A Review on Diverse Bimetallic Nanoparticles and Their Innovative Roles in Degrading Dyes

Manav, Kashif Raees*

Department of chemistry, Chandigarh University, Mohali, Punjab 140413, India

Email: kashif.e11790@cumail.in

Abstract: Water is a vital for all living organism, unfortunately it is being polluted and degraded in quality due to rise in industrial waste. The rise of industrialization has brought about significant adverse effect on human life causing them different kind of diseases due to that contaminated water which may include various dyes, heavy metals and organic pollutants. Interestingly bimetallic nanoparticles which comprise two distinct metals elements have proven more effective for dye treatment due to synergetic features. Bimetallic are to be a most promising class of materials that are often used for removal of contaminates detected in wastewater. Their applications extend to environmental challenges such as nitrate removal, dye degradation, organic pollutants and heavy metal elimination. In this review, we explored different kinds of bimetallic nanoparticles and their effectiveness in degrading dyes, analyzing their efficiency in terms of percentage degradation.

Keywords: Dye degradation, bimetallic nanoparticles, nanotechnology, heavy metals.

Introduction: Earth possess an ample supply of water, makes it one of the most plentiful natural resource. Although earth's water is plentiful, merely around 1% of it is intended towards human consumption. [1] The WHO estimates that Above 760 million persons lacked access to safe drinking water.[2] In regions wherever it is accessible, the price of drinking water is increasing due to the rising prices of energy, increasing population including Environmental challenges also such as climate issues.[3] The primary issue in the chain of water supply is the contamination of freshwater sources caused by diverse organic and inorganic pollutants.[4] Addressing concerns through wastewater and drinking water treatment is possible, but traditional methods prove inadequate in fully eliminating emerging contaminants and meeting rigorous water standards.[5] Moreover, modern waste water treatment technologies have a number of imperfections including high energy, poor pollutant removal, and generating of toxic sludge.[6] Though commonly used biological waste water treatment is typically inefficient, limited by presence of non biodegradable contaminant, and sometimes toxics to microorganism due to certain toxic substances.[7]Physical methods like filtering can eliminate pollutants by changing one phase into another, but this results in highly concentrated sludge that is hazardous and challenging to dispose off.[8,9] Thus, the efficient reuse of wastewater in the recovery of water, minerals, or energy is fast becoming a necessary focal point owing to the fact that extended various pollutants are emerging and threatening the integrity of water, of which dye effluents have proven to be one of the major and common felons.[10]

Man has employing dyes for wide range of applications since the beginning of time, including use in textile, paints, medicines and in others industries. The exposures of dyes to the aquatic environments has, unfortunately lead to the negative effects like inhibition of photosynthesis, carcinogenicity, increase in biochemical and chemical oxygen demand, mutagenticity etc.[11] Synthetic dyes play a crucial role in important sectors like leather, textiles and paper industries due to their ability to impart colour. After fulfilling their intended use, a majority of dyes are disposed of without proper consideration, often ending up in environmental water sources. Almost about 50% of dye effluents present in the environment originates from textile industry. Although the specific volume of dye effluent discharged by the textile industry into the environment is unclear, it can be asserted that quantity is considerable enough to pose notable environmental challenges. Among various industries that use dye, the textile sector is reported to be the largest consumer of dyestuffs, utilizing approximately 10,000 tons annually on a global scale.[12] Extensive use of dyestuffs in different textile processes leads to the production of substantial volume of wastewater containing dyes.

Moreover, textile industries generate a significant volume of dye effluent, primarily attributed to their substantial water needs. Dye effluents, more commonly recognized as di waste water is abundant in various dangerous chemicals. Dye effluents pose a threat to the well being of animals and humans due to their inherent toxicity. Identifying water bodies with dye effluent is simple because the colour is the clear indicator.[13] The existence of dye waste in water sources is regarded as inappropriate since water is necessary for daily activities such as cooking, bathing, washing and drinking for both animals and plants. In the present days, extraction of dye molecules from water sources is becoming an environmental problem as well as challenge.[14] The adverse effect mentioned has compelled the research community to continually explore environmentally friendly techniques.[15]

In this review we will discuss about the how nanotechnology will help us out in the elimination of several pollutants such as dyes which are discarded by various industries and stop to harming the aquatic and human life both. Nanotechnology’s progress has shown an immense potential in effectively addressing the removal of various dyes present in the water by the usage of nanoparticles.

Dyes serve as infamous agents

Dyes are vivid compounds designed to add colour to being materials like fabrics, paper or any surface capable of being coloured. These are the colour agents that penetrate fibres and resist removal through washing with water, detergent or exposure to light.[16] ,[17] Dyes consist of coloured organic compounds characterized by functional groups like auxochromes and chromophoric groups.[18] Different dyes of dyes are employed to colour various substrates. Acid dyes find common application in the dyeing of modified acrylics, nylon wool and silk. Acid dyes are used in food, paper, leather and cosmetics. The four major categories of these dyes are anthraquinone, nitro, azine and azo dyes.[19] Methyl orange, acid blue are the acid dyes. Basic dyes can be used for modified polyesters, nylons, as well in medicine and paper industry. These types of dyes are water soluble and yields coloured cations and are called as Cationic dyes.[20] The examples of basic dyes are malachite green, crystal violet, basic red 46 and methylene blue.

Significance of dye removal

An industry that uses dyes typically kept dye effluent as an industrial waste once the dyes have served their role in colouring materials. Subsequently these waste products are discharged into water bodies; transformed cleared water into polluted coloured water. Before discharging dye waste water into the environment, these industries should undertake the necessary measures to treat the water. Environmentalist and public find water pollution caused by the presence of dyes unbearable, considering them as harmful and toxic substances. Periodically, concentrated dye effluents with elevated temperature and PH are discharged promptly after the process of dyeing. This process will interfered the oxygen transfer mechanism and the self purification process of water bodies in the environment.[21]

