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A review on spinel chromites and their composites: synthesis, characterization, and applications

Uttam P. Timbadiya[1,2], *Ashish* R. Tanna[1], and *Harshal* B. Desai[1*]

[1]Department of Physics, School of Science, RK University, Rajkot 360020, Gujarat, India
[2]D.K.V. Arts and Science College, Jamnagar 361008, Gujarat, India

Abstract. Spinel chromite nanoparticles are highly attractive due to their unique structural, magnetic, optical, and catalytic properties. This review presents an overview of pure and doped spinel chromite with the standard chemical formula ACr_2O_4 (A = Mg, Ni, Co, Cu, Zn), focusing on the effects of cation substitution at tetrahedral (A) and octahedral (B) sites on their structural and functional behaviour. Various synthesis methods including sol–gel, green synthesis, solid-state, microwave-assisted, and ball milling are summarized, highlighting their impact on particle size, morphology, and crystallinity. Characterization techniques such as XRD, SEM, TEM, PL, UV–Vis., FTIR, and VSM have been carried out to study structural, morphological, optical, electrical, and magnetic properties. The review also emphasizes applications spinel chromites in photocatalysis, gas sensing, antimicrobial activity, and energy storage. Overall, this work provides a clear roadmap for future research and development of spinel chromite-based functional materials.

1 Introduction

Nanotechnology has become one of the most important areas of modern research, focusing on materials at the nanoscale (1–100 nm), where their size, shape, and morphology strongly determine their properties [1]. At this level, nanomaterials exhibit remarkable magnetic, electrical, thermal, and catalytic characteristics, which make them highly useful in industrial, medical, and environmental fields [2]. Among the various classes of nanomaterials, spinel oxides are especially noteworthy. Their excellent structural stability and multifunctional properties give them advantages far beyond those of simple binary oxides, making them highly relevant for advanced scientific and industrial applications [3].

Spinel oxide is an important class of mixed-metal oxides and has the general chemical formula AB_2X_4, where X is an anion from group 16 of the periodic table (like Oxygen (O), Sulphur (S), Selenium (Se) etc.), Here, A and B represent divalent (e.g. Mg, Zn, Fe, Ni, Cu, Co) and trivalent cations (e.g. Cr, Fe, Al) occupying the tetrahedral and octahedral sites, respectively. The cations occupy only one-eighth of the tetrahedral sites and one-half of the octahedral sites in the lattice [3]. The unit cell of spinel belongs to the cubic structure

* Corresponding author: harshal.desai@rku.ac.in

(space group Oh^7 - Fd3m) and contains eight AB_2O_4 molecules, comprising 32 O^{2-} anions. These oxygen anions form the close face-cantered cube (FCC) packing which is contained in 64 tetrahedral (A) and 32 octahedral (B) [4].

The distribution of cations in spinel structures gives rise to three types: normal spinel, inverse spinel, and mixed spinel. In a normal spinel, with the general formula AB_2O_4, the divalent cation (A^{2+}) occupies the tetrahedral sites, while the trivalent cation (B^{3+}) occupies the octahedral sites. Common examples include aluminates such as $MgAl_2O_4$, $CoAl_2O_4$, $FeAl_2O_4$, chromite like $MgCr_2O_4$, $ZnCr_2O_4$ and $CoCr_2O_4$ and ferrites like $ZnFe_2O_4$ and $CdFe_2O_4$. $CoCr_2O_4$ can be used as photocatalytic [5], sensing detection of hydrogen peroxide and glucose [6], supercapacitor [7], magnesium chromite used as photocatalyst [8], corrosion resistance [9], supercapacitor [10], acetone detection [11]. Inverse spinel follows the general formula $B(AB)O_4$, where the cation distribution is reversed, the divalent cation (A^{2+}) occupies octahedral sites, and the trivalent cation (B^{3+}) occupies tetrahedral sites. Example of inverse spinel was copper chromite ($CuCr_2O_4$), Nickel chromite ($NiCr_2O_4$). There are several applications of copper chromite such as Photodegradation [12], Energy Storage [13-14], Anti-Breast Cancer [15] and Nickel chromite use as Super Capacitor [16], Antibacterial [17], Photocatalyst [18-19]. Many ferrites, such as Fe_3O_4, $NiFe_2O_4$, and $CoFe_2O_4$, adopt this structure. Mixed spinels are intermediate between normal and inverse spinels, typically occurring when the sizes of the divalent and trivalent cations are comparable. Their general formula can be represented as $Me_{1-\delta}Cr_{\delta}[M_{\delta}Cr_{2-\delta}]O_4$, where δ indicates the degree of inversion. The mixed spinel $NiCoCr_2O_4$ showed potential application as a photocatalyst [20].

Chromite nanoparticles, typically characterized by the spinel structure AB_2O_4 (where A can be metals such as Zn, Mg, Cu, Co, or Ni), are of significant interest due to their inherent chemical stability and tuneable optical, magnetic, and electrical properties through doping [5]. Several synthesis methods have been developed for chromite, including sol–gel, hydrothermal, co-precipitation, sono-chemical, and combustion synthesis techniques [21].

2 Pure Chromite and its composite

2.1 Cobalt Chromite

Fathia et al. synthesized $CoCr_2O_4$ by green synthesis using Basella alba L. extract. They also studied the photocatalytic degradation of 70% degradation of malachite green, where pure ZnO/$CoCr_2O_4$ achieved 90.91% degradation and $CoCr_2O_4$ achieved 70% degradation [5]. De-Rui Kong et al. synthesized a $CoCr_2O_4$/graphene composite using the sol–gel and ultrasonic methods. The $CoCr_2O_4$/graphene/GCE electrode was employed for electrochemical sensing in 0.1 M NaOH solution. For hydrogen peroxide, the detection limit was 0.018 μM with a sensitivity of 1168.6 μA mM^{-1} cm^{-2} at 0.4 V, while for glucose, the detection limit was 0.012 μM with a sensitivity of 1722.5 μA mM^{-1} cm^{-2} at 0.55 V. The results showed that the modified $CoCr_2O_4$/graphene/GCE electrode exhibited high electrocatalytic activity for the detection of both hydrogen peroxide (H_2O_2) and glucose [6]. $CoCr_2O_4$/rGO composites were synthesized using the solution combustion method. The $0.5CoCr_2O_4$ + 0.5rGO polycrystalline composite exhibited the highest gas response of 97% when exposed to 500 ppb of LPG at room temperature. This composite also demonstrated the fastest response (40 Sec) and recovery (52 Sec) times. For gas-sensing tests, methane, ethane, propane, butane, and hexane were used, but LPG showed the maximum response

compared to the others. The CV curve revealed that the $0.5CoCr_2O_4$–0.5rGO material achieved a maximum specific capacitance of 226 Fg^{-1}, so this material can also be used for supercapacitor applications [7]. Cobalt chromite nanoparticles were synthesized through a green sol-gel inspired method using Azadirachta indica (neem) leaf extract as a natural reducing and stabilizing agent. The photocatalytic activity was evaluated against malachite green (MG) dye under direct sunlight. By varying the initial MG concentration from 10 to 30 ppm at an optimal H_2O_2 concentration of 0.2 mL and a $CoCr_2O_4$ loading of 25 mg, the highest degradation efficiency of 91.33% was achieved at 20 ppm MG. Reusability tests confirmed that the catalyst retained photocatalytic activity over several cycles, although with a gradual decline [21]. Cobalt chromite nanoparticles were synthesized by a green sol-gel method using tragacanth gum as a stabilizing agent. $CoCr_2O_4$ exhibited good photocatalytic activity. Eriochrome Black T (EBT) dye degradation under visible light at room temperature reached 90% within 90 minutes. By increasing the $CoCr_2O_4$ dosage from 0.02 g to 0.05 g, the degradation efficiency improved from 56% to 90%. When the temperature was increased from room temperature to 40 °C, the degradation efficiency further increased slightly from 90% to 93% after 90 minutes. This indicates that temperature has only a minor influence on the photocatalytic decomposition of the selected dye [22]. Cobalt chromite nanoparticles and their composites with graphitic carbon nitride were synthesized using the polyacrylamide gel method. The photocatalytic activity was evaluated using methylene blue (MB) dye under UV–Vis irradiation. The results showed that pure $CoCr_2O_4$ degraded MB completely in 160 minutes, while the $CoCr_2O_4$–15 wt% g-C_3N_4 composite achieved 100% degradation in 80 minutes, and the kinetic studies followed pseudo-first-order kinetics with the reaction rate constant (k) increasing from 0.0143 min^{-1} for pure $CoCr_2O_4$ to 0.029 min^{-1} for the 15% composite [23]. Rubia Shafique et al. synthesized a $CoCr_2O_4$/graphene oxide nanocomposite using the modified Hummer's method, while $CoCr_2O_4$ was synthesized using the sol–gel method. They demonstrated that the $CoCr_2O_4$/graphene oxide nanocomposite exhibited electrochemical performance with a specific capacitance of 574.8 F/g in 1 M KOH alkaline electrolyte and 488.6 F/g in 0.1 M H_2SO_4 acidic electrolyte. They concluded that this material was suitable for long-term energy storage, high-power delivery, and sustainability [24]. Suresh Ghotekar et al. synthesized $CoCr_2O_4$ nanoparticles using honey as a natural precursor via the green synthesis method. Furthermore, they employed the as-synthesized $CoCr_2O_4$ as a heterogeneous nanocatalyst for the preparation of 5-phenyl-[1,2,4]-triazolidine-3-thiones [25]. They synthesized two green nanopigments, Cr_2O_3 and $CoCr_2O_4$, using the polyol method. The measured zeta potential values for Cr_2O_3 and $CoCr_2O_4$ were 6.31 mV and 23.6 mV, respectively. Based on these results, they concluded that $CoCr_2O_4$ exhibited higher suspension stability compared to Cr_2O_3 [26]. $MgFe_2O_4$@$CoCr_2O_4$ MNC (1.5:3) was synthesized using a green sol–gel route with tragacanth gum and calcined at 600 °C for 4 hours. Reactive Blue 222 dye was used to study the photocatalytic properties of the MNC, and it was observed that 93% of the dye (40 mg/L) was degraded in 10 minutes using a 40 mg catalyst dose under visible light irradiation. The nanocomposite is ferromagnetic, allowing it to be easily separated from the solution with an external magnet and reused in subsequent applications [27]. Darius Jasaitis et al. synthesized cobalt chromite using the aqueous sol–gel method followed by calcination at 700 °C for 3 hours. XRD analysis confirmed that the pigment formed a fully crystallized, single-phase $CoCr_2O_4$with a spinel crystal structure [28]. $CoCr_2O_4$ nanoparticles were synthesized via the solvothermal method and calcined at 450 °C and 550 °C for 2 hours. The photocatalytic activity was tested using Congo Red dye at a concentration of 20 mg L^{-1}, with a CCO@450 dosage of 0.8 g L^{-1}. CCO@450 exhibited a CR removal efficiency of 53% at pH 3, which increased to 85% at

