presence of oxygen vacancies in ZnONPs enhances their photocatalytic activity by improving light absorption intensity and charge transfer. Studies have shown that ZnONPs synthesized using green methods, such as plant extracts, can achieve high degradation efficiencies for dyes like MB, with rates reaching up to 96%–98.5% under optimized conditions. Additionally, ZnONPs synthesized using the green extract of *Myrtus communis* exhibit 99% dye degradation with excellent photo-stability and biocompatibility, making them a cost-effective and eco-friendly option for wastewater treatment applications [36, 38, 39]. Their tunable optical bandgaps also allow for modifications that can enhance their photocatalytic activity under different light conditions.

3.1.2 | Silver Nanoparticles

AgNPs have emerged as highly efficient photocatalysts, particularly under visible light illumination, due to their rich optical properties. Their LSPR effect enables potential light absorption and conversion into chemical energy, facilitating photocatalytic reactions [35]. AgNPs have shown degradation of a range of organic pollutants, including MB and other dyes, with high efficiency under UV/sunlight irradiation. For instance, AgNPs synthesized using plant extracts have demonstrated impressive degradation rates for various pollutants. Additionally, when combined with other semiconductors like TiO_2 or ZnO, AgNPs enhance photocatalytic activity by reducing charge recombination and improving electron–hole separation, thereby increasing the overall photocatalytic activity [33, 36, 40–42]. This makes AgNPs promising candidates for sustainable water purification applications.

3.1.3 | TiO_2 Nanoparticles

TiO_2 NPs are renowned for their exceptional photocatalytic properties, making them a cornerstone in water purification and environmental remediation [23, 37]. Their efficacy stems from a high surface area and the ability to generate electron–hole pairs under UV irradiation, which facilitates the degradation of organic pollutants. The anatase phase of TiO_2 is particularly favored for its superior photocatalytic activity, about 96% dye degradation, due to its larger specific surface area and enhanced thermodynamic stability at the nanoscale [37]. However, TiO_2's wide bandgap limits its absorption to UV light, prompting research into doping strategies to extend its photocatalytic activity into the visible spectrum. Doping with metals like nickel or iron has shown promise in enhancing TiO_2's visible light–responsiveness, thereby improving its utility in practical applications where sunlight is the primary energy source. This adaptability, combined with TiO_2's nontoxicity and stability, underscores its potential as a versatile photocatalyst for sustainable water treatment processes.

Figure 2 illustrates the efficiency of different MMNPs in the degradation of MB dye at a concentration of 10 ppm over 120 min. The degradation percentages vary among the nanoparticles, with ZnO-Hyb showing the lowest degradation at approximately 75%, whereas TiO_2-Mul and ZnO-MC exhibit the highest, reaching around 99%. Ag-AO and ZnO-DP also demonstrate significant degradation capabilities, with values around 90% and 98%, respectively.

3.2 | Photocatalytic Properties of Bimetallic Nanoparticles

BMNPs, which are fabricated by incorporating two different metal salts with tunable sizes, have attracted more attention due to their synergetic multifunctional properties. The introduction of a second salt can help to tune or modify the electronic structure of BMNPs, which enhances the catalytic properties of BMNPs. The BMNPs are synthesized by various processing conditions such as homogeneous mixing of two salts at different concentrations, formation of two different domains in contact with each other, and core-shell structure (one surrounded by another metal shell). BMNPs have shown enormous potential in catalytic and water purification applications due to their selective metal concentrations, which help reduce electron–hole recombination. These BMNPs can also reduce the cost and toxicity of the metal composition by using low concentrations [12, 27, 33, 41, 42]. The dye degradation mechanisms of BMNPs depend on their electronic structure and optimum composition of both metal salts. For example, alloy BMNPs have enhanced electronic properties that affect their optical energy band gap, which reduces the recombination of electron–hole pairs.