After being used and released back into the environment, these effluent pores pose threat to ecosystem by polluting water sources and rendering them unsuitable for use. The combination of dye waste with natural water sources not only generates foul odour but also presents an unpleasant sight for observer. Textile effluents can pose threat to terrestrial life, starting with aquatic plants and animals.[22], [23] As dye waste mixes with water sources , the water's turbidity rises because the effluents, with their lower density, tends to create a visible layer above the water sources. This obstructs the penetration of sunlight for underwater process such as photosynthesis and respiration, leading to cessation of life beneath the water.[24], [25]
Soil productivity will suffer additional harm if dye waste finds way into forests or fields, causing the clogging of soil pores.[26] People in the rural areas and native groups that depend upon rivers for their water requirements may inadvertently ingest polluted water if the water source is depleted or contaminated with harmful substances leading to illness. [27] Discharging dye effluents into the environment only serves to progressively harm the ecosystem and diminish public health concerns over time.
Exposure of dye effluent with skin can lead to the skin irritation. When these dye effluent comes into the contact of eyes, it can lead to eye burns or permanent injuries, affecting both humans and animals.[28]
The chemicals from dumped dye effluents in water supplies can evaporate in the environment. Inhaling these vapours may cause symptoms such as difficulty in breathing.[29] Consumption of these toxics dyes can cause various health problems like mouth burns, mouth nausea, sweating, and vomiting.[30], [31] dyes

are traditional carcinogenic and enduring heath repercussions for both an individual and an unborn child. Hence, it is crucial to treat waste water containing harmful dye effluents to avert its detrimental effects on water reserves, wildlife and human well being.[32],[33]

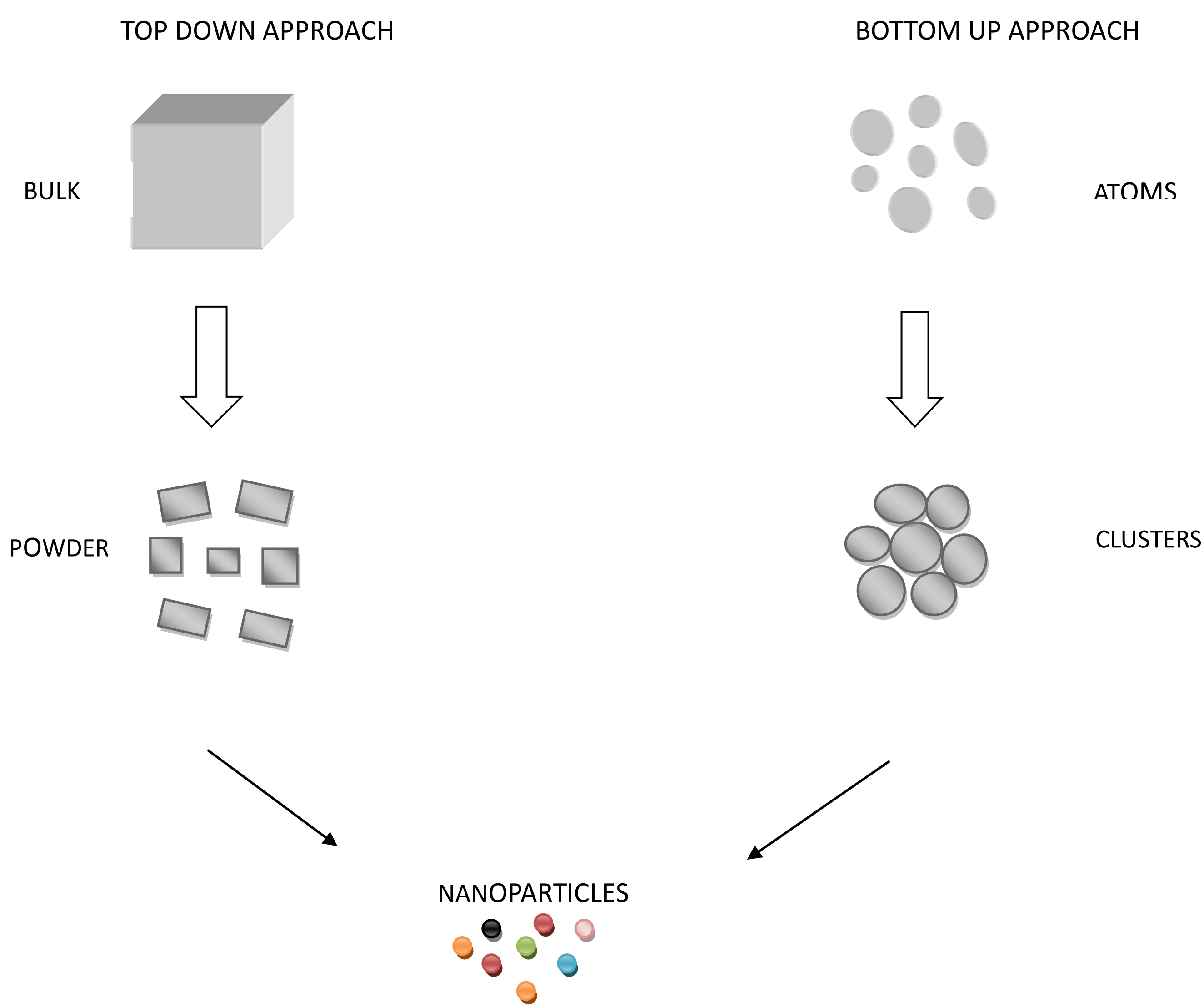
Industries that discharge dye containing waste water should commence efforts to mitigate the adverse impact they impose on environment and living organism. In addition to researchers striving to remove dye waste water from the surroundings, industries utilizing dyes should also put concerted effort to prevent the discharge of dye contaminated waste water into the environment. Industries using dyes should cease contributing to pollution and instead implement effective dye treatment plans.

The revelation indicates that these dyes have potential to instigate chromosomal mutations leading to cancerous tumours, elevate biochemical oxygen demand in aquatic ecosystem, reduce the development of photosynthetic organism, and disrupt the ecological system as well as fundamental ecological networking.[34] These harmful dye effluents possess carcinogenic, neurotoxin and mutagenic properties, posing a swift heart to the water quality of bodies within a moment.[35]

Hence there is an urgent need to treat the waste water and make the water free from dye effluents which in respect increase the life period of humans and of aquatic too. Nanoparticles are to be a most promising class of materials that are broadly used for the removal of pollutants like dyes found in wastewater.