pH 7 but dropped to 10% under alkaline conditions. Similarly, CCO@550 showed removal rates of 45% at pH 3, 82% at pH 7, and 8% at pH 10, indicating that the highest removal efficiency was observed at neutral pH ≈7 [29]. Chaibeddra D et al. synthesized cobalt chromite using the co-precipitation method and tested it as a photocatalyst for Congo Red dye degradation under sunlight. The results showed that Congo Red degradation reached 84.5% (10 mg/L dye, 0.2 g/L catalyst) under sunlight, which improved to 94% with the addition of H2O2 after 180 minutes [30]. Cobalt chromite and nickel oxide were synthesized using the sol–gel method and calcined at 700 °C for 3 hours. Their structural, morphological, and magnetic properties were studied. It was observed that with increasing measurement temperature, the exchange bias effect weakened and the coercive field decreased [31]. Pankaj et al. synthesized cobalt chromite and zinc chromite using the sol–gel auto-combustion method and calcined them at 800 °C for eight hours. The direct band gap energies of $ZnCr_2O_4$ and $CoCr_2O_4$ were estimated by absorption spectroscopy and were found to be 3.81 eV and 3.23 eV, respectively [32]. Cobalt chromite nanoparticles were synthesized via the co-precipitation method and calcined at 700 °C for 6 hours. The synthesized NPs were studied as photocatalysts for the degradation of BB41 dye under visible light. The results showed that with a photocatalyst dose of 0.5 g L^{-1} and 10 mg L^{-1} of BB41 solution at pH 9, the degradation efficiencies were 50% after 90 min and 95% after 180 min. The degradation also depended on the initial dye concentration and pH [33]. Hu J. et al. prepared $MgCr_2O_4$ and $CoCr_2O_4$ via the sol–gel method using glucose as a complexing agent, followed by calcination at 1400 °C for 3 hours. The $MgCr_2O_4$ catalyst exhibited superior activity for methane combustion, reaching 10% conversion at 400 °C and 90% conversion at 684 °C, which was significantly better than the $CoCr_2O_4$ catalyst that required higher temperatures, achieving 10% conversion at 480 °C and 90% conversion at 750 °C. This superior performance of $MgCr_2O_4$ was attributed to its larger BET specific surface area (1.1 m^2/g) compared to $CoCr_2O_4$ (0.4 m^2/g), which provided more active sites [34]. Zinc ferrite and Cobalt chromite nanoparticles were synthesized using the sol–gel process and the hydrothermal method, respectively. The mixed powders were prepared with $ZnFe_2O_4$:$CoCr_2O_4$ ratios (by weight) of 3:1, 1:1, and 1:3. VSM analysis revealed that the $ZnFe_2O_4$ - $CoCr_2O_4$ nanocomposite with an equimolar (1:1) ratio exhibited the highest magnetic properties among the samples, achieving a saturation magnetization of 51.20 emu/g and a remanence of 17.81 emu/g. In contrast, the $3ZnFe_2O_4$ - $CoCr_2O_4$ nanocomposite with a 3:1 ratio showed the maximum coercivity of 209 Oe [35]. M(Mg, Co, Zn)Cr_2O_4 nanoparticles were prepared via the polyacrylamide gel method. $ZnCr_2O_4$ was found to be the most effective for removing Congo Red dye, showing a maximum adsorption capacity of 44.038 mg/g under the initial test conditions [36]. Sachin et al. fabricated $CoCr_2O_4$@GeO_2@ZnO using the sol–gel method and examined it for the photocatalytic degradation of Basic Fuchsin dye. They observed that under visible light, the $CoCr_2O_4$@GeO_2@ZnO core–shell nanoparticles achieved 100% degradation of Basic Fuchsin (5 mg/L) in just 30 min, whereas $CoCr_2O_4$@GeO_2 degraded the dye in 45 min and $CoCr_2O_4$ in 60 min. They concluded that increasing the amount of catalyst decreases the photodegradation efficiency, because excess catalyst causes scattering of photons from the surface, reducing the degradation rate [37].

2.2 Copper Chromite

Asmine et al. synthesized copper chromite using the sol–gel method. They also investigated the degradation of SY dye under different pH conditions and dye concentrations. The results showed a degradation efficiency of 97% within 4 hours under the optimal conditions

of pH 4, a catalyst dose of 0.8 g/L, and an initial dye concentration of 10 ppm [12]. $CuCr_2O_4$/GO nanoparticles were successfully synthesized using a combination of the sol–gel and co-precipitation methods. Electrochemical studies demonstrated enhanced conductivity and high capacitance, with a maximum value of 370.5 Fg^{-1} achieved in a 0.1 M H_2SO_4 electrolyte. These results indicate that $CuCr_2O_4$/GO nanocomposites are promising electrode materials for supercapacitor energy storage applications [13]. Rubia Shafique et al. synthesized MXene/$CuCr_2O_4$ nanocomposites using the co-precipitation method and investigated their energy storage properties. Electrochemical studies showed enhanced conductivity and specific capacitance of the composite compared to pure $CuCr_2O_4$ or MXene. Cyclic voltammetry analysis showed that the MXene/$CuCr_2O_4$ nanoelectrode achieved a maximum specific capacitance of 445.5 Fg^{-1} in a 0.1 M H_2SO_4 electrolyte. These results suggested that MXene/$CuCr_2O_4$ nanocomposites are highly promising electrode materials for supercapacitor and energy storage applications [14]. Hiba Shihab et al. employed a green synthesis method using rosemary leaf extract to prepare $CuCr_2O_4$ nanoparticles. The study evaluated the efficacy of the synthesized nanoparticles against the MCF-7 breast cancer cell line in comparison with the commonly used drug Nolvadex-D. After 24 hours, the $CuCr_2O_4$ nanoparticles reduced cell viability, achieving cell death rates of up to 64.01% with an IC_{50} of 247.7 ppm. In contrast, Nolvadex-D induced cell death of up to 54.59% with an IC_{50} of 192.2 ppm. Overall, the findings demonstrated the superior anticancer efficacy of $CuCr_2O_4$ nanoparticles, along with their desirable lack of cytotoxicity compared to Nolvadex-D [15]. Salahaddin Abdollah et al. synthesized $CuCr_2O_4$ using sol–gel and green synthesis methods, followed by calcination at 650 °C for 3 hours. They studied and compared their performance as electrocatalysts in electrochemical hydrogen storage. The $CuCr_2O_4$ (sol–gel) sample exhibited a specific capacitance of 2427 Fg^{-1} from the cyclic voltammetry test and a maximum discharge capacity of 4304 mAh g^{-1}, while the $CuCr_2O_4$ (green) sample exhibited a specific capacitance of 1503 F g^{-1} and a maximum discharge capacity of 3011 mAh g^{-1}. The high specific capacitance is attributed to the large surface area, which provides more active sites for hydrogen adsorption and desorption, enhancing charge storage. The results indicated that $CuCr_2O_4$ nanoparticles were suitable for hydrogen storage [38]. $CuCr_2O_4$ nanoparticles were synthesized using the co-precipitation method. The results showed that the $CuCr_2O_4$ photocatalysts exhibited high activity in the degradation of RhB (93.6%) and MO (92.3%), but comparatively lower activity in the degradation of MB (80.6%). Moreover, the $CuCr_2O_4$ catalyst demonstrated excellent recyclability, maintaining its high activity against RhB dye even after five consecutive cycles without significant performance loss [39]. Habibi et al. synthesized $CuCr_2O_4$ using the sol–gel method with copper nitrate and chromium nitrate as precursors. FESEM images revealed nearly spherical particles with an average diameter of 33 nm. Optical spectra of the nanocomposite showed band gaps at 2.19 eV and 4.66 eV, corresponding to the band gap transitions of $CuCr_2O_4$ [40]. Mobini et al. synthesized $CuCr_2O_4$ using the hydrothermal method. They found that the sample prepared under specific conditions (pH = 12, 4 hours aging time, 180 °C autoclave temperature, and calcination at 500 °C) exhibited the highest surface area and an almost pure spinel phase. They also concluded that the application of the $CuCr_2O_4$ spinel catalyst in CO oxidation was a crucial and highly effective method for converting toxic CO gas into harmless CO_2, thereby mitigating air pollution [41]. $CuCr_2O_4$ was synthesized using the ball milling method. The photocatalytic activity was also evaluated for the degradation of anionic dyes, including eosin Y, erythrosine, and phenol red, as representative water pollutants [42]. Sarkar et al. synthesized nitrogen-doped graphene/ $CuCr_2O_4$ using the sol–gel method and studied its electrochemical, structural, and morphological properties. Cyclic voltammetry