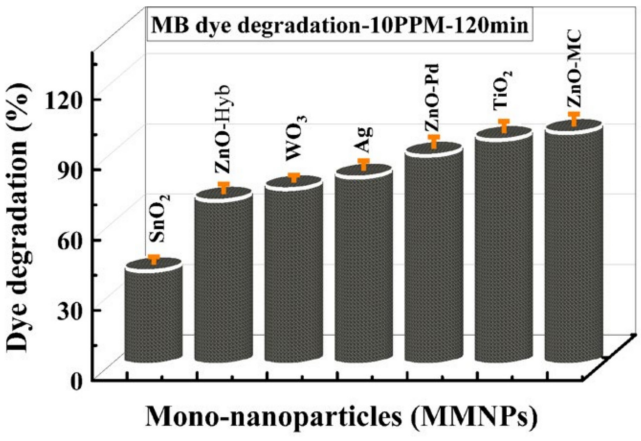

FIGURE 2 | Percentage dye degradation by MMNPs against MB dye.

TABLE 2 | Photocatalytic activity of BMNPs.

S. No	Name of nanoparticles	Name of the plant extract	Dye degradation %	Degradation time	Reference	Constraints
1	Ag-Cu BMNPs	*Croton bonplandianum*	75	180	[43]	10 PPM
2	Zn-Sn BMNPs	*Sutherlandia frutescens*	88	120	[33]	MB dye
3	Cu-Zn BMNPs	*Synadenium grantii*	91.3	120	[42]	UV light
4	CuO-TiO_2	*Citrus aurantium* juice	93	60	[27, 41]	Green synthesis
5	Sn-Wo BMNPs	*Psidium guajava*	95	150	[33]	Time duration
6	Ag-Zn BMNPs	*Carthamus tinctorius*	98	60	[40]	

BMNPs demonstrate superior photocatalytic performance compared to single-metal counterparts, primarily due to the combined catalytic advantages of their dual metallic components [33, 42]. This study investigated MB dye degradation under controlled parameters, including a fixed dye concentration of 10 ppm and UV light exposure. With these chosen constraints, our review study revealed that specific BMNPs combinations, such as silver-palladium (Ag-Pd) and zinc-tin (Zn-Sn) nanoparticles, achieved 96%–98% degradation efficiency by leveraging synergistic interactions between the metals' distinct multifunctional properties. Additional BMNPs compositions, mentioned in Table 2, also exhibited strong MB dye-removal capabilities. From this review data, we plotted MB dye degradation versus BMNPs composition, and this is shown in Figure 3. The enhanced activity stems from improved charge separation and surface reactivity in BMNPs, which broaden their photocatalytic spectrum while maintaining structural stability. These findings highlight BMNPs' potential for scalable environmental applications, particularly in treating organic pollutants like MB dye under UV conditions.

The photocatalytic efficiency of metal nanoparticle-based systems is highly sensitive to operational variables such as pH, light source characteristics, and catalyst loading [44]. However, the lack of standardized protocols for these parameters significantly obstructs meaningful cross-study comparisons. For instance, variations in pH can alter the surface charge of catalysts and the ionization state of pollutants, thereby affecting degradation kinetics, yet studies employ widely different pH conditions without always justifying these choices [44–46]. Similarly, the use of disparate light sources—ranging from narrow-wavelength UV lamps to broad-spectrum solar simulators—makes it difficult to decouple intrinsic catalytic activity from light input–dependent effects. Furthermore, catalyst loading concentrations are often optimized in a system-specific manner, leading to inconsistencies in reporting metrics such as apparent quantum yield or degradation rate constants. These methodological divergences complicate the extrapolation of findings across studies and hinder the rational design of scalable photocatalytic systems.

3.2.1 | Ag-Cu Nanoparticles

Ag-Cu BMNPs exhibit potential catalytic activity due to synergistic effects between the two noble metals. In the context of dye degradation, these BMNPs leverage both geometric and electronic factors to improve their performance compared to monometallic counterparts. The presence of Ag in the bimetallic structure accelerates the reduction process, which demonstrates superior dye reduction capabilities. Ag-Cu BMNPs have been found to enhance catalytic activity in various reactions, including the reduction of 4-nitrophenol, where the bimetallic configuration outperforms monometallic catalysts due to a synergistic electronic effect [47]. This synergy effect is crucial in dye degradation, as it allows for more efficient interaction with dye molecules, facilitating their breakdown under visible light and UV conditions. The enhanced surface area and charge transfer properties of Ag-Cu BMNPs also contribute to their superior catalytic performance, making them promising candidates for environmental remediation applications such as dye degradation. Overall, the combination of Ag and Cu in BMNPs creates a potential BMNPs catalyst for improving catalytic efficiency in dye sustainable degradation processes.