Nanotechnology

The study of material at the microscopic level called nanotechnology. The fundamental component of nanotechnology is nanoparticles.[36] The size of Nanoparticles is in between 1 to 100 Nano meter and they are generally composed of metal, metal oxides, carbon and exhibits unique properties.[37] Nanoparticles made of metals particularly those of noble metals are more efficient than several types of nanoparticles and this is because that metal based nanoparticles have high stability, more compatible and can be produced at large scale for the applications in environment.[38]Instead of having such properties, metal based nanoparticles still needs to improve due to toxicity, size, and chemical stability.[39] Nanoparticles like zero-valet iron[40] and aluminium have demonstrated effectiveness in eliminating water contaminants includes heavy metals, dyes and various organic pollutants. However, there are certain drawbacks to these monometallic materials includes poor stability as a result of leaching , a gradual decline in productivity, a limited pH range and low reusability.[41] It was successfully discovered that bimetallic nanoparticles which combine two different metals elements have applications for getting out these problems and enhancing the efficiency of nanomaterial both through their unique metallic properties and through the new qualities brought by the synergistic effect.[42]Bimetallic nanoparticles have drawn more interest recently because of their distinct physical characteristic such as quantum effect, mobility and larger dimensions as well as their thermal, chemical, optical and magnetic qualities.[43],[44],[45] Bimetallic nanoparticles are the greatest option for effective dye water treatment since their synthesis biogenetically preserves their sustainable and environmentally friendly properties. There are different kinds of bimetallic nanoparticles that have been synthesized and for the degradation of various dyes present in the wastewater. These nanoparticles are synthesized when two different metals are combined with each other in a reaction vessel under ideal conditions that results in variety of morphological and structural changes.[46] There are many different forms of bimetallic nanoparticles that can be possible which may include copper- based, nickel based, silver based, gold based, palladium and platinum based bimetallic nanoparticles. There are two methods used for the formation of bimetallic nanoparticles which include breaking of bulk material into small particles or generating the small particles from their own particles. There are two methods named as top down approach and bottom up approach that involves mixing of two different metal precursors under favourable conditions to which reducing and stabilizing agent is added.[47]



The production of bimetallic nanoparticles may be classified within three methods such as physical, biological and chemical methods. There are different bimetallic combinations that have been reported in various research papers that are listed below:

Bimetallic Nanoparticles	Classification of bimetallic nanoparticles	Methods of synthesis	References
Copper based bimetallic nanoparticles	Cu-Co	Inverse Miceller encapsulation	48
	Cu-Ag	Green synthesis	49
	Cu-Fe	Electrical explosion	50
	Cu-Ni	Sol -Gel	51
	Cu-Pt	Hydrothermal method	52
Gold based bimetallic nanoparticles	Au-Ag	Green synthesis	53
	Au-Ni	Chemical synthesis	54
	Au-Pt	Green synthesis	55
	Au-Pd	Chemical synthesis	56
	Au-Cu	Galvanic replacement	57
Iron based bimetallic nanoparticles	Fe-Cu	Green synthesis	58
	Fe-Zn	Green synthesis	59
	Fe-Ag	Physical synthesis	60
	Fe-Ti	Chemical synthesis	61
Palladium based bimetallic nanoparticles	Pd-Cu	Green synthesis	62
	Pd-Au	DNA Ligand	63
	Pd-Zn	Chemical synthesis	64
Nickel based bimetallic nanoparticles	Ni-Pt	co- reduction	65
	Ni-Ru	Chemical synthesis	66
	Ni-Au	Physical synthesis	67
	Ni-Fe	Chemical synthesis	68
	Ni-Co	Chemical-co reduction	69

Exploring a spectrum of bimetallic nanoparticles covering various metal composition elucidate their unique ability to reduced various dyes each exhibiting distinct degradation efficiency with its reduced time

S .No	Name of the bimetallic nanoparticles	Name of the reduced dye	% degradation	Degradation time	References
1	Pd-Ni	Acid orange 8	80%	-	70
2	Cu-Ni	Methyl orange	98%	60 min	71
		Methyl blue	72%		
3	Pd-Fe	Methyl orange	96.16%	30 min	72
4	Zn-Fe	Malachite green	99.14%	60 min	73
5	Fe-Pd	Red ME4BL	92%	20 min	74
6	Ag-Zn	Methyl red	85%	60 min	75
		Phenol red	93%		
		Eosin yellow	78%		
7	Fe-Pd	Orange II	98%	12 hours	76
8	Fe-Zn	Malachite green Congo red	70%	60 min	77
9	Fe-Ni	Methyl Orange	99. 5%	15 min	78
10	Ag-Cu	Methylene blue	98. 57%	2 min	79
		Methylene orange	95. 21%	5 min	
11	Au-Pd	orange II	95%	60 min	80
12	Fe-Cu	orange II	77. 7%	-	81
13	Fe-Ni	Scarlet 4b	84.5%	3 hours	82
14	Ag-Ni	safranin O	100%	30 min	83
15	Fe-Cu	Methyl green	82%	105 min	84

16	Ag-Co	Malachite green	88.6%	120 min	85
17	Cu-Pd	Methyl Orange	95. 3%	45 min	86
18	Au-Ag	Methylene blue	34 .70%	3 hours	87
19	Au-Pd	Rhodamine	98%	-	88
20	Pd-Ni	Safranin	67%	-	89
21	Ag-CuO	Phenol red	88. 4%	30 min	90
22	Ce-Co	Methylene blue	97. 6%	120 min	91
23	Ag-Pt	Malachite green	94 .2%	50 min	92

Different approaches for removal of dyes

Dye removal methods were primarily limited to initial water purification steps such as sedimentation and equalisation, as there were no established discharge limits for dye effluents.[93] Due to discharge of dye's effluent standards were executed, prompting enhancements through the introduction of more efficient dye elimination techniques like dye degrading filter beds and active sludge processes.[94] Currently, many researchers are actively engaged in seeking an optimal approach for removing dyes, with the goal of enabling the recovery and reuse of waste water that contain dyes.[95] The approaches currently employed for dye removal can be classified into three main types: physical, biological and chemical treatments.