analysis showed that the NG/ $CuCr_2O_4$ nanocomposite achieved a high specific capacitance of 1,135 F/g at a current density of 0.5 A/g. The nanocomposite also exhibited excellent stability, retaining 94% of its initial capacitance even after 5,000 charge–discharge cycles [43]. $CuCr_2O_4$/rGO was synthesized using a facile sol–gel method, followed by hydrothermal and calcination processes, with NH_4OH as the precursor solution. BET analysis showed that the $CuCr_2O_4$ nanocomposite had a specific surface area of 174.8 m^2 g^{-1}, which provided more active sites for the oxygen reduction reaction. The nanocomposite material proved to be a highly effective cathode catalyst, exhibiting excellent long-term cycling stability of over 100 cycles at a capacity of 1000 mAh g^{-1} and a current density of 200 mA g^{-1}, indicating its potential application in battery systems [44]. Vankudoth et al. synthesized $CuCr_2O_4$ using the sol–gel method and studied its catalytic activity. The results showed that the $CuCr_2O_4$ catalyst exhibited high selectivity toward 2,6-dimethylpyrazine [45]. The nanocomposite photocatalyst, prepared by the mechano-thermal method, exhibited a small bandgap energy of 2.60 eV. Dye degradation was observed under visible radiation, and after 180 minutes of irradiation, the degradation efficiencies reached 84% for MB and 45% for MO. The degradation process for both dyes followed the pseudo-first-order kinetic model [46]. Ahmad et al. synthesized $CuCrO_2$ using the polymeric citrate precursor method and determined its direct band gap energy to be 3.09 eV. They also observed 79% degradation of Methylene Blue (MB) within 1 hour of sunlight exposure, reaching an overall efficiency of 88% after 1.5 hours, with the degradation process following pseudo-first-order kinetic behaviour [47]. The $CuCr_2O_4$ samples were synthesized by the sol–gel method and exhibited excellent photocatalytic activity, with degradation efficiencies of 98% for methylene blue and 87% for methyl orange. The DRS spectra revealed that the energy band gaps of $CuCr_2O_4$ and capped- $CuCr_2O_4$ were 2.4 and 2.5 eV, respectively [48]. Han M. et al. synthesized CuB_2O_4 (B = Fe, Cr, and Al) using a polyacrylamide gel method. They compared the three nanoparticles and found that $CuAl_2O_4$ exhibited an optimal optical band gap, higher adsorption capacity for Congo Red dye, and superior photocatalytic activity for the degradation of tetracycline hydrochloride, all of which were significantly better than those of $CuCr_2O_4$ and $CuFe_2O_4$ [49]. Copper chromite was synthesized by a modified sol–gel route, and its microwave absorption properties were evaluated. The results showed that the modified $CuCr_2O_4$ exhibited a maximum reflection loss of −65.57 dB at 14 GHz with a thickness of 2 mm, and the $CuCr_2O_4$ nanocomposite absorbed a bandwidth of 7.73 GHz above 10 dB at the same thickness [50]. Vinh et al. synthesized AB_2O_4 (A = Zn^{2+}, Cu^{2+}; B = Al^{3+}, Cr^{3+}) by the hydrothermal method at different hydrothermal temperatures in an autoclave and studied its structural, textural, and catalytic properties using DTA–TGA, XRD, TEM, and BET techniques [51]. $CuCr_2O_4$ was synthesized using the hydrothermal method and calcined at 500 °C for 5 hours. Cyclic voltammetry (CV) analysis showed that the specific capacitances were 168 F g^{-1} for the pure Ppy electrode and 725 F g^{-1} for the Ppy/$CuCr_2O_4$ nanocomposite electrode. This nearly fivefold enhancement suggested a significant synergistic effect between the $CuCr_2O_4$ nanoparticles and Ppy [52]. De Jesus et al. synthesized copper chromite by a self-combustion reaction and calcined it at 600 °C for 3 hours. They observed that $CuCr_2O_4$, as a photocatalyst, achieved 99.6% azo dye degradation within 120 min at a solution pH of 3.0 and a catalyst dosage of 0.5 g, demonstrating its high efficiency and promising potential under visible irradiation [53].

2.3 Magnesium Chromite

Haiyan He synthesized $MgCr_2O_4$ using the sol–gel method and calcined it at 900°C for 6 hours. The material showed visible-light photocatalytic activity for degrading methyl orange, particularly under alkaline conditions. The results indicated that $MgCr_2O_4$ exhibited weak reductive catalytic activity in the absence of light, whereas strong photocatalytic degradation occurred under light irradiation. Additionally, the reaction rate was pH-dependent, being faster at pH 9 than at pH 7 [8]. They synthesized $MgCr_2O_4$ via the solution combustion method and coated its surface with silanol groups using a silane coupling agent. They observed that silanol functionalization of the $MgCr_2O_4$ additive enabled magnesia-chrome refractories to achieve comparable strength, corrosion resistance, and hot modulus of rupture values at a 200°C lower sintering temperature [9]. S. Maitra et al. synthesized $MgCr_2O_4$ using a chemical sol–gel method. They observed that the sample exhibited a capacitance of 17 F/g at a current density of 0.25 A/g, an energy density of 11 Wh/kg, and a power density of 275 W/kg in 1 M Li_2SO_4, and a capacitance of 21 F/g at a current density of 0.5 A/g, an energy density of 14 Wh/kg, and a power density of 550 W/kg in 1 M $NaClO_4$, with capacity retention greater than 84 % over 1000 charge–discharge cycles, indicating enhanced electrochemical stability [10]. Spinel chromite MCr_2O_4 (M = Cu, Mg, Zn) nanoparticles were synthesized via the solution combustion method. They observed that the $MgCr_2O_4$ sensor exhibited a maximum response of 533 percent to 1 ppm acetone, which was significantly higher than the responses recorded for $ZnCr_2O_4$,153 percent and $CuCr_2O_4$,143 percent. The reason for this superior performance was that $MgCr_2O_4$ had the smallest average particle size of 26.14 nm and the largest specific surface area of 19.23 m^2/g, which enhanced its sensor response [11]. Mohamed A. et al. synthesized MCr_2O_4 (M = Co, Zn, Mg, and Cd) nanospinels using the microwave combustion method with glycine as the fuel. They observed that, in terms of magnetic properties, $CoCr_2O_4$ undergoes a Neel-type ferrimagnetic transition at a high Curie temperature of 92 K, while $ZnCr_2O_4$ shows an antiferromagnetic transition at 11 K. Furthermore, $MgCr_2O_4$ exhibits a suppressed antiferromagnetic transition at 10.5 K, and $CdCr_2O_4$ displays the lowest magnetic ordering with a blocking temperature of 5 K [54]. Yinglei et al. synthesized MCr_2O_4 (M = Co, Ni, Cu, Zn) using a modified sol–gel method. Their results showed that the addition of $CoCr_2O_4$, $NiCr_2O_4$, $CuCr_2O_4$, and $ZnCr_2O_4$ nanoparticles caused a significant decrease in activation energy and a reduction in the thermal decomposition temperatures of both FAP and CL-20 [55]. Abbasi et al. synthesized $MgCr_2O_4$ and $MgCr_2O_4$/Ag nanostructures via the co-precipitation method. The results showed that under UV irradiation at pH 7, the degradation efficiency of Rhodamine B decreased from 70% to 59% as the dye concentration increased from 10 to 20 ppm [56]. Magnesium chromite was synthesized by the co-precipitation method at pH 8.5 using waste tannery solution as a secondary source of chromium and magnesium ions. The effect of different calcination temperatures on the material's phase was studied. It was observed that heating the gel at 300 °C yielded an amorphous oxide phase. Increasing the temperature to 400 °C initiated crystallization, producing mixed phases of $MgCrO_4$, $MgCr_2O_4$, and traces of Cr_2O_3. Heating at 500 °C for 3 hours resulted in $MgCr_2O_4$ with partial decomposition of $MgCrO_4$, while extending the duration to 8 hours at the same temperature produced a pure $MgCr_2O_4$ spinel phase [57]. Vikash Kumar et al. synthesized monophasic $MgCr_2O_4$ by calcining the gel formed through the addition of epoxide to an ethanolic solution. They analyzed $MgCr_2O_4$ as a catalyst, which exhibited rapid oxidative degradation of XO, achieving 92 % degradation in 10 min with H_2O_2, and efficient photocatalytic degradation of Rh-6G, reaching 92.5 % in 150 min under UV–Visible [58]. Magnesium chromite was