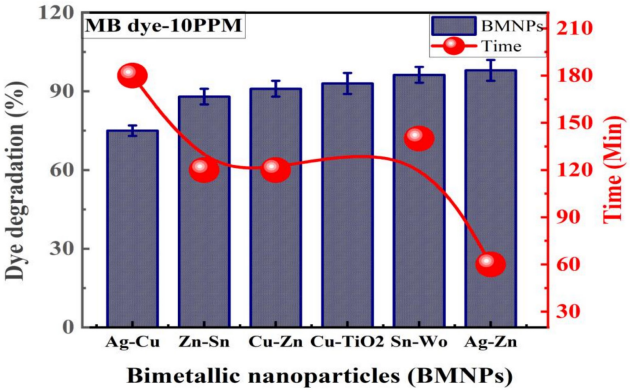

FIGURE 3 | Photocatalytic activity of BMNPs against MB dye.

3.2.2 | Zn-Sn Nanoparticles

Zn-Sn BMNPs synthesized using green methods, such as plant extracts, have shown promise in enhancing dye degradation through synergistic catalytic activity. Studies confirm the formation of BMNPs with varied structural morphologies, including heterostructures of spheres (ZnO) and rods (SnO_2), with sizes ranging from 5 to 60 nm [33]. The combination of ZnO and SnO_2 improves charge separation, reduces recombination of electron–hole pairs, and significantly enhances the adsorption of dye molecules, leading to improved photocatalytic efficiency [48]. For instance, a 1:1 Zn-Sn BMNP ratio achieved 88% degradation of

MB dye within 150 min, highlighting the synergistic effect and potential of these BMNPs for effective water treatment.

3.2.3 | Cu-Zn Nanoparticles

Cu-ZnO BMNPs have shown promising catalytic activity for enhancing dye degradation with 91% efficiency due to their synergistic effect in a shorter period (e.g., 120 min). Green synthesis methods, utilizing plant extracts such as *Synadenium grantii* leaf extract, offer an eco-friendly approach to producing these nanoparticles [42]. The introduction of copper dopants into the ZnO structure creates defects and new energy levels within the bandgap, improving light absorption and charge carrier separation. Studies have demonstrated that specific concentrations of Cu-doping, such as 3% and 5%, exhibit superior photocatalytic performance for the degradation of dyes like MB, indigo carmine, and rhodamine B [49]. The synergistic effect between Cu and ZnO enhances photocatalytic activity, making Cu-doped ZnO BMNPs a viable option for environmental remediation and the degradation of hazardous organic pollutants in wastewater.

3.2.4 | Sn-Wo Nanoparticles

Sn-Wo BMNPs exhibits significant catalytic activity, particularly in the degradation of dyes like MB [34]. Studies show that SnO_2/$WO_3 - x$ hetero-nanostructures, synthesized using green methods with *Psidium guajava* leaf extract, demonstrate enhanced photocatalytic degradation efficiency (94.5%) compared to their monometallic counterparts, SnO_2 (35.7%) and WO_3 (74.5%). This enhanced performance arises from the synergistic effect between the two metal oxides, which facilitates efficient charge transportation, extends light absorption, and increases dye adsorption due to the enlarged specific surface area. The BMNPs structure promotes better separation of electron–hole pairs, crucial for potential photocatalytic activity. Moreover, these hetero-nanostructures maintain their reusability for up to three cycles without significant loss in degradation efficiency or stability, highlighting their potential for sustainable environmental applications. The green synthesis approach further ensures an eco-friendly and economically feasible route for producing these highly active photocatalytic materials, making them a promising alternative to conventional methods for water treatment.