Biological dye removal approach

Most commonly employed and widely employed method for treating dye wastewater is the typical biological approach. Generally acknowledged as conventional approach, mixture of anaerobic and aerobic processes is implemented just before discharging dye effluents into the surrounding.[96] The selection of these methods as the preferred dye removal technique is primarily based on its cost effectiveness and ease of implementation.[97] The exclusive use of this treatment proves inadequate in fully eliminating hazardous particles from wastewater generated by textile dyes, leading to the continued presence of coloured water in the environment.[98] While the conventional addressees the chemical oxygen demand present currently waste water, it doesn't render the water free from dyes or eliminate toxicity. In addition to this technique other conventional biological approaches for dye removal include microbial biomass adsorption, fungal cultures, algae degradation, microbial cultures and the utilization of both pure and mixed cultures.

Several methods exist for eliminating water contaminants like dyes, but due to economic constraints and lengthy processes, the most effective solution for decolourization is the biological methods. In the domain of microorganism, including bacteria and fungi it has been observed that fungi are particularly effective in decolourizing waste water from textile, leather, and paper making industries. Their utilization is favoured due to factors like accessibility, cost effectiveness, environmental computability and quicker implementation timeframe compared to other methods.[99]

Physical dye removal approach

Physical approach for dye elimination is quite simple that are often achieved through mass transfer mechanism. Physical methods cover coagulation, adsorption, ion exchange and filtration among others. Among the various methods for dye removal, adsorption has shown to highly efficient and affordable. The separation of dye from industrial waste eater effluents is achieved through the utilization of adsorbents like activated carbon. Nevertheless, its widespread application in large scale applications is limited due to cost effectiveness. [100]

Adsorption has become a valuable technique for dye elimination due to its remarkable effectiveness in eliminating the wide range of dye substances.[101] These methods not only purify the industry waste water but also the drinking water. Conventional methods are inefficient in completely removing synthetic dyes from dye waste water.[102] Thus adsorption becomes one of the optimal methods for dye elimination. The application of the adsorption method to treat dye effluents led to the generation of treated water with superior quality in contrast with other alternative dye elimination methods.[103] The initial drawback for this method was the high price of the adsorbent, the discovery of inexpensive yet equally effective adsorbents has propelled it to become a globally economical approach for dye removal.[104] Adsorption is a mass transfer procedure in which elements deposit at the interface of two similar or different phases such as gas solid, gas liquid, liquid liquid, and liquid solid.[105], [106] it is a non reactive process where a substance originally exist in liquid or gaseous environment becomes concentrated on a solid surface.[107] This process reduces the amount of dissolved particles in an effluent. The material that describes absorption is termed as adsorbate, while the material employed to perform the absorption is referred to as adsorbent. Adsorption can be achieved through two methods physical sorption and chemical sorption.[108] Generally, adsorption is carried out through physisorption with random deviations where chemisorptions is opted for instead.

Effective dye removal is best achieved in the adsorption process when using porous material.[109], [110]The advantageous characteristic of the adsorption technique is that it is appropriate for pollution control application as it doesn’t produce any harmful elements at the end of the process.[111]

Chemical dye removal approach

\These dye removal approaches involve applying chemical principles in the complex process of eliminating dyes. Chemical dye elimination techniques comprise Fenton dye removal, electrochemical destruction, advanced oxidation process, ozonation, oxidation and ultraviolet radiations. While many chemical dye elimination approaches tend to be expensive when contrasted with physical and biological methods, an unusual occurrence is observed in the case of electrochemical degradation dye removal, which stands out as a more cost effective option. Chemical dye removal techniques are commercially unappealing, required specialized equipment and demand substantial electrical energy.[112] The widespread use of chemicals and reagents poses a common challenge for users employing chemical dye removal methods on a large scale.[113] A drawback of this approach is creation of harmful pollutants, marking the conclusion of the chemical dye elimination process and introducing an extra challenge in terms of disposal.[114]

Conclusion:

The life of an individual has been disturbed due to affected environment that cause so many disease due to rise in industrialization as it releases various dye effluents. These dye effluents not only destroy the human life but also aquatic life too. These dyes Posses the properties like carcinogenic, mutagenic. To remove this problem from the environment, nanotechnology plays a vital role in it. The field of nanotechnology has shown a significant progress in last few years. Nanotechnology have wide application in the field of science including environmental application which includes organic pollutants, presence of heavy metals and various dyes that are released by the industries. Nanoparticles as the basic unit of nanotechnology have been discussed with its simple synthesis method. In this review we have discussed about the basic information of dyes and how these dyes are affecting the human life and giving harm to it providing with the solution of bimetallic nanoparticles. These bimetallic nanoparticles show synergism affect and it is the greatest option for effective dye treatment. We have discussed different bimetallic nanoparticles which can reduce the different dyes with its degradation efficiency eliminated by the industries. We have also discussed generalized strategies of.dye removal which has been used for treating the dye waste water.

---

[1] Adeyemi S. Adeleye et al., "Engineered Nanomaterials for Water Treatment and Remediation: Costs, Benefits, and Applicability," *Chemical Engineering Journal* 286 (February 15, 2016): 640–62, https://doi.org/10.1016/j.cej.2015.10.105.

[2] Qilin Li et al., "Antimicrobial Nanomaterials for Water Disinfection and Microbial Control: Potential Applications and Implications," *Water Research* 42, no. 18 (November 1, 2008): 4591–4602, https://doi.org/10.1016/j.watres.2008.08.015.

[3] Muzammil Anjum et al., "Remediation of Wastewater Using Various Nano-Materials," *Arabian Journal of Chemistry* 12, no. 8 (December 1, 2019): 4897–4919, https://doi.org/10.1016/j.arabjc.2016.10.004.

[4] René P. Schwarzenbach et al., "The Challenge of Micropollutants in Aquatic Systems," *Science* 313, no. 5790 (August 25, 2006): 1072–77, https://doi.org/10.1126/science.1127291.