synthesized by the sol–gel auto-combustion method using fructose (FS), tartaric acid (TA), and hexamethylenetetramine (HMTA) as chelating/fuel agents. The catalytic activity of the three $MgCr_2O_4$ nanoparticle series was analyzed, and it was found that $MgCr_2O_4$ -TA exhibited substantially higher activity compared to $MgCr_2O_4$ - HMTA and $MgCr_2O_4$ - FS, whose activity toward H_2O_2 decomposition was almost negligible. This enhanced activity of $MgCr_2O_4$ (TA) was attributed to its smaller particle size and higher specific surface area [59]. Afsin Gungor et al. synthesized $MgCr_2O_4$ using the sol–gel method and calcined the samples at different temperatures, namely 750 °C and 950 °C. They determined the band gap energy from PL spectra, which was 4.03 eV for the sample calcined at 750 °C and 3.39 eV for that at 950 °C. The results indicated that the band gap energy decreased with increasing calcination temperature [60]. They synthesized Nano-crystalline magnesium chromite using the citrate sol–gel method, employing citric acid as the chelating agent. Analysis showed that the crystal grain size increased with higher annealing temperatures, indicating sensitivity to heat. The results showed that the $MgCr_2O_4$ spinel began crystallizing at around 550 °C and was fully crystallized at approximately 600 °C [61]. Tholkappiyan et al. synthesized $MgCr_2O_4$ using the co-precipitation method with eggshell membrane (ESM) as a natural bio-template.They reported that the fresh ESM-templated $MgCr_2O_4$ exhibited a maximum average crystallite size of 64.5 nm, while the boiled ESM-templated $MgCr_2O_4$ showed the highest surface area of 28.84 m^2/g and a direct band gap of 3.71 eV [62]. They synthesized pirochromite using the stearic acid-assisted sol–gel method and calcined it at 600°C, 700°C, and 750°C [63]. M. Rani et al. synthesized $MgCr_2O_4$ using the sol–gel method. Photoluminescence measurements indicated a band gap of 3.30 eV [64]. They synthesized $MgCr_2O_4$ by the solution combustion method using citric acid as the chelating agent and fuel. The results showed that a magnesia-chrome sample containing 1 wt.% $MgCr_2O_4$ exhibited superior thermomechanical and physical properties compared to a sample containing 1 wt.% $FeCr_2O_4$ [65]. Hariz et al. produced $MgCr_2O_4$ via the sol–gel route. They observed that the $MgCr_2O_4/WO_3$ photocatalyst achieved 100% conversion of 30 mg/L Cr(VI) into Cr(III) after 120 minutes of solar irradiation, following a first-order kinetic model with an apparent rate constant of 0.02 min^{-1} [66]. Magnesium chromite synthesized by sol-gel auto combustion method and XRD analysis with Rietveld refinement using Full Prof confirmed the formation of a single-phase cubic spinel structure. They observed The AC conductivity followed a universal double power law, and Arrhenius analysis of the relaxation and conduction data indicated that electrical conduction occurs via a hopping mechanism, with correlated barrier hopping identified as the dominant model [67]. Javed et al. prepared MCr_2O_4 (M = Mg, Ni) using the sol–gel self-combustion route. The photodegradation studies showed that the MCO catalyst achieved 70% and 85% degradation of MG and CV at 5 ppm, respectively, while the NCO catalyst exhibited 90% and 95% degradation of the same dyes at the same concentration within 120 minutes, without the addition of H_2O_2 [68].

2.4 Nickel Chromite

Vinothkumar et al. synthesized MCr_2O_4 (M = Ni and Co) using a simple co-precipitation method. The results showed that the $NiCr_2O_4$/NF electrode exhibited a specific capacitance of 442 F g^{-1} at a current density of 1 A g^{-1} in 3 M KOH electrolyte, retaining 90.82% of its initial capacitance after 5000 cycles, while the $CoCr_2O_4$/NF electrode displayed a higher specific capacitance of 550 F g^{-1} at 1 A g^{-1} in the same electrolyte, with excellent cycling stability of 94.15% retention after 5000 cycles. The improved electrochemical performance of $CoCr_2O_4$/NF can be attributed to its favorable structure with smaller particle size, which

provides a large number of reactive sites and enables faster redox reactions for efficient charge storage [16]. Nickel chromite and nickel oxide nanoparticles were prepared using a facile microplasma electrochemical process. They analyzed the concentration-dependent antibacterial activity of the nanocomposite using the disc diffusion assay, with inhibition zones observed against Staphylococcus aureus ranging from 29 mm to 40 mm and against Escherichia coli from 16 mm to 37 mm. Larger zones were observed at higher nanocomposite concentrations for both bacterial strains [17]. They synthesized zinc oxide and nickel chromite using a hydrothermal procedure and calcined the samples at 600 °C for 3 hours. They observed that when the $ZnO/NiCr_2O_4$ nanocomposite was used as a catalyst, the TC solution was degraded by about 98% within 20 minutes, while the degradation efficiency for phenol reached 81.4% after 90 minutes of visible light irradiation [18]. Ying Liu et al. synthesized $NiO/NiCr_2O_4$ via a facile one-pot hydrothermal method without any template, followed by calcination at 600 °C in an N_2 atmosphere. The urea oxidation performance, tested in 1 M KOH with 0.33 M urea at +0.5 V vs Ag/AgCl, showed that $NiO/NiCr_2O_4$ -2 delivered the highest current density of 49.7 mA cm^{-2}, a low Tafel slope of 15.9 mV dec^{-1}, and retained about 68% of its initial current after 1 hour, indicating excellent activity and stability [19]. Nickel chromite nanoparticles were prepared using a modified sol–gel method and calcined at 1073 K for 4 hours. Vibrating Sample Magnetometer measurements suggested that the $NiCr_2O_4$ nanoparticles exhibit paramagnetic behavior, whereas bulk $NiCr_2O_4$ is known to be ferromagnetic [69]. Syuhada et al. synthesized $NiCr_2O_4$ using a thermal treatment method and studied the effect of different calcination temperatures ranging from 550 °C to 850 °C. The nanoparticles exhibited paramagnetic behavior, with g-factor values of 1.92 and 2.15, and corresponding resonance magnetic fields of 342.04 and 306.49 Oe, respectively [70]. Jabbar et al. synthesized AB_2O_4 (A = Co, Ni; B = Cr, Al) using the polymeric route. The results showed that substitution of 50% of Al and Ni in the spinel $CoCr_2O_4$ improved the morphology of the powders, resulting in different shades of green, and the specific surface area increased from 7 m^2/g to 18 m^2/g after the substitution [71]. Syuhada et al. synthesized $NiCr_2O_4$ using a thermal treatment method followed by calcination. The results showed that the values of ΔH_{pp} and the g-factor of $NiCr_2O_4$ increased, whereas the values of Hr decreased with increasing calcination temperature [72]. Nickel chromite was synthesized using a facile, solvent-less ball milling method at different milling durations and speeds. Its efficiency as a photocatalyst for the decolorization of Acid Red 88 under visible light irradiation was investigated, showing more than 99% dye degradation after 150 min [73]. Rasool et al. synthesized $NiCr_2O_4$ and $CoCr_2O_4$ nanoparticles using the sol–gel technique and studied their temperature-dependent magnetic properties. For $CoCr_2O_4$ nanoparticles, the Curie temperature was observed at 98 K, and for $NiCr_2O_4$ nanoparticles, it was 84 K, indicating the presence of weaker A–B exchange interactions in this material [74]. Nickel chromite was prepared by the chemical co-precipitation method. They observed that with increasing annealing temperature, the crystal structure transitioned from cubic to tetragonal phase. They also found that as the annealing temperature increased, the ferrimagnetic transition point shifted toward lower temperatures [75]. $NiCr_2O_4$ was synthesized using the sol–gel auto-combustion route. Dielectric permittivity analysis showed that as the temperature increased, the dielectric constant decreased, while the dielectric loss increased. The reason behind this was the alignment of dipoles with the field direction as the temperature increased [76]. Ajith et al. used the sol–gel auto-combustion method for the production of nickel chromite nanoparticles. The photodegradation of MB showed 89% degradation in 60 min, with a degradation rate of 2.40×10^{-2} min^{-1}. Antibacterial activity showed that S. aureus (Gram-positive) exhibited the highest sensitivity with an inhibition zone of 9 mm, while E.

