A review on transition metal oxides based nanocomposites, their synthesis techniques, different morphologies and potential applications

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Abstract. In the field of nanotechnology and nanoscience, transition metal oxides based nanocomposites (TMONCs) are promising for various application uses such as Supercapacitors, Sensors, Bactericidal properties, Photocatalytic Degradation, Solar Cells etc. Modification of transition metal oxide nanoparticles (TMONPs) to TMONCs by doping/mixing of another transition metal and metal oxide, carbon based nanoparticles, conducting polymers etc. to achieve enhanced surface area, increasing surface activities or number of active surface sites, reducing electron-hole recombination, increasing charge transfer processes etc. have been reported in literature. These improved properties are the possible reason for the enhancement in its practical applications efficiencies. This review summarizes recent development on transition metal oxides based nanocomposites for different potential applications. Also synthesis methods of transition metal oxide based nanocomposites have obtained an increasing attractions to achieve cost effectiveness and environment friendly routes of synthesis with high rate of production, high yield of product and also less toxic waste production. Transition metal oxides nanocomposites have been fabricated by various methods such as Microwave assisted synthesis technique, Sol-Gel method, Biosynthesis method, Co-precipitation process, Simple Chemical method etc. Different morphologies of transition metal oxides based nanocomposites have been summarized in this review article.

Herein, this paper discuss about several reported synthesis techniques, various characterization techniques used for structural and surface properties identifications, different morphologies and various potential applications of transition metal oxide based nanocomposites.

Keywords: Nanocomposites; Biosynthesis; Co-precipitation; Sol-Gel method; Supercapacitors; Sensors; Photocatalytic Degradation

1. Introduction

A field of applied science which outlines fabrication, characterization and application of materials within at the minimum one dimension less than 100nm is referred to nanotechnology. Herein, a particle size within 1-100nm range displays drastically changes in chemical properties and physical properties contrast to corresponding bulk materials that bring about many opportunities as well as challenges. Nanoscience and Nanotechnology is a multidisciplinary field which integrate chemistry, physics, material science and biology etc. The use of nanoscience and nanotechnology for biomedical,
sensing, energy storage, energy generation, water treatment and other applications have potential changed the landscape of many issues of environment, energy, health etc [1-6].

Nanocomposites are the composites with at the minimum one of the dimensions is less than 100nm. Nanocomposites fascinated the attention of scientists worldwide by their unique design possibilities and multifunctional properties. Nanocomposites are the materials of the era due to their multifunctional capabilities. Researchers all over the world are working on maturing of new approach of synthesis of nanocomposites to achieve nanocomposites with unique properties. Research is focused on improvement in effectiveness, efficiency, durability of practical application of nanocomposites by mixing suitable constituents for the synthesis of particular nanocomposites [7-9].

Transition metal oxide nanoparticles turned out to be widely explored for many applications such as supercapacitors, sensors, solar cell and Photocatalytic applications etc [10-14]. To improve their efficiency further research have been reported modification of these transition metal oxides mixed/doping with other nanoparticles such as carbon based nanoparticles, metal oxide nanoparticles, conducting polymers etc, it might be useful for new applications in different field of sciences such as chemistry, physics, biology, material science etc. Modification of transition metal oxide based nanoparticles achieve new sets of properties such as enhance surface area, enhanced surface activities, enhanced porosity, decrease in electron hole recombination, increase in conductivities etc [13,24,25,140,141]. In recent studies, transition metal oxide based nanocomposites are attracted considerable attention as versatile and favorable material in almost all fields of sciences for their wide range of practical applications. Many transition metal oxides based nanocomposites are reported in literature for their useful vital practical applications such as Carbon nanotube - ZnO nanocomposite reported as electrode material for supercapacitor escorted by maximum calculated specific capacitance of 323.9 Fg$^{-1}$ [15], Synthesized CuO-ZnO nanocomposite were reported as antibacterial agent [16], ZnO/CuO nanocomposites was reported with humidity sensor property [17]. And many other such as GO/ZnO nanocomposite for phctocatalytic degradation of basic fuchsin dye [18], Polyaniline/ZnO nanocomposite as sensor [19], Graphene – ZnO nanocomposite as Photovoltaic cells [20] etc were reported in last few years.

In this Review we are going to study brief about synthesis techniques of TMONCs, such as co-precipitation technique, hydrothermal technique, sol-gel technique and wet chemical technique. Also we are going to study different characterization techniques with have been used in literature for structural and surface properties identifications of TMONCs. Morphologies have been proven as an important parameter for nanomaterials study; we are going to reviewed some of the reported morphologies of TMONCs. This article also reviewed various practical applications of various transition metal oxide based nanocomposites in the field of health, sensors, energy storage/generation and nature remediation.

2. Several synthesis techniques of TMONCs

The most common nanocomposites currently implemented are transition metal based nanocomposites, Transition Metal Oxide based nanocomposites (TMONCs), Carbon based nanocomposites and Polymer based nanocomposites. Among these, Transition metal oxide based nanocomposites are most interested due to their unique properties. As nanomaterials shows various sized based properties, the synthesis of nanomaterials has been considered as the preference field in the nano-science. Method of synthesis governs morphologies, physical properties and chemical properties of synthesized nanomaterials which further govern various potential applications of these nanomaterials. Researcher are focused to introduce new method of synthesis which are cost efficient, fast, environment friendly and products show good practical application with high efficiency. This article summarizes the potentially used synthesis method of transition metal oxide based nanocomposites. Currently, the
developed method are like Hydrothermal method, Sol – Gel method and Chemical vapor deposition. Now, we discuss these methods one by one in brief.

2.1. Co-precipitation technique

This method is a very important technique to synthesize the nanomaterials. It has been explored that fabrication of nanomaterials in solution chemistry is preferred over solid and vapor phase for its properties such as short diffusion paths, more purities in products, less agglomeration, it simplicity, uniform and controllable particle size and cost effective [21-25]. Hadi Eslami et al. has reported aeration co-precipitation technique for mesoporous Iron-Manganese bi-metal oxide nanocomposite fabrication. Where, molar ratio of 2:1 of Manganese sulfate and ferric chloride were separately prepared and mixed at 70°C with stirring at 50rpm. 10% NH$_4$OH was added to get pH of 9 and kept at 50rpm for 4 hours to get precipitated nanocomposites [26]. In a similar manner NiFeO$_4$ nanocomposite was fabricated by chemical precipitation by using 1:1 molar ratio of FeSO$_4$.7H$_2$O and NiSO$_4$.7H$_2$O at pH= 12. Herein, hydrazine hydrate was acting as a reducing agent [27].

Many practically applicable transition metal oxide based nanocomposites were reported in literature with co-precipitation route of fabrication such as CO$_2$ hydrogenation to methanol was reported by Thongthai witoon on Cu/ZnO [29], Zno-CuO nanocomposite had show antibacterial properties [25]. Graphene oxide / Fe$_3$O$_4$ nanocomposite used for waste water treatment was synthesized by shengyan Pu with In situ co-precipitation method [29] etc. Also several type of transition metal oxide combination were also reported in several years such as CuWO$_4$, CuWO$_4$ / NiO [21], NiO-ZnO [24], CeO$_2$/CuO.ZnO [30], CeO$_2$/ZnO/ZnAl$_2$O$_4$ ternary nanocomposite [23], ZnO/Ag [22] and many more. This shows that co-precipitation method is one of the effective, easy and vital techniques for fabrication of transition metal based nanocomposites.