3.2.5 | Ag-Zn Nanoparticles

The synergistic catalytic activity of Ag-ZnO BMNPs significantly enhances dye degradation of 98% in a shorter period (e.g., 60 min), offering a promising solution for water treatment. The deposition of plasmonic Ag nanoparticles (NPs) onto ZnO leads to a decrease in the bandgap energy, improving the photocatalytic characteristics [50]. The SPR effect of AgNPs induces a synergistic enhancement of the optical response and promotes the separation of photo-induced charge carriers. This process results in an extended electron–hole pair lifespan, crucial for efficient dye degradation. In the degradation of MB dye, a primary textile industry pollutant, the BMNPs achieve high degradation rates under UV light irradiation, primarily through the production of hydroxyl radicals. The plasmon-induced electrons transfer from Ag to ZnO, facilitating oxygen reduction and enhancing the overall photo-decomposition performance [40]. This synergistic effect makes Ag-Zn BMNPs a promising nanocatalyst for the direct photocatalytic degradation of textile and organic wastes in water.

A comprehensive comparative analysis of MB dye degradation efficiency using five different BMNPs based on research work at a constant dye concentration of 10 PPM is shown in Figure 3. The data reveal significant variations in both degradation performance and required degradation time (red line, right axis). Ag-Zn nanoparticles demonstrate superior performance with approximately 98% dye degradation achieved in the shortest time (about 60 min), indicating exceptional catalytic efficiency. In contrast, Ag-Cu BMNPs exhibit the lowest degradation efficacy (around 75%) while requiring the longest processing time (approximately 180 min). The intermediate performers Zn-Sn, Cu-Zn, and Sn-Wo show progressively increasing degradation efficiencies (approximately 88%, 90%, and 95%, respectively) with varying time requirements between 120 and 140 min. This inverse relationship between degradation percentage and processing time suggests that the composition of the BMNPs significantly influences their catalytic activity, with Ag-Zn emerging as the most promising candidate for efficient environmental remediation applications involving dye contaminants [51–55].

The comparison of dye degradation versus MMNP/BMNPs is shown in Figure 4. We compare the dye degradation efficiency of different metal nanoparticles (MNPs) for a 10 PPM MB dye solution. AgNPs show approximately 80% degradation. ZnNPs and a Cu-Zn BMNPs combination show slightly improved degradation. Tin-tungsten (Sn-Wo) BMNPs exhibit the highest degradation efficiency, reaching 95% [56–60]. An Ag-Zn BMNPs combination also demonstrates high 98% dye degradation, with the reaction time significantly reduced (60 min) compared to other MNPs.

4 | Photocatalytic Activity Mechanism of MMNPs/BMNPs

4.1 | Photocatalytic Activity Basic Mechanism

The photocatalytic detoxification of dyes such as MB leverages the advanced oxidation process (AOP), whether employing MMNPs or BMNPs [32, 61–64]. The electron–hole pairs' exposure to suitable light initiates a series of redox reactions (see Figure 5).

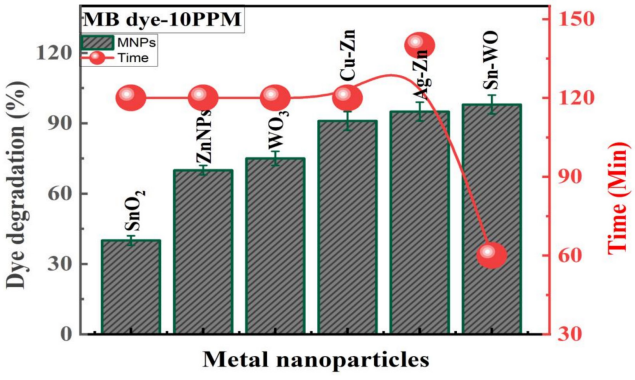

FIGURE 4 | Comparative dye degradation efficiency of MMNPs and BMNPs against MB dye.