coli (Gram-negative) exhibited the lowest sensitivity with an inhibition zone of 5 mm [77]. Nickel chromite was prepared by the combustion method using citric acid as a fuel agent. They observed that the Curie temperature of $NiCr_2O_4$ depended on particle size, with 78 nm and 28 nm particles exhibiting T_n values of 70 K and 80 K, respectively, while bulk $NiCr_2O_4$ showed 65 K. They also analyzed crystallites of 28 nm, which showed a notable improvement with a dielectric constant of ε' ~ 5738 at room temperature, whereas 78 nm crystallites exhibited a much lower value of ε' ~ 174 [78]. Chaibeddra et al. synthesized $NiCr_2O_4$ using the co-precipitation method. They observed that $NiCr_2O_4$ alone achieved 58% degradation of methylene blue, while a 50%-50% mixture of $NiCr_2O_4/TiO_2$ (1 g/L dosage) degraded 90% of methyl green after 240 min at an initial dye concentration of 10 mg/L, which was significantly higher than that of pure $NiCr_2O_4$ [79]. Nickel chromite was prepared by the polyacrylamide gel method using citric acid as a chelating agent. They observed that during the degradation of TCH, the photocatalytic activity of ACr_2O_4 (A = Mg, Cu, Ni)/MIL-101(Cr) photocatalysts was superior to that of pure MCO, CCO, NCO, and MIL-101(Cr), with the 10% MMCO photocatalyst exhibiting the highest efficiency under the optimal conditions of 10% MIL-101(Cr) content, 1 g/L catalyst dosage, 50 mg/L initial concentration, pH 7, and 120 min irradiation time [80]. Mirad et al. synthesized spinel $NiCr_2O_4$ via the sol–gel route. They observed that the $NiCr_2O_4$ (60%)/ZnO heterojunction photocatalyst degraded 68% of Orange II under solar irradiation at pH ≈ 7 [81]. Nickel chromite was prepared by the sol–gel route. They analyzed that under optimized conditions, a catalyst dose of 1.2 g/L, a solution pH of 9, and thiosulfate ($S_2O_3^{2-}$) as the hole scavenger, the $NiCr_2O_4$ photocatalyst achieved a maximum hydrogen evolution rate of 8.6 μmol g^{-1} min^{-1} under visible light irradiation [82]. Novikov et al. synthesized $NiCr_2O_4$ by the Solution Combustion Synthesis method. They studied that using this method, 93% nanostructured $NiCr_2O_4$ spinel could be prepared, which showed good CO-to-CO_2 conversion at 150–300°C and was suitable for industrial applications [83].

2.5 Zinc Chromite

Zinc chromite was synthesized by a green synthesis route using natural leaf extracts of Hibiscus rosa-sinensis. The UV–Vis diffuse reflectance analysis revealed that the band gap of $ZnCr_2O_4$ nanoparticles at room temperature was 2.47 eV, while those annealed at 200 °C, 500 °C, and 700 °C exhibited band gaps of 2.40 eV, 3.19 eV, and 3.09 eV, respectively [2]. Priyanka et al. synthesized $ZnCr_2O_4$ using a chemical combustion route with urea (ZCOU) and a green-mediated route using Aloe Vera gel extract (ZCOA). CV analysis revealed that the specific capacitance ranged from 51.4 to 28.8 F/g at different scan rates ranging from 10 to 50 mV/s. The results showed that the materials were capable of storing electrical energy effectively [84]. They synthesized zinc chromite nanoparticles using cow urine as a green precursor and employed them as a heterogeneous nanocatalyst for the formation of Biginelli adducts. The reaction was performed using $ZnCr_2O_4$ nanoparticles, which served as an efficient heterogeneous nanocatalyst for the one-pot synthesis of dihydropyrimidinone analogs under reflux conditions in ethanol, and it was observed that, under optimized conditions of 35 mg catalyst dose and 60 min reflux time, the model reaction yielded 91% [85]. Suresh et al. synthesized $ZnCr_2O_4$ nanorods using a facile sol-gel auto-combustion method. They examined the antifungal and antibacterial activities of $ZnCr_2O_4$ nanorods against pathogenic strains using the disc diffusion technique, and the results showed significant antibacterial, antifungal, and antimalarial activities [86]. Zahra et al. synthesized $ZnCr_2O_4$ using the co-precipitation method. They observed that zinc chromite efficiently catalyzed the decomposition of Eosin-Y and phenol red, reaching 95.26% and 13.42%,

respectively, under UV irradiation for 30 minutes [87]. $ZnCr_2O_4$ nanoparticles were synthesized using the sol-gel auto-combustion technique, and their antibacterial activity was analyzed, showing pathogen growth inhibition with the highest sensitivity against Bacillus subtilis (10±0.0 mm) and the lowest against Salmonella (7±0.03 mm). Their anticancer activity was assessed on HeLa and MCF-7 cell lines using the MTT assay, and their photocatalytic performance was evaluated against methylene blue, achieving 96.5% degradation within 70 minutes [88]. Mohammad et al. synthesized $ZnCr_2O_4$ using the sol–gel method with oxalic acid as a chelating agent. They selected the reactive azo dye RB5 as a model dye. The highest degradation efficiency after 20 minutes was observed to be 96% in the presence of $ZnCr_2O_4$ combined with UV irradiation, whereas it was 90% in the presence of $ZnCr_2O_4$ alone and only 13% under UV irradiation alone [89]. Zinc chromite nanocrystals were synthesized by a co-precipitation and post-calcination method [90]. Mykhailovych et al. synthesized $ZnCr_2O_4$ using a simple sol–gel auto-combustion method and calcined it at temperatures ranging from 500 °C to 900 °C. They analyzed the sample annealed at 900 °C for 11 hours and identified it as the most promising for device fabrication because it was a single-phase material that exhibited a high, stable dielectric permittivity across the frequency range along with the lowest dielectric loss [91]. Nano-crystalline ZnM_2O_4 (M = Al, Fe, Cr, Mn) particles have been prepared by various methods, such as combustion, hydrothermal, and sol–gel methods [92]. Miranda et al. prepared ceramic nanopigments of $ZnCr_2O_4$ using the solution combustion method with glycine, urea, and citric acid as fuels. Colorimetric coordinates showed that the glycine-based pigment appeared light greenish-yellow, the urea-based pigment exhibited a darker yellow-green hue, and the citric acid-based pigment displayed a dark reddish-yellow color, confirming that the final color depends on the type of fuel used during synthesis [93]. They synthesized nanocrystalline zinc chromite using the hydrothermal method. Impedance spectroscopy showed that the dielectric constant exhibited dispersion at lower frequencies below 60 Hz due to interfacial polarization and electrode effects, whereas at frequencies greater than 2×10^6 Hz, the dielectric constant became independent of frequency, which was attributed to atomic and electronic polarizations [94]. Sankudevan et al. synthesized nanocrystalline $ZnCr_2O_4$ using a microwave-assisted solution combustion method with different fuels, namely citric acid, succinic acid, maleic acid, glycine, and urea. VSM analysis showed that the synthesized zinc chromite exhibited the highest coercivity, remanence, and magnetization values of 51.98 Oe, 10.34 emu/g, and 49.56 emu/g, respectively, when urea was used as the fuel [95]. Peng et al. synthesized $ZnCr_2O_4$ using the hydrothermal route and found that the direct band gap was 3.46 eV. They observed that $ZnCr_2O_4$ exhibited significant photocatalytic activity toward methylene blue, degrading 87% in 2 hours, with complete decomposition under UV light occurring in about 3 hours [96]. They synthesized a series of chromium spinels, MCr_2O_4 (M = Zn, Co, Cu, and Ni), by a combustion reaction using urea as the fuel. They observed that the type of divalent metal ion (M) in the spinel structure determines the unique final color of the pigment, which is quantitatively reflected by clear differences in their L*, a*, and b* colorimetric coordinates [97]. Bangale et al. prepared zinc chromite by the solution combustion method using glycine as a fuel. They studied its electrical properties and observed that the conductivity increased with an increase in temperature, indicating a negative temperature coefficient and confirming that the material behaves as a semiconductor [98]. Mimouni et al. synthesized $ZnO/ZnCr_2O_4$ nanocomposites using the spray pyrolysis technique at 400 °C under nitrogen at 0.35 bar. They observed that the $ZnO/ZnCr_2O_4$ nanocomposite degraded nearly 93% of methylene blue dye after two hours of UV irradiation, a performance superior to that of pure ZnO and $ZnCr_2O_4$ [99]. Gene et al. synthesized spinel zinc chromite nanocrystallites

by the thermal treatment method and calcined them at 773, 823, 873, 923, and 973 K for 3 hours. ESR spectroscopy revealed that as the calcination temperature increased from 773 K to 973 K, the g-factor increased while the resonance magnetic field decreased, indicating an enhancement in the magnetic properties of the samples due to the increase in particle size with rising calcination temperature [100]. $ZnCr_2O_4$ was synthesized via the thermal decomposition method and calcined at temperatures ranging from 450 to 800 °C. They observed that the $ZnCr_2O_4$ photocatalyst exhibited about 60% photocatalytic efficiency, indicating that humic acids were effectively degraded and mineralized into harmless compounds CO_2 and H_2O, following a pseudo-first-order kinetic model characteristic of light-driven reactions [101]. Poschmann et al. synthesized $ZnCr_2O_4$ via thermal decomposition of $(NH_4)_2[Zn(NH_3)_2(CrO_4)_2]$. They observed that $ZnCr_2O_4$ efficiently degraded Eosin Y dye with high photocatalytic activity, achieving a rate constant of 47.1×10^{-3} min^{-1}, which is 4–5 times higher than that of TiO_2 and N:TiO_2, even without the addition of H_2O_2 [102].