2.2. Sol–Gel method

Physical method like (ball milling, laser ablation, sputtering) and chemical methods like (sol-gel method, co-precipitation method, chemical vapor deposition) are the general method of synthesis for transition metal oxide based nanocomposites. Where, sol-gel method is another fascinating type of wet chemical methods. Sol-Gel method is consist of a route where, formation of a Sol followed by formation of a Gel and then drying of the solvent. Various applications such as catalysis, sensing, antibacterial etc. are widely depends on size, morphology, dimensions, composition and structure of nanomaterial. Sol-Gel technique of synthesis is vital technique, because it is easy to operation, low temperature reaction conditions, defined size, high purity and homogeneity of product [31-34].

Ardiansyah Taufik et al. was able to fabricate ternary CuO/TiO$_2$/ZnO nanocomposites by simple sol-gel method where, that synthesized transition metal oxide based nanocomposite enhanced Photocatalytic degradation of organic dye (methylene blue (MB)) [35]. Degradation of MB organic dye was also reported by NiO/TiO$_2$ nanocomposite which also prepared by sol-gel method [36]. Alexis Lavin et al. had prepared ZnO/CuO nanomaterial by sol-gel technique dissolved and dispersed of calculated amount of zinc nitrate and copper oxide in the solvent, afterword the PVA was add on to that previous solution. And followed by stirring with in ultrasound bath at 353K to get homogeneous gel. That gel was dried at 773K for 8 hours to get required nanocomposite [37]. TiO$_2$-Ag nanocomposite was reported with antibacterial activity against E. coli and was also fabricated by sol-gel route of synthesis [38]. Literature shows sol-gel synthesis technique is a flexible approach to obtaining a diverse range of transition metal oxide based nanocomposites such as CNTs/TiO$_2$ [39], WO$_3$/TiO$_2$ [40], ZnO/Reduced graphene oxide [41], ZnO-SiO$_2$ [42], CdO-ZnO [43], CoTiO$_3$/CoFe$_2$O$_4$ [44] and ZnO-SnO$_2$ [45].
2.3. Chemical vapor deposition

Nowadays, the researchers have shown a big attraction in refining and developing efficient technique for fabrication of TMONCs. One such method is chemical vapor deposition. This method has matured significantly over last few years. Chemical vapor deposition is deposition of different precursors onto a substrate [46-49].

Literature is full of transition metal oxide synthesized by chemical vapor deposition. Jian Shan Ye et al. prepared a supercapacitor electrode material of Aligned carbon nanotube-Ruthenium Oxide by chemical vapor deposition [50]. Davide Barreca et al reported ZnO-TiO$_2$ synthesized by same technique and shows application as gas sensor. Where, TiO$_2$ nanoparticles were dispersed on ZnO nanoplatelets [51]. Aerosol Assisted chemical vapor deposition of Slippery Liquid Infused porous TiO$_2$/SnO$_2$ nanocomposite was reported by Frances L. Heale et al [52]. Chemical vapor deposition is a vital route of synthesis of TMONCs. As Lei Ma et al. fabricated Fe-Ni doped TiO$_2$ and used this nanocomposite to synthesized CNTs/Fe-Ni/ TiO$_2$ by fluidized bed chemical vapor deposition [53]. One-step synthesis of nanocomposite MWCNT/ZnO also reported in literature by taking co-chemical vapor deposition route [54].

2.4. Hydrothermal technique

Several strategies were tested for synthesizing transition metal oxide based nanocomposites. Hydrothermal method was extensively utilized in the fabrication of transition metal oxide based nanocomposites. Hydrothermal method is easy, uncomplicated, fast and cost-effective in contrast with other sophisticated synthesis routes. Also products are formed directly from the solution with control size, shape, and composition. Even calcinations and milling is not required in many cases of hydrothermal synthesis. Hydrothermal technique of synthesis takes place at above ambient temperature and pressure. Where, a sealed solution is heated [55-59].

Yupeng Gao et al. synthesized TiO$_2$/Ti$_3$C$_2$ nanocomposite by hydrothermal method. Where, he prepared titanium sulfate solution in deionized water and afterward added 500mg TiC$_2$ to that solution. That mixture was stirred to get homogeneous solution and kept in Teflon autoclave. That autoclave was kept in oven at 180°C for 18h. TiO$_2$/Ti$_3$C$_2$ then separated, washed and dried in vacuum at 80°C for 10 hours. The fabricated TiO$_2$/Ti$_3$C$_2$ nanocomposite was able to degrade organic dye (Methyl orange (MO)) photocatalytically [60]. Similar manner using Teflon-lined autoclave Zhang et al. reported synthesis of ZnFe$_2$O$_4$ nanocomposites. Certain amount of ZnSO$_4$.7H$_2$O, FeCl$_3$.6H$_2$O, and sodium dodecyl sulfate were added and dissolved in deionized water. After that, 10ml of NaOH was also added, after stirring solution was poured to Teflon lined autoclave followed by heating for 15h at certain temperature. Transition metal oxide based nanocomposite then washed and dried [61]. Herein, we reviewed hydrothermal synthesis of some transition metal oxide based nanocomposites. Aijian Wang et al prepared TiO$_2$-reduced graphene oxide nanocomposites by facile hydrothermal method [62]. Hydrothermal synthesis of CoFe$_2$O$_4$/graphene nanocomposites by using graphene oxide and aqueous precursors solution of Fe(NO$_3$)$_3$.9H$_2$O and Co(NO$_3$)$_2$.6H$_2$O [63]. From the literature, there have been reported synthesis of number of TMONCs by simple hydrothermal method such as Carbon nanotube/Cubic Fe$_3$O$_4$ [64], α-Fe$_2$O$_3$-ZnO [65], MnO$_2$-CNT [66], TiO$_2$/reduced graphene oxide [67] and CuO-ZnO [68].

2.5. Wet Chemical synthesis technique

Wet chemical synthesis technique of fabrication of TMONCs is very simple, cost effective and reproducible. It also has some disadvantages of producing chances of having defects within the crystal because of low temperature reaction conditions than other methods [69].
Different researchers have been prepared transition metal oxide based nanocomposites by simple wet chemical method using different precursors. L. Zgura et al prepared ZnO-CdS nanocomposites by two step procedure where in first step he was synthesized CdS nanoparticle using Na$_2$S and Cd(NO$_3$)$_2$·4H$_2$O in 1:1 molar ratio at room temperature with 30min stirring. After that, in second step this synthesized CdS nanoparticle were dispersed in water and Zn(NO$_3$)$_2$ and NaOH were added drop wise, then this whole solution has been stirred for 30min at room temperature. Then that obtained powder form product was dried at 100ºC for 2 hours to get ZnO-CdS nanocomposite [70]. Alejandra Mazabuel-Collazos et al synthesized ZnO-TiO$_2$ nanocomposite by using Zinc acetate dehydrate and titanium terabutoxide as precursors [71]. Wet chemical method is very useful and easy. Many transition metal oxide based nanocomposites are reported in literature. As, CdO-MgO-Fe$_2$O$_3$ multi metal based nanocomposite was synthesized by simple wet chemical method which was showing photo-catalytic properties [72]. Sharif Hussein Sharif Zein et al reported wet chemical synthesis of manganese oxide/carbon nanotube nanocomposite [73]. SnO$_2$/Fe$_2$O$_3$ nanocomposites also synthesized by wet chemical method [74]. Wet chemical method synthesized nanocomposites with different practical applications such as, High quality MgO:CuO nanocomposite were obtained by wet chemical method was reported with complete catalytic degradation of Rhodamine B within 15 minutes and 91% removal of 4-chlorophenol in 300 minutes [76]. Tongtong Jiang et al prepared S doped Co$_3$O$_4$ nanosheets/reduced graphene oxide by wet chemical method to achieve a dye sensitized solar cell [77].