[5] Xiaolei Qu et al., "Nanotechnology for a Safe and Sustainable Water Supply: Enabling Integrated Water Treatment and Reuse," *Accounts of Chemical Research* 46, no. 3 (March 19, 2013): 834–43, https://doi.org/10.1021/ar300029v.
[6] Nassira Ferroudj et al., "Maghemite Nanoparticles and Maghemite/Silica Nanocomposite Microspheres as Magnetic Fenton Catalysts for the Removal of Water Pollutants," *Applied Catalysis B: Environmental* 136–137 (June 5, 2013): 9–18, https://doi.org/10.1016/j.apcatb.2013.01.046.
[7] Grigory Zelmanov and Raphael Semiat, "Phenol Oxidation Kinetics in Water Solution Using Iron(3)-Oxide-Based Nano-Catalysts," *Water Research* 42, no. 14 (August 1, 2008): 3848–56, https://doi.org/10.1016/j.watres.2008.05.009.
[8] Ebru Ç. Çatalkaya, Ulusoy Bali, and Füsun Şengül, "Photochemical Degradation and Mineralization of 4-Chlorophenol," *Environmental Science and Pollution Research* 10, no. 2 (March 1, 2003): 113–20, https://doi.org/10.1065/espr2002.10.135.
[9] U. Bali, E.Ç. Çatalkaya, and F. Şengül, "Photochemical Degradation and Mineralization of Phenol: A Comparative Study," vol. 38, 2003, 2259–75, https://doi.org/10.1081/ESE-120023373.
[10] Jaimy Scaria, P.V. Nidheesh, and M.Suresh Kumar, "Synthesis and Applications of Various Bimetallic Nanomaterials in Water and Wastewater Treatment," *Journal of Environmental Management* 259 (April 1, 2020): 110011, https://doi.org/10.1016/j.jenvman.2019.110011.
[11] Stephen Sunday Emmanuel et al., "Greenly Biosynthesized Bimetallic Nanoparticles for Ecofriendly Degradation of Notorious Dye Pollutants: A Review," *Plant Nano Biology* 3 (February 1, 2023): 100024, https://doi.org/10.1016/j.plana.2023.100024.
[12] Susana Rodríguez-Couto, Johann Faccelo Osma, and José Luis Toca-Herrera, "Removal of Synthetic Dyes by an Eco-Friendly Strategy," *Engineering in Life Sciences* 9, no. 2 (April 1, 2009): 116–23, https://doi.org/10.1002/elsc.200800088.
[13] Mahmoud A.M. Al-Alwani et al., "Application of Dyes Extracted from Alternanthera Dentata Leaves and Musa Acuminata Bracts as Natural Sensitizers for Dye-Sensitized Solar Cells," *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy* 192 (March 5, 2018): 487–98, https://doi.org/10.1016/j.saa.2017.11.018.
[14] Chandrakant R. Holkar et al., "A Critical Review on Textile Wastewater Treatments: Possible Approaches," *Journal of Environmental Management* 182 (November 1, 2016): 351–66, https://doi.org/10.1016/j.jenvman.2016.07.090.
[15] S.S. Emmanuel and A.A. Adesibikan, "Bio-Fabricated Green Silver Nano-Architecture for Degradation of Methylene Blue Water Contaminant: A Mini-Review," *Water Environment Research* 93, no. 12 (2021): 2873–82, https://doi.org/10.1002/wer.1649.
[16] Angelika Tkaczyk, Kamila Mitrowska, and Andrzej Posyniak, "Synthetic Organic Dyes as Contaminants of the Aquatic Environment and Their Implications for Ecosystems: A Review," *Science of The Total Environment* 717 (May 15, 2020): 137222, https://doi.org/10.1016/j.scitotenv.2020.137222.
[17] Abida Kausar et al., "Dyes Adsorption Using Clay and Modified Clay: A Review," *Journal of Molecular Liquids* 256 (April 15, 2018): 395–407, https://doi.org/10.1016/j.molliq.2018.02.034.
[18] V.K. Gupta and Suhas, "Application of Low-Cost Adsorbents for Dye Removal – A Review," *Journal of Environmental Management* 90, no. 8 (June 1, 2009): 2313–42, https://doi.org/10.1016/j.jenvman.2008.11.017.
[19] Mohamad Amran Mohd Salleh et al., "Cationic and Anionic Dye Adsorption by Agricultural Solid Wastes: A Comprehensive Review," *Desalination* 280, no. 1 (October 3, 2011): 1–13, https://doi.org/10.1016/j.desal.2011.07.019.
[20] Feriel Bouatay et al., "Application of Modified Clays as an Adsorbent for the Removal of Basic Red 46 and Reactive Yellow 181 from Aqueous Solution," *Desalination and Water Treatment* 57, no. 29 (June 20, 2016): 13561–72, https://doi.org/10.1080/19443994.2015.1061953.
[21] Zineb B. Bouabidi et al., "Steel-Making Dust as a Potential Adsorbent for the Removal of Lead (II) from an Aqueous Solution," *Chemical Engineering Journal* 334 (February 15, 2018): 837–44, https://doi.org/10.1016/j.cej.2017.10.073.
[22] Afshin Maleki et al., "Amine Functionalized Multi-Walled Carbon Nanotubes: Single and Binary Systems for High Capacity Dye Removal," *Chemical Engineering Journal* 313 (April 1, 2017): 826–35, https://doi.org/10.1016/j.cej.2016.10.058.