3 Doped Chromite

3.1 Doped Cobalt Chromite

Dave P. et al. prepared $NiCoCr_2O_4$ using the co-precipitation method. They observed that $NiCoCr_2O_4$ lowered the decomposition peak of AN by 40 °C (from ≈280 °C to 240 °C) and reduced its activation energy, confirming that the catalyst significantly accelerates and facilitates AN decomposition, making AN/$NiCoCr_2O_4$ a more efficient energetic material [20]. Chengwei Zhang et al. synthesized rare-earth-doped cobalt chromates, $CoCr_{2-x}Dy_xO_4$ (x = 0, 0.01, 0.03, and 0.05; where Dy^{3+} is a rare-earth element), using the combustion method with glucose and urea as fuels. The specific capacitance values ranged from 0.29 to 0.38 F/cm^2 at a scan rate of 1 mV/s in CV measurements, and from 0.21 to 0.23 F/cm^2 at a current density of 3 mA/cm^2 in GCD measurements. The results indicated that the substitution of Dy^{3+} ions into the $CoCr_2O_4$ lattice increased the capacitance, suggesting that Dy^{3+} doping improved the electrical conductivity and active surface area of the material [103]. They synthesized magnesium-doped cobalt chromite, $Co_{1-x}Mg_xCr_2O_4$ (x = 0, 0.2, 0.4, 0.5, 0.6, 0.8, and 1), using the sol–gel method. They studied the magnetic properties and found that undoped $CoCr_2O_4$ was ferrimagnetic below the Curie temperature (T(C) = 97 K), whereas pure $MgCr_2O_4$ exhibited a highly frustrated antiferromagnetic structure with a Néel temperature (T(N) ≈ 15 K). As the composition (x) increased from 0 to 1, both the Curie temperature and spiral ordering temperature gradually decreased, indicating that the substitution of magnetic Co^{2+} ions with non-magnetic Mg^{2+} ions weakened the magnetic exchange interactions. The composition at x = 0.6 represented a critical point, exhibiting both ferrimagnetic and antiferromagnetic transitions [104]. For $CoCr_{2-x}Fe_xO_4$, Mössbauer spectroscopy revealed the site occupancy of Fe ions as a function of Fe content. At x = 0.1, approximately 60% of Fe ions occupied the tetrahedral (A) sites. With an increase to x = 0.3, Fe ions were almost equally distributed between the tetrahedral (A) and octahedral (B) sites. At a higher concentration of x = 0.5, only 40% of Fe ions remained at the A site, while the majority shifted to the octahedral (B) sites [105]. Saeed et al. synthesized $Co_{1-x}Ni_xCr_2O_4$ (x = 0.2, 0.4, 0.6, and 0.8) using the sol–gel method and studied the effect of Ni concentration on their bandgap, structure, and optical properties [106]. Cu-doped cobalt chromite nanoparticles, $Cu_xCo_{1-x}Cr_2O_4$ (x = 0.0, 0.1, 0.2, and 0.3), were prepared by the co-precipitation method. They observed that the dilution of the total magnetic moment

occurs because the substitution replaces the strongly magnetic Co^{2+} ions (3.87 μB) with less magnetic, paramagnetic Cu^{2+} ions (1.73 μB), thereby weakening the magnetic super exchange interactions within the cobalt chromite lattice as the Cu content increases [107]. Choudhary P et al. synthesized Cu^{2+} doped cobalt chromite, $Co_{1-x}Cu_xCr_2O_4$ (x = 0.0, 0.5), using a low-temperature fired sol-gel auto-combustion method. Substituting 50% of Co^{2+} with Cu^{2+} disrupts the lattice symmetry, and the difference in ionic radii along with the Jahn-Teller effect of Cu^{2+} induces a distortion from cubic to tetragonal structure with space group $I4_1/amd$. The Cu-doped chromite exhibited lower dielectric loss compared to pure $CoCr_2O_4$, indicating that $Co_{0.5}Cu_{0.5}Cr_2O_4$ can store energy more efficiently with minimal losses, making it suitable for electronic applications requiring stable dielectric materials [108]. Garg et al. prepared Zn-doped cobalt chromite, $Co_{1-x}Zn_xCr_2O_4$ (x = 0, 0.5, and 1.0), using the solid-state technique. They studied the dielectric properties and found that the maximum dielectric constant at 50% Zn doping was 24,843.271 at 100 Hz, which was approximately six times higher than that of pristine $CoCr_2O_4$, while the lowest dielectric loss was observed for the 100% Zn-doped sample, with a value of 0.02452 [109]. The direct optical band gap, estimated from Tauc plots, increased slightly with Zn doping. The values were 3.15 eV for $CoCr_2O_4$, 3.24 eV for $Co_{0.8}Zn_{0.2}Cr_2O_4$, and 3.27 eV for $Co_{0.6}Zn_{0.4}Cr_2O_4$ [110]. Ghosh P. et al. synthesized Gd^{3+} doped cobalt chromite, $CoCr_{2-x}Gd_xO_4$ (x = 0.00, 0.04, 0.08, and 0.12), using the co-precipitation technique. They studied the magnetic properties of the nanoparticles and found that the Curie temperature (T(C)) of pure $CoCr_2O_4$ nanoparticles (94.8 K) was slightly lower than that of the bulk material (≈97 K), but it increased with Gd^{3+} doping 95.2 K (x = 0.04), 95.7 K (x = 0.08), and 96.3 K (x = 0.12), which was attributed to the substitution of Cr^{3+} ions (≈3.8 μB) with Gd^{3+} ions having a higher magnetic moment (≈7.9 μB) [111]. Mohanty et al. synthesized nickel-doped cobalt chromite ($(Co_{1-x}Ni_x)Cr_2O_4$, x = 0.5 and 0.25) using the sol-gel technique. They studied the magnetic properties of both samples and observed that both exhibit ferrimagnetic behavior below their Curie temperatures (T(C)), where the magnetic moments of ions are antiparallel but unequal, resulting in net magnetization. The absence of saturation even at high magnetic fields (up to 12 T) indicates strong magnetic interactions within the spinel lattice [112]. Zinc, magnesium, and copper-doped cobalt chromites ($Co_{1-x}M_xCr_2O_4$; M = Zn, Mg, Cu; x = 0.0, 0.5) were synthesized via a low-temperature sol-gel auto-combustion method. The tetragonal distortion was attributed to the substitution of Jahn–Teller active Cu^{2+} ions, leading to cooperative Jahn–Teller distortion. The electrical properties showed that at 20 Hz, the highest dielectric constant (252175) and the lowest dielectric loss (1.99) were observed for $Co_{0.5}Zn_{0.5}Cr_2O_4$ [113]. Kumar et al. synthesized Fe-doped $CoCr_2O_4$ powders using the co-precipitation technique. Magnetic studies showed that in $CoCr_{2-x}Fe_xO_4$, as the Fe content (x) increased from 0.1 to 0.4, the Curie temperature (T(C)) increased from 102 K to 160 K, and the spiral spin transition temperature (T(S)) increased from 26 K to 40 K. This enhancement in both T(C) and T(S) was attributed to the strengthening of the A–B (Co–O–Fe/Cr) exchange [114].

3.2 Doped Copper Chromite

Rajeswari et al. synthesized La-doped $CuCr_2O_4$ using the microwave-assisted method. They evaluated the synthesized materials as electrodes in dye-sensitized solar cells (DSSCs). The results showed that the maximum short-circuit photocurrent density was 17.63 mA cm^{-2}, the maximum fill factor was 0.77±0.06, and the maximum power conversion efficiency reached 26.65±0.09% for the 0.03 La-doped $CuCr_2O_4$ electrode [115]. Cadmium- and neodymium-doped copper chromite, $Cu_{1-x}M_xCr_2O_4$ (M = Nd, Cd), was synthesized using