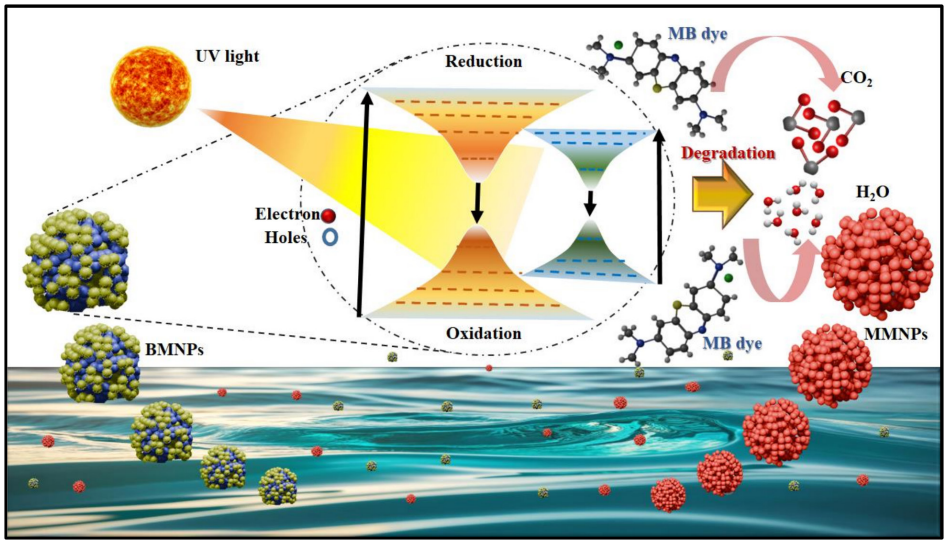

FIGURE 5 | Proposed mechanism of photocatalytic activity of metal nanoparticles in the degradation of MB dye.

Light absorption and charge carrier generation: When NPs are exposed to light with energy equal to or more than their band gap energy, electrons transition from the valence band to the conduction band, creating electron–hole pairs. BMNPs enhance this process by facilitating efficient charge separation and minimizing electron–hole recombination, attributed to their tailored electronic properties.

ROS formation: The photogenerated electrons react with adsorbed oxygen molecules to produce superoxide radicals (O_{2}-*), while the holes react with water molecules to form hydroxyl radicals ($^{-}$OH*). These ROS are potent oxidizing agents that drive the potential degradation of organic pollutants in water.

Dye degradation process: The ROS attack the complex dye molecules, breaking them down into less harmful byproducts. Hydroxyl radicals (OH^{-}) act as primary reactive species, effectively degrading water-soluble dyes, enhancing the long-term effectiveness of the photocatalytic process. The reduction of dye pollutants occurs through the following basic mechanism.

$$\text{Photo-catalyst material (MMNPs/BMNPs)} + \text{UV/visible light} \Rightarrow e^{-} + h^{+}$$

$$\text{Photo-catalyst material (MMNPs/BMNPs)} + \text{UV/visible light} + e^{-} \Rightarrow O^{*}_{-2}\ \text{(free radical)}$$

$$\text{Photocatalyst material (MMNPs/BMNPs)} + \text{UV/visible light} + OH^{-} \Rightarrow OH^{*}\ \text{(free radical)}$$

$$O^{*}_{-2} + OH^{*} + \text{pollutants (complex MB dye etc.)} \Rightarrow \text{Degraded material (byproducts)}$$

Key factors influencing efficiency: The efficiency of dye degradation is influenced by several factors, including dye concentration, catalyst concentration, the intensity and wavelength of light, and the properties of the NPs themselves. Optimal doping or concentration of both metals in BMNPs enhances catalytic activity by promoting faster release of charge carriers, leading to improved dye degradation efficiency.

4.1.1 | Kinetic Model Analysis

The kinetic model analysis of photocatalytic degradation provides critical insights into the reaction mechanism and efficiency of the catalyst [65, 66]. By fitting experimental data to models such as the Langmuir–Hinshelwood or pseudo–first-order kinetics, the rate constants and adsorption characteristics can be determined, which are essential for scaling laboratory results to real-time applications [65]. Such analysis not only validates the photocatalytic pathway but also plays a pivotal role in designing and optimizing large-scale photocatalytic reactors for wastewater treatment [67].