[23] Guangyong Zeng et al., “Application of Dopamine-Modified Halloysite Nanotubes/PVDF Blend Membranes for Direct Dyes Removal from Wastewater,” *Chemical Engineering Journal* 323 (September 1, 2017): 572–83, https://doi.org/10.1016/j.cej.2017.04.131.
[24] V.K. Gupta and Suhas, “Application of Low-Cost Adsorbents for Dye Removal – A Review,” *Journal of Environmental Management* 90, no. 8 (June 1, 2009): 2313–42, https://doi.org/10.1016/j.jenvman.2008.11.017.
[25] Muhammad A. Rauf and S. Salman Ashraf, “Survey of Recent Trends in Biochemically Assisted Degradation of Dyes,” *Chemical Engineering Journal* 209 (October 15, 2012): 520–30, https://doi.org/10.1016/j.cej.2012.08.015.
[26] Lin Tang et al., “Sustainable Efficient Adsorbent: Alkali-Acid Modified Magnetic Biochar Derived from Sewage Sludge for Aqueous Organic Contaminant Removal,” *Chemical Engineering Journal* 336 (March 15, 2018): 160–69, https://doi.org/10.1016/j.cej.2017.11.048.
[27] Akil Ahmad et al., “Recent Advances in New Generation Dye Removal Technologies: Novel Search for Approaches to Reprocess Wastewater,” *RSC Advances* 5, no. 39 (2015): 30801–18, https://doi.org/10.1039/C4RA16959J.
[28] Tim Robinson et al., “Remediation of Dyes in Textile Effluent: A Critical Review on Current Treatment Technologies with a Proposed Alternative,” *Bioresource Technology* 77, no. 3 (May 1, 2001): 247–55, https://doi.org/10.1016/S0960-8524(00)00080-8.
[29] Rodríguez-Couto, Osma, and Toca-Herrera, “Removal of Synthetic Dyes by an Eco-Friendly Strategy.”
[30] Mohd. Rafatullah et al., “Adsorption of Methylene Blue on Low-Cost Adsorbents: A Review,” *Journal of Hazardous Materials* 177, no. 1 (May 15, 2010): 70–80, https://doi.org/10.1016/j.jhazmat.2009.12.047.
[31] Salleh et al., “Cationic and Anionic Dye Adsorption by Agricultural Solid Wastes: A Comprehensive Review.”
[32] Al-Alwani et al., “Application of Dyes Extracted from Alternanthera Dentata Leaves and Musa Acuminata Bracts as Natural Sensitizers for Dye-Sensitized Solar Cells.”
[33] Jian Wang et al., “Polyvinylpyrrolidone and Polyacrylamide Intercalated Molybdenum Disulfide as Adsorbents for Enhanced Removal of Chromium(VI) from Aqueous Solutions,” *Chemical Engineering Journal* 334 (February 15, 2018): 569–78, https://doi.org/10.1016/j.cej.2017.10.068.
[34] Mohamed Berradi et al., “Textile Finishing Dyes and Their Impact on Aquatic Environs,” *Heliyon* 5, no. 11 (November 1, 2019): e02711, https://doi.org/10.1016/j.heliyon.2019.e02711.
[35] H.A. Kiwaan et al., “Photocatalytic Degradation of Organic Dyes in the Presence of Nanostructured Titanium Dioxide,” *Journal of Molecular Structure* 1200 (January 15, 2020): 127115, https://doi.org/10.1016/j.molstruc.2019.127115.
[36] Dahir S. Idris and Arpita Roy, “Synthesis of Bimetallic Nanoparticles and Applications—An Updated Review,” *Crystals* 13, no. 4 (2023), https://doi.org/10.3390/cryst13040637.
[37] S Anu Mary Ealia and M P Saravanakumar, “A Review on the Classification, Characterisation, Synthesis of Nanoparticles and Their Application,” *IOP Conference Series: Materials Science and Engineering* 263, no. 3 (November 1, 2017): 032019, https://doi.org/10.1088/1757-899X/263/3/032019.
[38] Bartosz Klębowski et al., “Applications of Noble Metal-Based Nanoparticles in Medicine,” *International Journal of Molecular Sciences* 19, no. 12 (2018), https://doi.org/10.3390/ijms19124031.
[39] Mélanie Auffan et al., “Chemical Stability of Metallic Nanoparticles: A Parameter Controlling Their Potential Cellular Toxicity in Vitro,” *The Behaviour and Effects of Nanoparticles in the Environment* 157, no. 4 (April 1, 2009): 1127–33, https://doi.org/10.1016/j.envpol.2008.10.002.
[40] R.A. Crane and T.B. Scott, “Nanoscale Zero-Valent Iron: Future Prospects for an Emerging Water Treatment Technology,” *Nanotechnologies for the Treatment of Water, Air and Soil* 211–212 (April 15, 2012): 112–25, https://doi.org/10.1016/j.jhazmat.2011.11.073.
[41] Emmanuel et al., “Greenly Biosynthesized Bimetallic Nanoparticles for Ecofriendly Degradation of Notorious Dye Pollutants: A Review.”
[42] Adriana Zaleska-Medynska et al., “Noble Metal-Based Bimetallic Nanoparticles: The Effect of the Structure on the Optical, Catalytic and Photocatalytic Properties,” *Advances in Colloid and Interface Science* 229 (March 1, 2016): 80–107, https://doi.org/10.1016/j.cis.2015.12.008.
[43] Anindita Behera et al., “Chapter 25 - Bimetallic Nanoparticles: Green Synthesis, Applications, and Future Perspectives,” in *Multifunctional Hybrid Nanomaterials for Sustainable Agri-Food and Ecosystems*, ed. Kamel A. Abd-Elsalam (Elsevier, 2020), 639–82, https://doi.org/10.1016/B978-0-12-821354-4.00025-X.