the sol–gel method. The photoluminescence spectra indicated a decrease in the band gap from 4.96 eV (pure sample) to 2.43 eV and 2.42 eV for Cd- and Nd-doped samples, respectively [116]. Kumari P.S. et al. fabricated Ni-doped copper chromite, $Cu_{1-x}Ni_xCr_2O_4$ (x = 0.0, 0.2, 0.4, 0.6, 0.8, and 1.0), using the citrate gel auto-combustion technique, with citric acid used as both the chelating agent and fuel. The photocatalytic results revealed that the maximum dye degradation efficiency was observed for x = 1.0, indicating that the synthesized materials were highly effective in degrading methylene blue and acid red dyes. The anticancer study concluded that Cu–Ni nanochromites with higher nickel content, particularly $Cu_{0.2}Ni_{0.8}Cr_2O_4$, exhibited the strongest cytotoxicity against HeLa cells, as indicated by the lowest IC_{50} value of 21.83 µg/ml [117]. Lanthanum-doped $CuCr_2O_4$ was prepared by the sol–gel Pechini approach using citric acid. $CuCrLaO_4$ showed the highest photocatalytic activity among the La-doped samples because its optimal La content improved charge carrier generation and reduced electron-hole recombination. Moreover, the catalyst could be reused up to five times without significant loss of activity, and its weak magnetic properties made it easy to separate from water [118]. Batool K. et al. prepared zinc-doped copper chromite, $Cu_{1-x}Zn_xCr_2O_4$ (with x = 0.2, 0.4, 0.6, and 0.8), using the sol–gel method and studied its properties with techniques such as XRD, EDS, SEM, UV–Vis, Raman spectroscopy, and photoluminescence [119]. Magnesium-doped copper chromite, $Cu_{1-x}Mg_xCr_2O_4$ with x = 0.2, 0.4, 0.6, and 0.8 was synthesized via the sol–gel method. UV–Visible spectra showed that the parent $CuCr_2O_4$ sample had an optical band gap of 5.02 eV, which decreased to 4.17 eV upon Mg doping [120]. Sankudevan et al. prepared $CuCr_2O_4$ and Mn-doped $CuCr_2O_4$ (Mn 0.01, 0.02, and 0.03 wt%) nanoparticles using the microwave combustion process. They observed that the electrical conductivity of Mn-doped $CuCr_2O_4$ (2.13×10^{-2} S/cm) was nearly double that of pristine $CuCr_2O_4$ (0.98×10^{-2} S/cm). The activation energies were found to be 0.87 eV for pristine $CuCr_2O_4$ and 0.69 eV for Mn-doped $CuCr_2O_4$ [121]. Harrabi et al. synthesized $Mg_{0.6}T_{0.4}Cr_2O_4$ (T = Ni, Cu) using the sol–gel method. From VSM measurements, they found that Mn-doped $CuCr_2O_4$ showed slightly improved magnetic properties compared to pristine $CuCr_2O_4$. The saturation magnetization (Ms) increased from 0.058 to 0.061 emu/g, the remanent magnetization (Mr) increased from 4.90×10^{-3} to 8.4×10^{-3} emu/g, and the coercivity (Hc) went up from 40 to 53 Oe, demonstrating that Mn doping enhanced the magnetic response of the spinel chromite [122]. Magnesium-doped copper chromite ($CuCr_2O_4$, Mg – 0.01%, 0.02%, and 0.03%) was synthesized using a microwave technique, with thioglycolic acid used as the fuel. UV–Vis. spectra showed that the estimated band gap energy for undoped $CuCr_2O_4$ was 1.954 eV, while Mg-doped $CuCr_2O_4$ exhibited increased band gap values of 2.303 eV, 2.38 eV, and 2.59 eV for Mg doping concentrations of 0.01%, 0.02%, and 0.03%, respectively [123].

3.3 Doped Magnesium Chromite

Moridnia F et al. synthesized $MgFeCrO_4$ using a green sol-gel method with tragacanth gum (TG). They observed that the $MgFeCrO_4$ MNPs showed excellent photocatalytic performance under visible light, degrading 96% of DB122 in just 60 s. The results also showed that increasing the initial dye concentration led to a decrease in efficiency from 96% at 10 mg/L to 71% at 40 mg/L, because higher concentrations blocked photons from reaching the catalyst surface and consumed more reactive radicals than were available. Despite this, the photocatalyst remained highly stable over four consecutive runs, with decolorization only slightly decreasing from 96% to 91%, indicating good reusability [124]. Deshmukh S. P. et al. prepared manganese-substituted magnesium chromite, $Mg_{1-x}Mn_xCr_2O_4$ (x = 0.0, 0.25, 0.50, 0.75, 1.0), using the sol–gel auto-combustion method

with citric acid as a chelating agent. They analyzed the samples using the Vibrating Sample Magnetometer (VSM) technique and found that the maximum coercive field (79.925 G) and remanent magnetization (38.473×10^{-3} emu) were observed for $MgCr_2O_4$, while the maximum saturation magnetization (16.648×10^{-3} emu) was obtained for $MnCr_2O_4$ [125]. They synthesized Ni- and Cu-doped magnesium spinel chromites, namely $Mg_{0.6}Ni_{0.4}Cr_2O_4$ and $Mg_{0.6}Cu_{0.4}Cr_2O_4$, using the sol–gel method. From the UV–Vis spectra, it was observed that the band gap and Urbach energy values were lower for MCCO compared to MNCO, suggesting that Cu doping enhances the optical absorption properties of the material [126]. Khalaf K. A. et al. prepared Zn^{2+}-doped magnesium chromite, $Mg_{1-x}Zn_xFeCrO_4$ ($0.0 \le x \le 1.0$), using the conventional double-sintering ceramic method. XRD analysis showed that increasing Zn^{2+} content expands the lattice due to the larger ionic radius of Zn^{2+} compared to Mg^{2+}. Moreover, higher Zn^{2+} levels lead to a gradual transformation from a mixed normal-inverse spinel to a fully normal spinel structure, indicating improved structural ordering [127]. Gismelseed et al. synthesized Zn-substituted magnesium ferrite chromate, $Mg_{1-x}Zn_xFeCrO_4$ ($0.0 \le x \le 1.0$), using the conventional solid-state double sintering ceramic technique. XRD analysis showed that the lattice constant of $MgFeCrO_4$ ($x = 0.0$) was 8.3558 Å, while that of the end member $ZnFeCrO_4$ ($x = 1.0$) increased to 8.3835 Å. This increase in the lattice parameter with Zn^{2+} substitution was attributed to the larger ionic radius of Zn^{2+} (0.82 Å) occupying the tetrahedral (A) sites, which displaced the smaller Fe^{3+} ions (0.67 Å) to the octahedral(B) sites [128]. Nadeem et al. synthesized Mg-doped nickel chromite, $Mg_xNi_{1-x}Cr_2O_4$ ($x = 0$, 0.2, 0.4, 0.6, and 1), using the sol-gel method. They observed that Mg doping in $NiCr_2O_4$ nanoparticles weakened magnetic interactions, resulting in a decrease in Curie temperature, saturation magnetization, coercivity, and magnetocrystalline anisotropy, while inducing an antiferromagnetic phase that became fully stable in $MgCr_2O_4$ at 15 K [129]. $MgFe_xCr_{2-x}O_4$ ($0 \le x \le 1.0$) nanoparticles were synthesized by a microwave method. They observed that $MgFe_xCr_{2-x}O_4$ nanoparticles exhibited antiferromagnetic behaviour, with the Néel temperature increasing from 13 K ($MgCr_2O_4$) to 20 K ($MgFe_{0.6}Cr_{1.4}O_4$). Below TN, magnetization increased rapidly, whereas above TN, spontaneous magnetization disappeared and the material became paramagnetic [130]. Wu Qi et al. prepared copper-doped magnesium chromite, $Mg_{1-x}Cu_xCr_2O_4$ ($0.1 \le x \le 0.4$), using the solid-state reaction method combined with ball milling for better powder mixing. They observed that increasing the Cu concentration decreased the band gap from 3.59 eV for pure $MgCr_2O_4$ to 2.67 eV for $Mg_{0.6}Cu_{0.4}Cr_2O_4$ [131]. The compound $Mg_{0.6}Cu_{0.2}Ni_{0.2}Cr_2O_4$ spinel was prepared by the sol-gel process. UV–Visible spectroscopy analysis revealed a band gap of 1.60 eV and an Urbach energy of 0.57 eV, confirming the presence of disorder in the prepared compound [132]. Yin et al. prepared cobalt- and aluminium-doped cobalt chromite, $Mg_xCo_{1-x}Cr_{2-y}Al_yO_4$ ($0 \le x \le 1$, $0 \le y \le 2$), using the gel-casting method. They observed that the optical and structural properties of $Mg_xCo_{1-x}Cr_{2-y}Al_yO_4$ spinels were strongly influenced by cation substitution and site occupancy. Substitution of Al^{3+} enhanced the blue tone by increasing Co^{2+} ions in tetrahedral sites, whereas substitution of Mg^{2+} or calcination in a reducing atmosphere reduced the blue intensity due to decreased Co^{2+} occupancy in tetrahedral sites [133].