2.6. Microwave assisted Method

Process of absorption and transformation of electromagnetic energy into heat energy is possesses heating from microwave radiation. Microwave radiations have been use in many organic and inorganic reactions. Fabrication of TMOCNs by microwave assisted method is a greener and environment friendly route of synthesis. Microwave assisted heating for the fabrication of TMOCNs have several advantages like faster the reaction, less energy required, controllable and uniform particle size compared to conventional heating [78-83].

K. Karthik et al synthesized CdO-NiO-ZnO using simple Microwave assisted synthesis for removal of MB dye photocatalytically and for antibacterial activity. They were mixed Cadmium acetate dihydrate solution and Nickel acetate tetrahydrate solution and kept for stirring for 30 minutes at 303K. After that Zn(CH$_3$COO)$_2$·2H$_2$O and NaOH solutions were added to aforementioned solution and kept for stirring for 1hour at 303K and irradiated for 30 minutes in a microwave oven in the convection mode. After washing with ethanol and double distilled water, they once more kept that powder for irradiation for 15 minutes. Synthesized powder was calcinated at 673K for 2 hours [84]. K. Karthik et al have also synthesized CdO-ZnO TMOCNs by simple microwave assisted synthesis technique for bactericial activity. He took certain ratio of ZnCl$_2$ and CdCl$_2$·2H$_2$O and dissolved them in water. After stirring for 15min he added ammonia solution drop wise to maintain pH 8. Then that solution was irradiated in microwave oven for 20minutes. After washing precipitate again irradiated with microwave for another 10 minutes and then that powder was kept in 773K for 4 hours and was to get CdO-ZnO nanocomposite [85].

Many TMOCNs have been synthesized by microwave assisted synthesis technique for their different potential uses, for example Pingtao Dou et al. were able to fabricated Ag/ZnO/graphene for Photocatalytic activity [86], Li et al prepared Ag/ZnO-TiO$_2$ for Photocatalytic degradation of Rhodamine B [87], Rajesh Kumar et al reported Mn$_3$O$_4$-Fe$_2$O$_3$/Fe$_3$O$_4$/rGO nanocomposites for supercapacitor application [88].
2.7. Biological Method

The well recognized classical chemical methods of nanomaterials synthesis have their own disadvantages as, using hazardous reagents, mostly high temperature reaction conditions, chemical waste production and other. Wherein, biological method of nanomaterials synthesis plants and microorganisms are using a capping agents. Therefore this method is environmental friendly, non-toxic and simple method of synthesis of nanomaterials. Nowadays, the biological method of synthesis of transition oxide based nanocomposites is an interesting issue of nanoscience. Among both organisms and plants, the plants are easy available, easy to handle and required no special conditions that why they seem to be best candidates for biological synthesis of transition metal oxide based nanocomposites [89-92]. Different parts of plants such as roots, bark, leaves, fruits etc can be used for the biological method of transition metal oxide based nanocomposites synthesis, some of the examples are given below.

Qiujie Liu et al synthesized Fe,Cu oxide nanocomposite by using *Loquat* leaf extract through biological synthesis method [93]. Ramin Mohammadi-Alouchech et al have been prepared ZnO/CuO nanocomposite by dissolving certain amounts of zinc nitrate and copper acetate in deionized water, after that some amount of *Mentha longifolia* leaf extract was added followed by NaOH to achieve pH of 10. That solution was then irradiated for 10 minutes in the microwave oven to get ZnO/CuO nanocomposite with antibacterial applications [94]. Elias E. Elemike et al also fabricated Cu$_2$O/CuO-ZnO nanocomposites with Anticancer application by simply using *Alchornea cordifolia* leaf extract [95]. Yoki Yulizar also reported synthesis of TiO$_2$ nanoparticle using *Averrhoa bilimbi* fruits extract, Au nanoparticle using *Pandanus amaryllifolius* leaves extract and by using these already synthesized TiO$_2$ nanoparticles he was able to synthesized Au/TiO$_2$ nanocomposite with help of HAuCl$_4$ and *Pandanus amaryllifolius* leaves extract [96].

Many plant extract mediated synthesized nanocomposites have been reported in literature such as Ag-ZnO nanocomposite synthesized by using leaf extract of *Trigonella foenum-graecum* [97], Fe$_3$O$_4$-Ag TMONCs by using leaf extract of *Psidium guajava* [98], ZnO-NiO nanocomposite by using *Azadirachta indica* (Neem) leaves extract [92], ZnFe$_2$O$_4$ nanocomposite by using *Moringa Oleifera* extract [91], ZnO/CuO nanocomposite prepared by using seed bark extract of *Theohroma cacao* [89] and more. Figure1. Shows the general mechanisms involved in synthesis of nanomaterial by plant extract.

![Figure 1. Simplified block diagram of general mechanisms involved in synthesis of nanomaterials by plant extract using above literature survey [89-96].](image-url)
2.8. Ball-milling method

Ball-milling is a physical or mechanical method of transition metal oxide based nanocomposite synthesis. In this process reduction of particle size to get more fine particles by applying impact force and friction by blending or crushing them. Also size of product and time of synthesis highly depend on milling energy applied during milling. Ball-milling synthesis route is an important type of top-down approach of nanomaterials fabrications. Ball-milling technique of synthesis of transition metal oxide based nanocomposite has its own advantages such as environmental friendly, cost effective, fine particle size etc [99-102].

Henry Kahimbi et al. synthesized NiO/reduced graphene oxide by ball-milling method. For that, Graphene oxide and nickel powder in weight ratio 1:1 were kept in ball-mill and milled for total 1h under dried condition at 1200rpm to get NiO/Reduced graphene oxide nanocomposite [103]. Funda Aksoy Akgul et al also prepared Ti doped ZnO nanocomposite using ball milling method. He has taken certain amounts of ZnO and TiO₂ in a ball-mill and milled for 20h with 500rpm to get desired product [104]. Rahul Mundiyaniyil Thankachan et al. fabricated ZnFe₂O₄-C nanocomposite by ball milling method of synthesis. Already synthesized ZnFe₂O₄ nanoparticle and carbon black powder were taken in a milling container. And milling was done for 24h at 75 rpm under argon atmosphere of 100 kPa to get ZnFe₂O₄-C nanocomposite [102]. Other researcher also reported synthesis by ball milling method few of them are, Xingxing Gu et al. synthesized ZnO/sulphur/carbon nanotubes nanocomposite [105], Sunil P. Lonkar et al. prepared ZnO-graphene nanocomposite [100] and many more.