[44] Tawfik A. Saleh, "Nanomaterials: Classification, Properties, and Environmental Toxicities," *Environmental Technology & Innovation* 20 (November 1, 2020): 101067, https://doi.org/10.1016/j.eti.2020.101067.
[45] Qiong Wu et al., "Mechanical Properties of Nanomaterials: A Review," Nanotechnology Reviews, 9, no. 1 (2020): 259–73, https://doi.org/10.1515/ntrev-2020-0021.
[46] A. L. Padilla-Cruz et al., "Synthesis and Design of Ag–Fe Bimetallic Nanoparticles as Antimicrobial Synergistic Combination Therapies against Clinically Relevant Pathogens," *Scientific Reports* 11, no. 1 (March 5, 2021): 5351, https://doi.org/10.1038/s41598-021-84768-8.
[47] Idris and Roy, "Synthesis of Bimetallic Nanoparticles and Applications—An Updated Review."
[48] M. Bernal et al., "CO2 Electroreduction on Copper-Cobalt Nanoparticles: Size and Composition Effect," *Nano Energy* 53 (November 1, 2018): 27–36, https://doi.org/10.1016/j.nanoen.2018.08.027.
[49] Mayur Valodkar et al., "Synthesis and Anti-Bacterial Activity of Cu, Ag and Cu–Ag Alloy Nanoparticles: A Green Approach," *Materials Research Bulletin* 46, no. 3 (March 1, 2011): 384–89, https://doi.org/10.1016/j.materresbull.2010.12.001.
[50] O.V. Bakina et al., "«Janus»-like Cu-Fe Bimetallic Nanoparticles with High Antibacterial Activity," *Materials Letters* 242 (May 1, 2019): 187–90, https://doi.org/10.1016/j.matlet.2019.01.105.
[51] E.L. de León-Quiroz et al., "Synthesis and Characterization of Alloys and Bimetallic Nanoparticles of CuNi Prepared by Sol-Gel Method," *MRS Online Proceedings Library* 1479, no. 1 (December 1, 2012): 9–14, https://doi.org/10.1557/opl.2012.1590.
[52] Meixia Wu et al., "Cu@Pt Catalysts Prepared by Galvanic Replacement of Polyhedral Copper Nanoparticles for Polymer Electrolyte Membrane Fuel Cells," *Electrochimica Acta* 306 (May 20, 2019): 167–74, https://doi.org/10.1016/j.electacta.2019.03.111.
[53] M. Meena Kumari, John Jacob, and Daizy Philip, "Green Synthesis and Applications of Au–Ag Bimetallic Nanoparticles," *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy* 137 (February 25, 2015): 185–92, https://doi.org/10.1016/j.saa.2014.08.079.
[54] Amiripour, Ghasemi, and Azizi, "A Novel Non-Enzymatic Glucose Sensor Based on Gold-Nickel Bimetallic Nanoparticles Doped Aluminosilicate Framework Prepared from Agro-Waste Material."
[55] Chaturvedi et al., "Two Birds with One Stone: Oyster Mushroom Mediated Bimetallic Au-Pt Nanoparticles for Agro-Waste Management and Anticancer Activity."
[56] Appa et al., "Structure Controlled Au@Pd NPs/rGO as Robust Heterogeneous Catalyst for Suzuki Coupling in Biowaste-Derived Water Extract of Pomegranate Ash."
[57] Amiripour, Azizi, and Ghasemi, "Gold-Copper Bimetallic Nanoparticles Supported on Nano P Zeolite Modified Carbon Paste Electrode as an Efficient Electrocatalyst and Sensitive Sensor for Determination of Hydrazine."
[58] Appa et al., "Structure Controlled Au@Pd NPs/rGO as Robust Heterogeneous Catalyst for Suzuki Coupling in Biowaste-Derived Water Extract of Pomegranate Ash."
[59] Oruç et al., "Green Synthesis of Biomass-Derived Activated Carbon/Fe-Zn Bimetallic Nanoparticles from Lemon (Citrus Limon (L.) Burm. f.) Wastes for Heterogeneous Fenton-like Decolorization of Reactive Red 2."
[60] Lozhkomoev et al., "Development of Fe/Cu and Fe/Ag Bimetallic Nanoparticles for Promising Biodegradable Materials with Antimicrobial Effect."
[61] Lin Chen et al., "Fe—Ti Oxide Nano-Adsorbent Synthesized by Co-Precipitation for Fluoride Removal from Drinking Water and Its Adsorption Mechanism," *Emerging Particle Technology* 227 (September 1, 2012): 3–8, https://doi.org/10.1016/j.powtec.2011.11.030.
[62] Sultana et al., "Green Synthesis of Graphene Oxide (GO)-Anchored Pd/Cu Bimetallic Nanoparticles Using Ocimum Sanctum as Bio-Reductant: An Efficient Heterogeneous Catalyst for the Sonogashira Cross-Coupling Reaction."
[63] Zhang et al., "Pd@Au Bimetallic Nanoplates Decorated Mesoporous MnO2 for Synergistic Nucleus-Targeted NIR-II Photothermal and Hypoxia-Relieved Photodynamic Therapy."
[64] Doğan Özcan et al., "Preparation and Characterization of Bimetallic Pd–Zn Nanoparticles on Carbon for Borohydride Electrooxidation."
[65] Sevim and Kaplan, "Ketjen Black Supported Monodisperse Nickel–Platinum Alloy Nanoparticles for the Efficient Catalyst in the Hydrolytic Dehydrogenation of Ammonia Borane."
[66] Chen et al., "Synthesis of Ni–Ru Alloy Nanoparticles and Their High Catalytic Activity in Dehydrogenation of Ammonia Borane."