BMNPs, such as Cu-Zn or Ag-Zn BMNPs, offer enhanced photocatalytic activity due to enhanced charge separation and synergistic effects [68–71]. The combination of two metals promotes better separation of electron–hole pairs, reducing recombination and increasing the availability of charge carriers for redox reactions. The interaction between the two metals can modify the electronic structure, leading to improved light absorption and ROS generation.

The superior photocatalytic performance of BMNPs compared to their monometallic counterparts (MMNPs) is fundamentally rooted in the sophisticated electronic interactions at the metal–metal interface. This interface, whether in a core-shell, heterostructure, or alloy configuration, acts as a nanoscale

engineering platform for manipulating charge carrier dynamics. The primary mechanisms through which they occur are the formation of a Schottky barrier and the facilitation of directed electron transfer, both of which synergistically suppress the rapid recombination of photogenerated electron–hole pairs, a major limiting factor in photocatalytic efficiency.

4.2 | The Critical Role of the Bimetallic Interface in Charge Separation

The interface in BMNPs creates a unique electronic environment that monometallic systems cannot replicate. In a structure like a core-shell nanoparticle, the contact between two metals with different work functions spontaneously leads to electron flow until Fermi level equilibration is achieved [72]. This process creates a localized space-charge region and a potential energy barrier known as a Schottky barrier at the interface [73]. This barrier acts as a highly efficient and nanoscopically precise electron valve; it readily accepts photogenerated electrons from a semiconductor support or from one metallic component, but its inherent electric field presents a large energy obstacle for the backflow of those electrons [74, 75]. Consequently, electrons are effectively trapped on one side of the interface, spatially separating them from their complementary holes and drastically increasing their lifetime for participating in surface reduction reactions. In alloyed structures, where atomic-level mixing occurs, the electronic coupling is even more direct [76]. The d-band centers of the metals modify each other, creating a novel electronic structure that promotes rapid electron delocalization across the entire nanoparticles. This delocalization, a form of facilitated electron transfer, prevents the localization of charge that typically precedes recombination [77]. The combined effect, whether through a defined Schottky junction or a synergistic electronic coupling, is a dramatic reduction in recombination rates [78]. This makes BMNPs not merely additive but multiplicative in their function, as the interface itself becomes the active site for intelligent charge management, a feature entirely absent in MMNPs.

5 | Conclusion

Photocatalytic water purification using green-synthesized nanoparticles offers a promising path for resolving the dual challenges of safe drinking water provision and sustainable agriculture practices. The integration of UV/visible light–driven photocatalysts enables efficient decomposition of a broad spectrum of organic pollutants and pathogens without generating hazardous byproducts. Green-synthesized BMNPs owe their unique electronic structure and synergistic systems to the MMNP systems. The adoption of plant-mediated synthesis not only reduces environmental impact but also enhances the scalability and economic feasibility of these materials. As global policy shifts increasingly favor green technologies, they can play a pivotal role in meeting stringent water quality standards and supporting a circular water economy. Continued interdisciplinary research and supportive regulatory frameworks will be essential to translate these laboratory-scale innovations into practical, large-scale water treatment solutions. In future research, we will focus on tackling scale-up challenges, optimizing reactor configurations (such as fixed-bed versus slurry systems), and conducting comprehensive techno-economic and life-cycle assessments to determine both the real-world feasibility and the long-term environmental advantages of the process beyond laboratory conditions.

Author Contributions

Parvathalu Kalakonda: visualization of the project and project supervision. **Sai Bhargava Vipparla, Naveen Debbata, Satyavardhan Dharmapuri, Pranay Bhasker Kalakonda, Dayanand Aitipamula:** review of literature and analysis. **Anil Kumar Busi, Moses Kigozi, Pritam Mandal and Krishna Kumar Balu:** review and graphical schematics.

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Conflicts of Interest

The authors have no relevant financial interest to disclose.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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