It is clear from above study that TMONCs have been synthesized by numerous synthesis methods with many application properties. Previous researchers have reported various synthesized transition metal oxide based nanocomposite by various routes of synthesis methods as shown in Table1.

Table1. Synthesized transition metal oxide based nanocomposites by various synthesis routes.

| S.N | Transition metal oxide based nanocomposites | Precursor used | Synthesis Routes | Ref. |
|-----|------------------------------------------|----------------|-----------------|-----|
| 1   | ZnO-CuO                                  | ZnCl₂ and CuCl₂ | Co-precipitation method | 25  |
| 2   | NiFe₂O₄                                  | FeSO₄·7H₂O and NiSO₄·7H₂O | Co-precipitation method | 27  |
| 3   | CeO₂/ZnO/ZnAl₂O₄                         | Ce(NO₃)₂·6H₂O, Al(NO₃)₃·9H₂O and Zn(NO₃)₂·4H₂O | Co-precipitation method | 23  |
| 4   | ZnO-SnO₂                                 | Zn(CH₃COO)₂·2H₂O and SnCl₄·5H₂O | Sol-Gel technique | 45  |
| 5   | CdO-ZnO                                 | Cd(NO₃)₂·4H₂O and Zn(NO₃)₂·6H₂O | Sol-Gel technique | 43  |
| 6   | TiO₂-Ag                                 | Titanium tetraisopropoxide and Silver nitrate | Sol-Gel technique | 38  |
| 7   | ZnO-TiO₂                                 | Ti(OiPr)₂ (dpm); Zn(hfa)₂.TMEDA (OiPr: isopropoxy; dpm: 2,2,6,6-tetramethyl3,5-heptanedionate; hfa: 1,1,1,5,5,5-hexafluoro-2,4-pentanedionate; and TMEDA: N,N,N′,N′-tetramethylethlenediamine | Chemical vapor deposition | 51  |
| 8   | TiO₂/SnO₂                               | Titanium isopropoxide and Butyltin trichloride | Chemical vapor deposition | 52  |
| No | Chemical formula | Description | Method |
|----|------------------|-------------|--------|
| 9  | CNT/Fe-Ni/TiO₂ | Tetrabutylorthotitanate, Ni(NO₃)₂.6H₂O, Fe(NO₃)₃.9H₂O and acetylene | Chemical vapor deposition |
| 10 | CoFe₂O₄/graphene | Graphite powder, Co(NO₃)₂.6H₂O and Fe(NO₃)₃.9H₂O | Hydrothermal technique |
| 11 | α-Fe₂O₃-ZnO-Au | FeCl₃.6H₂O, ZnSO₄.7H₂O and HAuCl₃.3H₂O | Hydrothermal technique |
| 12 | MnO₂-CNT | Multi-wall carbon nanotubes (CNTs) and MnSO₄.H₂O | Hydrothermal technique |
| 13 | ZnO/Au | HAuCl₃.3H₂O and Zinc Acetate | Wet chemical method |
| 14 | MgO:CuO | Mg(NO₃)₂ and Cu(NO₃)₃ | Wet chemical method |
| 15 | SnO₂/Fe₂O₃ | SnCl₂.5H₂O and Fe(NO₃)₃ | Wet chemical method |
| 16 | Ag/ZnO-TiO₂ | Zinc acetate dehydrate, silver nitrate and titanium isopropoxide | Microwave assisted method |
| 17 | CdO-ZnO | ZnCl₂ and CdCl₂.2H₂O | Microwave assisted method |
| 18 | CdO-NiO-ZnO | Cd(CH₃COO)₂.2H₂O, Zn(CH₃COO)₂.2H₂O and Ni(CH₃COO)₂.4H₂O | Microwave assisted method |
| 19 | ZnO/CuO | Zn(NO₃)₂.6H₂O and Cu(NO₃)₂.3H₂O | Biological method |
| 20 | ZnFe₂O₄ | Fe(NO₃)₃.9H₂O and Zn(NO₃)₂.6H₂O | Biological method |
| 21 | Fe₂O₃-Ag | AgNO₃ and Fe(NO₃)₃ | Biological method |
| 22 | Ti doped ZnO | ZnO Powder and TiO₂ powder | Ball-milling technique |
| 23 | NiO/reduced graphene oxide | GO powder and Nickel powder | Ball-milling technique |
| 24 | ZnO-graphene oxide | ZnO powder and Graphene oxide powder | Ball-milling technique |

3. Some basic characterization techniques and morphology of TMONCs

Characterization techniques do have an important role in the study of TMONCs. TMONCs we have reported in this review were synthesized by different method and even different reaction conditions and precursors therefore all of them show different shape, size, particle distribution, structure, morphology, elemental configuration, even different practical applications. All these physical and chemical properties are crucial for designing a nanomaterial with required practical applications. Therefore characterization of synthesized nanomaterial is extremely important to find out its size, shape, morphology, chemical composition and all other properties for its complete study and application. Herein, we are going to review some important characterization techniques used for various reported TMONCs.

3.1. XRD (X-ray diffraction technique)

XRD technique is widely utilized for identification of phase and the crystallite size of each phase of nanocomposite. Almost all the researchers have reported XRD studies of their synthesized transition metal oxide based nanocomposites for their crystalline quality and phase study. Shengyan Pu et al. reported XRD data of their synthesized graphene oxide/Fe₃O₄ nanocomposite and the XRD data revealed successful synthesis of graphene oxide/Fe₃O₄ nanocomposite [29]. Hadi Eslami et al. has also...
done XRD data study for the verification of successful fabrication of Iron-Manganese metal oxide nanocomposite. He has also reported the calculated size of nanocomposite by using Scherrer’s equation.

\[ D = \frac{0.89\lambda}{\beta \cos \theta} \]  

Here, \( \lambda \) = X-ray wavelength, \( D \) = Size of the crystal, \( \beta \) = the full-width at half-maximum and \( \theta \) = Diffraction angle [26].

In a very similar manner many researchers synthesized transition metal oxide based nanocomposites and studied their XRD data as K. Egizbek reported XRD data of NiFe\(_2\)O\(_4\) nanocomposite [27], Thongthai Witoon et al reported XRD data study of Cu/ZnO nanocomposite [28], Tariq Jan et al studied XRD data of synthesized ZnO-CuO nanocomposite [25] and many others. It is clear from above that XRD is basic and Crucial required characterization technique for nanomaterials.

3.2. SEM and TEM (Electron Microscopy)

The properties and application are very much depending on the morphology and particle size of nanomaterials. Researchers have been using Electron microscope for observing the morphology and size of their synthesized transition metal oxide as well as other nanomaterials. Transmission electron microscopy (TEM) and Scanning electron microscopy (SEM) are two type of electron microscopy which are widely used by researcher for this purpose.