[67] Masoumeh Pak et al., "Nickel-Gold Bimetallic Nanostructures with the Improved Electrochemical Performance for Non-Enzymatic Glucose Determination," *Journal of Electroanalytical Chemistry* 900 (November 1, 2021): 115729, https://doi.org/10.1016/j.jelechem.2021.115729.
[68] Shelby L. Foster et al., "Removal of Synthetic Azo Dye Using Bimetallic Nickel-Iron Nanoparticles," ed. Victor M. Castaño, *Journal of Nanomaterials* 2019 (March 19, 2019): 9807605, https://doi.org/10.1155/2019/9807605.
[69] Seyed Ghorban Hosseini, Setareh Gholami, and Mojtaba Mahyari, "Superb Catalytic Properties of Nickel Cobalt Bimetallic Nanoparticles Immobilized on 3D Nitrogen-Doped Graphene for Thermal Decomposition of Ammonium Perchlorate," *Research on Chemical Intermediates* 45, no. 3 (March 1, 2019): 1527–43, https://doi.org/10.1007/s11164-018-3677-5.
[70] Umar et al., "Synthesis and Characterization of Pd-Ni Bimetallic Nanoparticles as Efficient Adsorbent for the Removal of Acid Orange 8 Present in Wastewater."
[71] Hashemizadeh and Biglari, "Cu:Ni Bimetallic Nanoparticles: Facile Synthesis, Characterization and Its Application in Photodegradation of Organic Dyes."
[72] Kubendiran et al., "Removal of Methyl Orange from Aqueous Solution Using SRB Supported Bio-Pd/Fe NPs."
[73] Jing et al., "Zn/Fe Bimetallic Modified Spartina Alterniflora-Derived Biochar Heterostructure with Superior Catalytic Performance for the Degradation of Malachite Green."
[74] Krishnan et al., "Degradation of Azo Dye RED ME4BL Treated with Immobilised Bimetallic Zero-Valent Iron Nanoparticles Doped with Palladium."
[75] Idris et al., "Bio-Fabrication of Silver–Zinc Bimetallic Nanoparticles and Its Antibacterial and Dye Degradation Activity."
[76] Luo et al., "One-Step Green Synthesis of Bimetallic Fe/Pd Nanoparticles Used to Degrade Orange II."
[77] Gautam et al., "Synthesis of Bimetallic Fe–Zn Nanoparticles and Its Application towards Adsorptive Removal of Carcinogenic Dye Malachite Green and Congo Red in Water."
[78] Sarvari et al., "Removal of Methyl Orange from Aqueous Solutions by Ferromagnetic Fe/Ni Nanoparticles."
[79] Ali et al., "Ag–Cu Embedded SDS Nanoparticles for Efficient Removal of Toxic Organic Dyes from Water Medium."
[80] S.S et al., "Heteronuclear Nanoparticles Supported Hydrotalcites Containing Ni(II) and Fe(III) Stable Photocatalysts for Orange II Degradation."
[81] Wang et al., "Iron–Copper Bimetallic Nanoparticles Supported on Hollow Mesoporous Silica Spheres: The Effect of Fe/Cu Ratio on Heterogeneous Fenton Degradation of a Dye."
[82] Lin et al., "Degradation of Scarlet 4BS in Aqueous Solution Using Bimetallic Fe/Ni Nanoparticles."
[83] Mohan and Devan, "Photocatalytic Activity of Ag/Ni Bi-Metallic Nanoparticles on Textile Dye Removal."
[84] Suvarna et al., "Cyclea Peltata Leaf Mediated Green Synthesized Bimetallic Nanoparticles Exhibits Methyl Green Dye Degradation Capability."
[85] Dye, "Plant Mediated Green Synthesis of Novel Bimetallic Nanoparticles: Characterization and Investigation of Photocatalytic Activity for Degradation of Malachite."
[86] Sun, Lee, and Park, "Bimetallic CuPd Alloy Nanoparticles Decorated ZnO Nanosheets with Enhanced Photocatalytic Degradation of Methyl Orange Dye."
[87] Das et al., "Sericin Mediated Gold/Silver Bimetallic Nanoparticles and Exploration of Its Multi-Therapeutic Efficiency and Photocatalytic Degradation Potential."
[88] Al-nayili et al., "A Novel Bimetallic (Au-Pd)-Decorated Reduced Graphene Oxide Nanocomposite Enhanced Rhodamine B Photocatalytic Degradation under Solar Irradiation."
[89] Ameen et al., "Microwave-Assisted Synthesis of Vulcan Carbon Supported Palladium–Nickel (PdNi@VC) Bimetallic Nanoparticles, and Investigation of Antibacterial and Safranine Dye Removing Effects."
[90] Idris and Roy, "Biogenic Synthesis of Ag–CuO Nanoparticles and Its Antibacterial, Antioxidant, and Catalytic Activity."
[91] Ma et al., "Cerium-Cobalt Bimetallic Metal–Organic Frameworks with the Mixed Ligands for Photocatalytic Degradation of Methylene Blue."
[92] Mohammed Al-Balawi, Zaheer, and Kosa, "Silver-Platinum Bimetallic Nanoparticles as Heterogeneous Persulfate Activator for the Oxidation of Malachite Green."
[93] Robinson et al., "Remediation of Dyes in Textile Effluent: A Critical Review on Current Treatment Technologies with a Proposed Alternative."

[94] Gergo Mezohegyi et al., "Towards Advanced Aqueous Dye Removal Processes: A Short Review on the Versatile Role of Activated Carbon," *Journal of Environmental Management* 102 (July 15, 2012): 148–64, https://doi.org/10.1016/j.jenvman.2012.02.021.
[95] Sarro et al., "ZnO-Based Materials and Enzymes Hybrid Systems as Highly Efficient Catalysts for Recalcitrant Pollutants Abatement."
[96] Al-Alwani et al., "Application of Dyes Extracted from Alternanthera Dentata Leaves and Musa Acuminata Bracts as Natural Sensitizers for Dye-Sensitized Solar Cells."
[97] Robinson et al., "Remediation of Dyes in Textile Effluent: A Critical Review on Current Treatment Technologies with a Proposed Alternative."
[98] Pan et al., "Removal of Azo Dye in an Up-Flow Membrane-Less Bioelectrochemical System Integrated with Bio-Contact Oxidation Reactor."
[99] Abbasi, "Removal of Dye by Biological Methods Using Fungi."
[100] Kandisa et al., "Dye Removal by Adsorption: A Review."
[101] Adegoke and Bello, "Dye Sequestration Using Agricultural Wastes as Adsorbents."
[102] Rodríguez-Couto, Osma, and Toca-Herrera, "Removal of Synthetic Dyes by an Eco-Friendly Strategy."
[103] Hethnawi et al., "Polyethylenimine-Functionalized Pyroxene Nanoparticles Embedded on Diatomite for Adsorptive Removal of Dye from Textile Wastewater in a Fixed-Bed Column."
[104] Ahmad et al., "Recent Advances in New Generation Dye Removal Technologies: Novel Search for Approaches to Reprocess Wastewater."
[105] De Gisi et al., "Characteristics and Adsorption Capacities of Low-Cost Sorbents for Wastewater Treatment: A Review."
[106] Yagub et al., "Dye and Its Removal from Aqueous Solution by Adsorption: A Review."
[107] Nguyen and Juang, "Treatment of Waters and Wastewaters Containing Sulfur Dyes: A Review."
[108] Tang et al., "Sustainable Efficient Adsorbent: Alkali-Acid Modified Magnetic Biochar Derived from Sewage Sludge for Aqueous Organic Contaminant Removal."
[109] Datta, Christena, and Rajaram, "Enzyme Immobilization: An Overview on Techniques and Support Materials."
[110] Ganiyu et al., "Boron-Doped Activated Carbon as Efficient and Selective Adsorbent for Ultra-Deep Desulfurization of 4,6-Dimethyldibenzothiophene."
[111] Bouabidi et al., "Steel-Making Dust as a Potential Adsorbent for the Removal of Lead (II) from an Aqueous Solution."
[112] dos Santos, Cervantes, and van Lier, "Review Paper on Current Technologies for Decolourisation of Textile Wastewaters: Perspectives for Anaerobic Biotechnology."
[113] Crini, "Non-Conventional Low-Cost Adsorbents for Dye Removal: A Review."
[114] Wang et al., "Polyvinylpyrrolidone and Polyacrylamide Intercalated Molybdenum Disulfide as Adsorbents for Enhanced Removal of Chromium(VI) from Aqueous Solutions."