Abdessalem Hamrouni et al. reported TEM image of ZnO-SnO\(_2\) nanocomposite and observed that the size of nanocomposite was in 30-80nm range [45]. Ardiansyah Tanfik et al studies FESEM image of CuO/TiO\(_2\)/ZnO and observed spherical and clew like CuO/TiO\(_2\)/ZnO nanocomposites were formed [35]. M. A. Ahmed synthesized NiO/TiO\(_2\) with 1, 2, 5 and 10% of NiO. He analyzed TEM images and found out, reduction of particle size on increasing nickel oxide percentage. Also size range of nanocomposite was in 4-32nm [36]. Literature survey revealed that electron microscopy is widely used for nanomaterials study and very crucial characterization technique. Alexin Lavin et al synthesized ZnO/CuO nanocomposite and analyzed them under SEM and TEM for finding the SEM image that shows irregular shaped semispheroidal nanoparticles and TEM confirmed agglomeration of spheroidal particles (10nm) connected with the rod-shaped particles (50nm) [37]. Shahab Ansari Amin et al. used TEM for morphology and size study of his synthesized TiO\(_2\)- Ag nanocomposite [38]. Bin Gao et al synthesized CNTs/TiO\(_2\) nanocomposites and studied its morphology and size through TEM images [39]. Above example explained that morphology is crucial parameter for specific application use of any nanomaterial.

3.3. EDX (Energy dispersive X-ray)

EDX is useful to indentifying elemental content present in synthesized transition metal oxide based nanocomposites also other nanomaterials. Susanta Kumar Biswal et al. synthesized Fe\(_2\)O\(_3\)-Ag nanocomposite and reported its EDX characterization which confirmed the presence of oxygen (weight % of 51.12), silver (weight % of 23.25) and iron (weight % of 25.63) elements [98]. Zahra Noohpisheh et al reported EDX which showed that the weight percentage of Ag was 5.60 and the weight of ZnO was 86.02 in the synthesized Ag-ZnO nanocomposite [97]. Yoki Yulizar et al synthesized Au/TiO\(_2\) nanocomposite and indentified its elemental composition by using EDX. EDX showed the presence of Au (weight % of 9.53), Ti (weight % of 32.66), and O (weight % of 57.81) elements in Au/TiO\(_2\) nanocomposite [96].
EDX is an important characterization technique. Elemental composition determination by EDX together with other characterization techniques such as XRD, FTIR, UV etc give complete structural information of any nanomaterial.

### 3.4. FTIR (Fourier transform infrared spectrometer)

Numerous research works have been published for synthesis and characterization of transition metal oxide based nanocomposites, where researchers investigated functional groups in their synthesized nanomaterials by using FTIR spectroscopy. K. Karthik studied FTIR spectra for CdO-ZnO nanocomposite. Where he concluded that 861 cm\(^{-1}\) peak was for cubic CdO and 505 cm\(^{-1}\) peak was for hexagonal ZnO [85]. Mohammadreza Mansournia et al. synthesized CuO-ZnO composites and studied their FTIR spectra, he observed that all 0.4% CuO-ZnO, 2% CuO-ZnO, 10% CuO-ZnO and 50% CuO-ZnO showed a band in the range of 400-600 cm\(^{-1}\) for metal-oxygen (M-O) stretching vibrations [68]. Zahra Noohpisheh et al reported FTIR spectra with 520 cm\(^{-1}\) which was related to the vibration of the Zn-O bond and 900 to 1500 cm\(^{-1}\) belonged to extract components present on the surface of the Ag-ZnO nanocomposites [97]. Above example shows the importance of FTIR spectra, it is useful for complete structural studies along with other characterization techniques discussed before.

### 3.5. Some other characterization techniques

Some other techniques also have being popular for the characterization of transition metal oxide based nanocomposites and other nanomaterials such as UV-Visible spectroscopy, Atomic force microscopy (AFM), Brunauer-Emmett-Teller (BET), Thermogravimetric analysis (TGA), Differential thermal analysis (DTA) etc. Abdur Rahman et al reported fabrication of CdO-MgO-Fe\(_3\)O\(_4\) nanoparticles. He had also calculated band gap which was 1.76eV for CdO-MgO-Fe\(_3\)O\(_4\) nanocomposite [72]. AFM was also being used for imaging nanocomposite as K. Kaviyarasu et al synthesized MgO:CuO nanocomposite and seen its images through Atomic force microscopy [75]. The BET is useful for surface area observations and pore properties analysis. Ramin Mohammad-Aloucheh et al reported BET studies of ZnO/CuO nanocomposite. He observed images with mesopores and calculated specific surface area for ZnO/CuO(5%) and ZnO/CuO(10%) were 36.0 and 26.0 m\(^2\) g\(^{-1}\) respectively. Also he calculated pore volumes for ZnO/CuO(5%) and ZnO/CuO(10%) were 0.0939 and 0.0984 cm\(^3\) g\(^{-1}\) respectively [94]. Researchers are using TGA/DTA for thermal performance studies of a sample. Mohammad A. Khalizadeh et al synthesized Fe\(_3\)O\(_4\)/CNC/Cu nanocomposite and studied its TGA/DTA results showing its thermal stability [106].

It is clear from above studies that all characterization are having its own role and they work together for complete study of structural and chemical properties of a transition metal oxide based nanocomposites. Figure.2 give a brief summary of characterization techniques used in transition metal oxide based nanocomposites.

### 3.6. Morphology

The morphologies of transition metal oxide based nanocomposites are playing extremely important role for their practical uses in various field of sciences or we can say that practical applications of transition metal oxide based nanocomposites and even other nanomaterials are strongly related to their morphologies. Various method of fabrication have been used to control morphologies of transition metal oxide based nanocomposites. Literature survey revealed variety of morphologies of transition metal oxide based nanocomposites for example, Sharma parveen et al synthesized Al(OH)\(_3\)/MnO\(_2\) nanocomposite, and he also reported its FESEM images from where it was clear that Al(OH)\(_3\)/MnO\(_2\)
nanocomposite having dandelion-fiber flake-like surface morphology [107]. G. Jenita Rani et al. reported SEM images of her synthesized Fe\(_3\)O\(_4\)/rGO, and concluded that Fe\(_3\)O\(_4\)/rGO showed *Watsonia Meriana* flower like morphology [108]. Razieh Aladpoosh et al. reported star-like Ag/ZnO nanocomposites on cotton fabric [109].

Different transition metal oxide combinations have been reported with different application uses such as T. K. Jana et al reported fabricated of CdS-ZnO nanocomposites with flower shaped morphologies and its photocatalytic study for degradation of organic dye (rhodamine B (RB)) [111], P. Vennila et al synthesized flower like Ni-Co/Fe\(_3\)O\(_4\) nanocomposite. And that nanocomposite was reported for glucose sensor application [112], Jun Geng et al. reported ZnO/Au with hollow doughnut like morphology. ZnO/Au showed biosensors and biomedical properties [113] and many others.

Above study revealed various unique morphologies were achieved in literature. Figure 3 shows some already reported SEM and FESEM images with different morphologies of transition metal oxide based nanocomposites.

![Figure 2](image)

**Figure 2.** Simplified block diagram of the general characterization techniques for transition metal oxide based nanocomposite study using above literature survey [25, 27, 37, 45, 68, 72, 96, 98, 106].
Figure 3. Different morphologies of some reported transition metal oxide based nanocomposites, (a) [107], (b) [110], (c) [108], (d) [112], (f) [114] (copyrights reserved to the Elsevier) and (e) [113] (copyrights reserved to the American chemical society publications).

4. Various practical applications of Transition metal Oxide based nanocomposites

4.1. Supercapacitors

Supercapacitors are acting as a tie between dielectric capacitors and batteries by their higher power density and higher energy density. Electrode materials for supercapacitors application should have to be conducting and having high surface area. Therefore carbon based nanoparticles, TMONPs and TMONCs (hybridization of TMONPs with carbon nanomaterials or with other metal/metal oxide nanomaterials) attracts wide interest due to their greater specific capacitance and longer cycle life. Several researchers have utilized TMONCs for the ultracapacitor/supercapacitor application, for example, Guangyu et al. reported Co$_3$O$_4$/graphene nanocomposite with supercapacitor applications. He calculated maximum specific capacitance of Co$_3$O$_4$/graphene nanocomposite was 430F/g at 1 A/g (using three electrode system) and 215F/g at 0.4 A/g (using two electrode system). Specific capacitance obtained by two electrode system is less than three electrode system. He was able to achieve good cyclic stability of Co$_3$O$_4$/GO in both three electrode and two electrode systems [115].

D.V. Leontyeva et al synthesized carbon supported NiO (NiO/C) nanocomposite and studied its electrochemical behavior for supercapacitor applications. He calculated specific capacitance from cyclic voltammetry curve was 1100 to 777F/g with increase of scan rate from 5 to 40mV/s. And 970 F/g at 0.5A/g mass normalized current was calculated by galvanostatic charge-discharge curve. He performed thousand cycles and found out excellent cycle life (with 840Fg$^{-1}$) [116]. Pintu Sen et al. fabricated Poly 3,4-ethylenedioxythiphene (PEDOT)-MnO$_2$ and Polyaniline (PANI)-MnO$_2$ nanocomposites. He studied their electrochemical properties and compared to pure MnO$_2$. Calculated higher specific capacitance for PEDOT-MnO$_2$ was 315F/g, for PANI-MnO$_2$ was 221F/g and for only MnO$_2$ was 158F/g. Where, nanocomposites showed higher specific capacitance because of their higher internal pore volume [117].

Anantha kumar Ramadoss et al synthesized graphene/ZnO nanocomposite with supercapacitor applications. He calculated maximum 109F/g capacitance at 5mV/s [118]. Thibearchews Prasankumar et al fabricated supercapacitor electrode (Polyaniline /Fe$_3$O$_4$ nanocomposite), and obtained topmost specific capacitance of 572F/g, 82% of capacitance retention after more than 5000 cycles at 1A/g [119].
Many other researchers also investigated the application of transition metal oxide based nanocomposites for supercapacitor applications such as, Sivalingam Ramesh et al. reported supercapacitor application of MWCNT/GO/NiCo$_2$O$_4$ nanocomposites [120], Ian Y.Y. Bu et al studied supercapacitor applications of ZnO/Reduced graphene oxide [121], Irum Shabeen et al investigated supercapacitor properties of MoO$_3$/ZnMoO$_4$ nanocomposite [122], Montree Sawangphruk et al also reported MnO$_2$-rGO for supercapacitor properties.

Above study shows transition metal oxide based nanocomposites are very good candidate for the use of supercapacitors electrode material. The possible reason of better supercapacitor performance is high conductivity and high specific surface area [123,124].

4.2. Hydrogen generation

Transition metal oxide based nanocomposites have acquired significant attention in recent time for their potential use for water splitting.

Moumita Chandra et al synthesized CuS/TiO$_2$ nanocomposite with varied TiO$_2$ contents. Where, CuS/TiO$_2$ with mole ratio 1:0.4 showed maximum H$_2$ production rate of 6310μmol g$^{-1}$ in 5 hours or 1262μmol g$^{-1}$ h$^{-1}$ under LED [125]. Nagappagai Lakshmana Reddy et al reported synthesis of 1.3% Cu-TiO$_2$ (at reaction condition of 500ºC/4h) and 1.5% Cu-TiO$_2$ (at reaction condition of 500ºC/4h) nanocomposites, and revealed a highest rate of H$_2$ generation of 20.36 mmol h$^{-1}$ g$^{-1}$ (under LED) and 21.7mmol h$^{-1}$ g$^{-1}$ (under Solar light) [126]. Karim R. Diab et al synthesized NiTiO$_3$/rGO with 100:0, 99:1, 97:3, 95:5 and 93:7 weight ratios. Among all NiTiO$_3$/rGO with 95:5 showed maximum rate of H$_2$ generation (8383 µmol g$^{-1}$ h$^{-1}$) also NiTiO$_3$/rGO with 95:5 weight ratio was showing maximum pore volume (0.176 mL/g) and maximum pore diameter (3.92nm) [127]. Several other transition metal oxide based nanocomposites also reported in literature for H$_2$ generation applications for example, CdO-CdS [129], Au/TiO$_2$ [130], reduced graphene oxide –TiO$_2$ [128], In and N co-doped TiO$_2$-Pd nanomaterial [131].

Hydrogen is an environmental friendly fuel which is promising alternative to fossil fuels. From above study, we can understand that transition metal oxide based nanocomposites are promising photocatalysts for Hydrogen production from water splitting because of their enhanced surface area and surface activity [125-127].

4.3. Solar cell applications

We have studied about H$_2$ as an alternative source of fossil fuel earlier in this article. Here, we are coming to review transition metal oxide based nanocomposites application as solar cells. Solar cell is most promising alternative of fossil fuels as solar energy is most abundant energy on earth also is most green and environmentally friendly energy.

Zohreh Dehghani Mahmoudabadi et al synthesized two CuO/TiO$_2$ nanocomposites by microplasma assisted electrochemical method. Where, CuO/TiO$_2$ (a) was synthesized by 15min irradiation with plasma and CuO/TiO$_2$ (b) by 25min irradiation with plasma. Reported conversion efficiency (CE), short-circuit current density (SCCD) and open circuit voltage (OCV) for CuO/TiO$_2$ (a) were 7.4%, 15.38mA/cm$^2$ and 0.70V respectively, and for CuO/TiO$_2$ (b) were 9.3%, 18.80mA/cm$^2$ and 0.68V respectively in order to dye sensitized photovoltaic cell application [132]. Gaurav K. Upadhyay et al reported fabrication of CdO:TiO$_2$ by adding various volume of the precursor solutions, Where 3:2 CdO/TiO$_2$ showed better CE, SCC and OCV with 3.23%, 7.6mA, 0.26V values respectively for solar cell applications [133]. Junling Song et al reported rGO-TiO$_2$ (coated on FTO (fluorine-doped tin oxide)) with solar cell application and studied its photovoltaic performance for solar cell applications.
He observed SCCD, OCV, fill factor and overall CE were 18.2 mA/cm$^2$, 576 mV, 57.9% and 6.06% respectively [134]. Abdul-Mojeed Ilyas et al. reported synthesis of TiO$_2$/CdO by coupling 10%, 20% and 40% weight of CdS with TiO$_2$. And observed photovoltaic studies for solar cell applications. He found that 10% CdS/TiO$_2$ was showing maximum CE among all with SCCD, OCV, fill factor and CE were 1.248 mA/cm$^2$, 0.5581 V, 0.4935% and 4.30% respectively [135]. Shahram Ghasemi et al synthesized Fe$_3$O$_4$/rGO nanocomposite and reported its properties for dye sensitized photovoltaic cell applications. Calculated values of short of SCCD, OCV, fill factor, and CE were 24.45 mA/cm$^2$, 0.755 V, 0.32% and 5.91% respectively which are better than only rGO [136].

Above study reveal that transition metal oxide based nanocomposites are widely used for solar cell application because when transition metal oxide semiconductors doped with other semiconductor or nanomaterials which can increase the charge transfer processes also decrease electron/hole recombination that enhances the performances of solar cell device [137-139].

4.4. Sensors

Sensitivity and selectivity are important and challenging in the wide field of sensors. To improve sensor performance different methods have been used such as doping, surface modification etc. TMONCs sensors were proved increased selectivity and sensitivity than individual transition metal oxide nanoparticles because of their enhanced surface area and surface activity or introduction of meso-porosity etc. [140-142]

Mehrnaz Joulazadeh et al fabricated Polypyrrole (PPy)/ZnO and PPy/SnO$_2$ nanocomposites sensors for ammonia detection. He reported that transition metal oxide based nanocomposite (PPy/ZnO) showed maximum response of ~34% towards ammonia than PPy/SnO$_2$ (~25%) and only PPy (~15%). He suggested possible reason for higher response of PPy/ZnO than PPy/SnO$_2$ was higher conductivity of PPy/ZnO due to presence of Zn$^{2+}$ cations [143]. Meenakshi Dutt et al. used synthesized Li$_2$O-doped Fe$_3$O$_4$ and SnO$_2$–Fe$_3$O$_4$ nanocomposites as sensors in response to formaldehyde and ethanol in operating temperature range of 25-200ºC. Where, reported response of 6.08 and 5.82 for HCHO and C$_2$H$_2$OH respectively at 25ºC with Li$_2$O-doped Fe$_3$O$_4$ sensor, and SnO$_2$–Fe$_3$O$_4$ exhibits response of 6.44 and 4.93 for HCHO and C$_2$H$_2$OH respectively at temperature 150ºC [140]. Ehab Salih et al fabricated ZnO/GO nanocomposites and studied its sensing properties towards H$_2$O$_2$ by electrochemical system. Where, cyclic voltammetry measurements confirmed oxidation peak currents of H$_2$O$_2$ at ~1.1V by using synthesized nanocomposite electrode due to direct electron transfer. That reflected sensing activity of ZnO/GO nanocomposites towards H$_2$O$_2$ [141]. Hung et al. synthesized series of WO$_3$/p-MWCNT nanocomposites with different % weight. Among all amount of MWCNT was 0.5% weight showed maximum response towards sensing NO$_2$ at its concentration of 5ppm with response of 18 and response time of 87s at 150ºC [144].

Several other researchers also analyzed sensing capability of their synthesized transition metal oxide based nanocomposites for example, R. Sivasubramanian et al used synthesized copper (I) oxide-reduced graphene oxide nanocomposite for dopamine sensing [147], Bose Dinesh et al. fabricated rGO-Co$_3$O$_4$ for effective sensing of serotonin in the existence of dopamine and ascorbic acid [142], M.R. Mahmoudian et al reported sensing behavior of MnO$_2$/rGO nanocomposite for H$_2$O$_2$ [145], Hyoun Woo Kim et al. synthesized ZnO nanoparticles and ZnO/Graphene nanocomposites and compared the sensing behavior ZnO-G which was synthesized by microwave irradiation show higher response than only ZnO nanoparticles towards NO$_2$, Ethanol, Acetone, Toluene, Benzene and CO gases [146].

Overall summery of above study is that, transition metal oxide based nanocomposite sensors mostly showed improved sensor performance than individual transition metal oxide nanoparticles.
4.5. Biomedical applications

Iman Gholamali et al prepared a series of oxidized starch/CuO nanocomposites (hydrogels with 0.00, 0.01, 0.02 and 0.03M of Cu$_2$). He studied the relation between encapsulation and release of ibuprofen drug in all oxidized starch/CuO nanocomposites at pH of 2.1 and 7.4. This study revealed a higher swelling capacity and controlled delivery of drug by oxidized starch/CuO nanocomposites than pure oxidized starch [148]. Dedhila Devadathan et al compared antifungal activities of their synthesized polyindole based nickel-zinc oxide nanocomposite, nickel-zinc oxide, polyindole, nickel oxide and zinc oxide and observed that polyindole based nickel-zinc oxide nanocomposites showed antifungal activity of 1cm, nickel-zinc oxide showed antifungal activity of 0.7cm and polyindole, nickel oxide and zinc oxide showed no antifungal activity [149]. Faisal Mukhtar et al reported antibacterial properties against E. coli of synthesized binary NiO-Fe$_2$O$_3$ and NiO-CdO nanocomposites and ternary NiO-Fe$_2$O$_3$-CdO nanocomposite. For that he prepared various concentrations (10, 20, 30 and 40g/mL) solutions of each and all nanocomposites. Among them 40g/mL solutions of each nanocomposite showed maximum antibacterial activities. He compared each nanocomposite (with 40g/mL concentration) and observed that NiO-Fe$_2$O$_3$-CdO showed maximum zone of inhibition (~1.7mm) than NiO-Fe$_2$O$_3$ (~9mm) and NiO-CdO (~14mm). He suggested possible reason for antibacterial activity increase was contact stress or direct oxidation and penetration of heavy metals ions to negatively charged cell membrane [150]. Maqsood Ahamed et al synthesized ZnO nanoparticles, SnO$_2$-doped ZnO (SnO$_2$-ZnO) nanocomposite and SnO$_2$-ZnO/rGO (SnO$_2$-doped ZnO/reduced graphene oxide) nanocomposite and studied their anticancer activities via oxidation stress pathway. Fluorescent microscopic images revealed that ROS (Reactive Oxygen Species) and MDA (Malondialdehyde) levels were higher with all ZnO, SnO$_2$-ZnO and SnO$_2$-ZnO/rGO nanomaterials rather than control cells. Higher the ROS production more will be the oxidative damage to the cancer cells. They treated Michigan Cancer Foundation-7 (MCF-7 which are breast cancer cells) with certain amount of ZnO, SnO$_2$-ZnO and SnO$_2$-ZnO/rGO nanomaterials for 24h with and without of N-acetylcysteine (NAC) and found decrease in ROS generation in presence of NAC. Herein, SnO$_2$-ZnO/rGO nanocomposite reported with higher anticancer activity against MCF-7 cells in compared to pure ZnO nanoparticles [151].

It is clear from these examples that transition metal oxide based nanocomposites have been actively reported with several vital biomedical applications such as anticancer, biosensors, antifungal, antibacterial and in drug delivery. Further more such examples are reported in Table 2.

| S.N. | Transition metal oxide Abased nanocomposites | Synthesis methods | Biomedical application uses | Ref. |
|------|---------------------------------------------|-------------------|----------------------------|------|
| 1    | Zeolite/zinc oxide-copper oxide              | The facile chemical method | Antibacterial properties | 152  |
| 2    | WO$_3$-GO                                   | Ultrasonic method  | Antibacterial properties  | 153  |
|      |                                             |                   | And Anticancer properties |      |
| 3    | Chitosan coated zinc oxide                  | Green chemistry approach | Antibacterial properties | 154  |
| 4    | GO-SnO$_2$-TiO$_2$                          | Solvothermal method | Biosensor for detection of acetone in diabetes mellitus patient’s breath | 155  |
| 5    | ZnO/GO                                     | Co-precipitation method | Antibacterial properties | 156  |
| 6    | rGO/NiO                                    | Microwave-assisted hydrothermal | Glucose sensors in diabetes | 157  |
4.6. Photocatalytic degradation of organic dyes

Discharge of industrial effluent streams is becoming environmental threats in modern world of fast development of technology and world economy. Organic dyes, one of the major pollutants which is causing the most serious water pollution. Where, Photocatalytic degradation of organic dyes is effective, efficient and low cost way to solve this major water pollution issue of dyes. In the last few decades, many researchers have been indentified transition metal oxide based nanocomposites as good photocatalysts over semiconductor transition metal oxide nanoparticles by overcoming of their limitation of wide band gap, fast electron hole recombination, slower reaction rate of photocatalysis etc. Many researchers have been focused on modifying and doping of transition metal oxide nanoparticles to achieve a nanocomposite with inhibition of electron hole recombination, fast reaction rate of photocatalysis [160-163]. Table 3. Presents various reported TMONCs for photocatalytic applications.

Table 3. Photocatalytic application of transition metal oxide based nanocomposites for different toxic dyes.

| S.N. | Transition metal oxide nanocomposites | Synthesis technique | Toxic dyes | Photocatalytic η (%) | Time | Light source | Ref. |
|------|-------------------------------------|---------------------|------------|----------------------|------|--------------|------|
| 1    | Fe₂O₃/RGO                          | Green hydrothermal method | 4-Nitrophenol | 98% | 50min | Visible light | 164 |
| 2    | Graphene-Zinc oxide nanocomposites | Chemical precipitation method | Rhodamine-B | 100% | 90min | Visible light | 165 |
| 3    | ZnO/Fe₂O₃                          | Solvothermal techniques | GRL dye | 81.1% | 200min | Ultra violet Sunlight | 166 |
| 4    | Graphene-V₂O₅                      | Solution mixing method with hydrothermally grown V₂O₅ | Methylene Blue | 100% | 90min | Sunlight | 167 |
| 5    | LaFeO₃/Ag₂CO₃                      | Co-precipitation method | Rhodamine-B And p-chlorophenol | 99.5% And 59% | 45min | Sunlight | 168 |
| 6    | Fe/Al/Ti oxide                     | Chemical routes Simple precipitation method | Methylene Blue | 98.4% | 10min | Visible light | 169 |
| 7    | Zinc Oxide activated charcoal Polyaniline | Simple precipitation method | Rhodamine-B | 95% | 120min | Visible light | 170 |
| 8    | Polyaniline/CdO                    | Chemical | Malachite | 99% | 4h | Sunlight | 162 |
5. Conclusion and future perspective

Many useful strategies have been investigated for the synthesis of several TMONCs such as sol-gel method by Taufik et al [35], hydrothermal techniques by Gao et al. [60], chemical vapor deposition by Ye et al. [50], wet chemical method by Collazos et al. [71], microwave assisted method by Karthik et al [85] and green methods by Elemike et al [95] respectively. Herein, the transition metal oxide based nanocomposites have been synthesized and modified by various technique of synthesis. As we know that on the basis of modified technique of synthesis, we can achieve unique sets of properties like, high surface area, enhanced surface activity/ more number of active site on surface, introduction of mesoporosity, decreasing electron hole recombination by doping and increasing charge transfer process. These characteristic properties have been investigated for different potential applications in the literature [24-25, 140-141]. Herein, we have also reviewed different reported characterization technique of synthesized metal oxide based nanocomposites like XRD, EDX, SEM, TEM and FTIR for structural and morphological studies. Herein, authors have investigated unique applications of transition metal oxide nanocomposites based on their different morphologies. Morphologies and surface properties play a vital role in practical application uses of these transition metal oxide based nanocomposites [108-111]. Nanocomposites are known as the materials of the era for their broad extend of applications in almost all fields of sciences such as physics, biology, environmental sciences chemistry and material sciences. Many potential real-life application of TMONCs have been reported such as sensors by Joulazadeh et al.[143], Photocatalytic degradation of toxic dyes by Liu et al. [163], biomedical applications like for drug delivery, antimicrobials , biosensors and anticancer by Alsawat et al., Bharathi et al. and Kalidoss et al. respectively [152, 154, 155], in energy production by Mahmoudabadi and Dubey et al. [132, 128], solar cell and H2 generation, supercapacitors for energy storage by Chen et al. [115] and various other.

Further more research is required in the area of fabrication and designing of new TMONCs with enhanced surface area, morphological control, size control, porosity control and homogeneity of all the homogenous dispersion of all materials in nanocomposites. Still, the researchers and scientists have to hard work for developing cost effective and environmental friendly routes of synthesis of transition metal oxide based nanocomposites with high rate of product at normal temperature and in moderate reaction conditions. Applications of many transition metal oxide based nanocomposites are somewhat limited to laboratory level only therefore further research should be focused towards industrial scale production and industrial applications of these nanocomposites.

Conflict of interest

No conflict of interest was declared by authors.

Abbreviations

TMONCs, Transition metal oxides based nanocomposites; CNTs, Carbon nanotubes; rGO, Reduced graphene oxide; PVA, Polyvinyl alcohol; E. coli, Escherichia coli; MWCNTs, Multi-wall carbon nanotubes; OiPr, Isoproxy; SEM, Scanning electron microscopy; hfa, 1,1,1,5,5,5-hexafluoro-2,4-
pentanedionate; FESEM, Field emission scanning microscopy; dpm, 2,2,6,6,-tetramethyl3,5-heptanedionate; TEM, Transmission electron microscopy; EDX, Energy dispersive X-ray; TMEDA, N,N,N',N'-tetramethylethlenediamine; FT-IR, Fourier transform infrared spectrometer; XRD, X-ray diffraction technique; AFM, Atomic force microscopy; BET, Brunauer-Emmett-Teller; TGA, Thermogravimetric analysis; DTA, Differential thermal analysis; PEDOT, Poly3-4-ethylene dioxythiphene; PANI, Polyaniline, ppy, Polypyrrole; ROS, Reactive oxygen species; MDA, Malondialdehyde; MCF-7, Michigan cancer foundation; NAC, N-acetylcysteine; CV, Conversion efficiency; SCCD, Short-circuit current density; OCV, open circuit voltage.

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