3.4 Doped Nickel Chromite

Noshahi et al. synthesized Mn-doped nickel chromite ($Ni_{1-x}Mn_xCr_2O_4$, $x = 0$, 0.2, 0.3, 0.4, 0.6, 0.8) using the sol–gel method. They investigated the magnetic properties of $Ni_{1-x}Mn_xCr_2O_4$ nanoparticles and found that the Curie temperature (T(c)) was 87 K for pure $NiCr_2O_4$ ($x = 0$), which initially increased to 146 K at $x = 0.2$ due to enhanced crystallite

size and stronger A–B site exchange interactions; however, with further Mn substitution (x > 0.2), T(c) gradually decreased because of lattice distortion, cation redistribution, magnetic inhomogeneity, and competing exchange interactions [134]. $(Ni_{1-x}Co_x)Cr_2O_4$ (x = 0, 0.50, 0.75, 1.00) was prepared using the chemical co-precipitation technique. It was observed that both $(Ni_{0.5}Co_{0.5})Cr_2O_4$ and $(Ni_{0.25}Co_{0.75})Cr_2O_4$ exhibited ferrimagnetic behavior with Curie temperatures of 56.2±0.9 K and 76.8±0.4 K, respectively. The corresponding frustration indices were 7.1 and 6.5, indicating that $(Ni_{0.5}Co_{0.5})Cr_2O_4$ is more magnetically frustrated due to stronger competing magnetic interactions and higher magnetic disorder compared to $(Ni_{0.25}Co_{0.75})Cr_2O_4$ [135]. Ragupathi et al. prepared Mn-doped nickel chromite (Mn content: 0.00%, 0.01%, 0.02%, and 0.03%) using the microwave synthesis method. VSM measurements revealed that as the Mn concentration increased, the coercivity varied from 13.1234 to 22.4523 Oe, the remanence (retentivity) increased from 1.0051 to 2.9457 emu/g, and the saturation magnetization increased from 24.1278 to 66.1265 emu/g [136]. Polycrystalline $NiCr_{1.9}Mn_{0.1}O_4$ was synthesized by the sol–gel method and calcined at 400 °C for 5 hours. The magnetic study revealed horizontal and longitudinal shifts in the hysteresis loop, confirming the presence of a strong exchange bias (EB) effect in $NiCr_{1.9}Mn_{0.1}O_4$. This behavior indicates effective exchange coupling between ferrimagnetic and spin-glass-like phases, leading to enhanced interfacial magnetic interactions and asymmetric magnetization reversal [137]. Hcini F et al. prepared $Ni_{0.5}Mn_{0.5}Cr_2O_4$ using the sol-gel route. UV–Vis spectroscopy showed that the sample had a direct band gap energy of Eg = 1.9 eV, indicating strong absorption of visible light, which favored photocatalytic applications. Magnetic measurements indicated a ferromagnetic to paramagnetic phase transition of second-order type at T(c) = 40 K [138]. The zinc-doped nickel chromite samples, $Ni_{1-x}Zn_xCr_2O_4$ (where $0 \le x \le 1$, in steps of 0.2), were synthesized using the citrate gel auto-combustion method. The photocatalytic degradation of methylene blue was studied at different concentrations and various time intervals. The results showed that all the synthesized samples achieved complete degradation under UV light, indicating excellent photocatalytic efficiency. In addition, the anticancer activity of the samples was evaluated using an assay on HeLa cell lines, and all samples exhibited cytotoxic effects with IC_{50} values ranging from 21.83 to 74.15 µg/mL, reflecting variations in their biological efficacy [139]. Ragupathi et al. synthesized Ce-doped nickel chromite using the microwave method. They studied the magnetic properties of Ce-doped $NiCr_2O_4$ samples and observed that at 0.03% Ce doping, the maximum values of coercivity (Hc), remanent magnetization (Mr), and saturation magnetization (Ms) were 16.56 Oe, 13.123 emu/g, and 32.12 emu/g, respectively. These values were significantly higher than those of the samples doped with 0.01% and 0.02% Ce, indicating that increasing the Ce concentration enhanced the overall magnetic performance of $NiCr_2O_4$ [140]. $Ca_{0.07}Ni_{0.93}Cr_2O_4$ was fabricated by the solid-state method. The optical band gap was found to be 1.784 eV for pure $NiCr_2O_4$ and 1.878 eV for $Ca_{0.07}Ni_{0.93}Cr_2O_4$. The slight increase in band gap upon Ca^{2+} substitution may be attributed to lattice distortion and modification of the electronic structure caused by Ca incorporation. This enhancement in band gap confirmed the semiconducting behavior of the material, making it more suitable for potential optical and electronic device applications [141]. Vanasundari K et al. synthesized Gd-doped nickel chromites, $NiCr_{2-x}Gd_xO_4$ (x = 0.0, 0.1, 0.2, and 0.3%), using an economical solution combustion method. They studied the magnetic properties of the samples and found that the maximum Ms, Mr, and Hc were 32.016 emu/g, 1.386 emu/g, and 36.901 Oe, respectively, for 0.3% Gd-doped nickel chromite, and attributed this increase to factors such as the increase in Ni^{2+} concentration, redistribution of cations, and the presence of vacancies and defects [142]. Kumari et al. prepared magnesium-doped nickel chromite, $Ni_{1-x}Mg_xCr_2O_4$ (x = 0.0, 0.2, 0.4, 0.6, 0.8, 1.0)

spinels using the citrate gel method. They observed photocatalytic activity in model dyes, methylene blue (MB) and acid red (AR), under UV light. Within 90 minutes, the $Ni_{0.6}Mg_{0.4}Cr_2O_4$ sample achieved 60% degradation of MB, while pure $NiCr_2O_4$ showed 62% degradation of AR. They also studied the antimicrobial properties against both Gram-positive and Gram-negative bacteria and the anticancer activity against HeLa cells [143].

3.5 Doped Zinc Chromite

El Hajjar et al. prepared $Zn_{0.33}Co_{0.33}Mg_{0.33}X_2O_4$ (where X = Fe, Cr, or Al) using the co-precipitation method. Among the synthesized samples, $Zn_{0.33}Co_{0.33}Mg_{0.33}Al_2O_4$ exhibited the most effective bactericidal activity, completely killing Staphylococcus aureus and Escherichia coli after 24 hours of incubation, and Enterococcus faecium after just 2 hours at MBC values. It was analyzed that this superior antimicrobial performance was associated with its smallest particle size (15.399 nm), lowest band gap energy (2.355 eV), and reduced magnetic parameters (Mr = 0.5769×10^{-2} emu/g and Hc = 6.2262 G). Therefore, it was concluded that $Zn_{0.33}Co_{0.33}Mg_{0.33}Al_2O_4$ possesses strong potential as an efficient antimicrobial nanomaterial against multidrug-resistant bacterial strains [144]. $Zn_{0.5}Cu_{0.5}Cr_2O_4$ ceramic pigments were synthesized using the solution combustion synthesis method. The results showed that the pigments exhibited stable black coloration and a spinel structure, indicating their suitability for ceramic decoration applications [145]. Choudhary P et al. prepared copper-doped magnesium zinc chromite, $Mg_{0.5}Zn_{0.5-x}Co_xCr_2O_4$ ($0.0 \le x \le 0.5$), using the high-temperature solid-state method. They studied the UV–Vis. spectra and found that the optical band gap decreased with increasing Co^{2+} concentration, as Co^{2+} ions replaced Zn^{2+} ions. The dielectric constant also increased with Co^{2+} concentration, reaching a maximum at x = 0.3, and decreased at higher concentrations [146]. Chromium-doped Ni-Cu-Zn Nano ferrites, $Ni_{0.2}Cu_{0.2}Zn_{0.6}Fe_{2-x}Cr_xO_4$ (x = 0.0, 0.2, 0.4, 0.6, 0.8, and 1.0), were synthesized using the sol–gel auto-combustion method [147]. Manjunatha et al. synthesized Zn^{2+}-substituted $MnCr_2O_4$ using the solution combustion method and studied its structural, electronic, vibrational, and magnetic properties. Zero-field-cooled (ZFC) and field-cooled (FC) measurements revealed that $Mn_{0.5}Zn_{0.5}Cr_2O_4$ nanoparticles exhibited a higher transition temperature and a larger frustration factor than bulk and nanoscale $ZnCr_2O_4$, indicating stronger magnetic interactions and a paramagnetic-to-antiferromagnetic phase transition [148]. $Zn_{0.5}Cu_{0.5}Cr_2O_4$ was synthesized by the solution combustion method using glycine, urea, and citric acid as fuels. The powders synthesized with urea and citric acid appeared darker black than those with glycine, indicating their potential use as ceramic pigments [149]. Priyanka et al. prepared samarium-doped $ZnCr_2O_4$ nanoparticles by the solution combustion method using Aloe Vera gel extract as a reducing agent. UV–Vis spectral analysis revealed that the energy band gap decreased from 2.91 eV to 2.87 eV with increasing dopant concentration. Cyclic voltammetry studies showed that the specific capacitance increased from 89.35 F/g to 130.92 F/g as the Sm concentration increased [150]. They prepared cobalt-substituted zinc chromite spinel $Zn_{1-x}Co_xCr_2O_4$ (x = 0.0, 0.25, 0.50, 0.75, 1.0) by the microwave-hydrothermal technique. The analysis showed that as the Co content increased, the resistivity decreased, while the dielectric constant and dielectric loss increased with both frequency and Co concentration. Mechanical studies further revealed that hardness and fracture toughness also increased with increasing Co concentration [151]. Melot et al. synthesized $Zn_{1-x}Co_xCr_2O_4$ (x = 0.2, 0.4, 0.6, 0.8, 1.0) by solid state routes. It was observed that the progressive substitution of Cobalt in $Zn_{1-x}Co_xCr_2O_4$ tuned the magnetic behavior from a spin glass state at low Co concentrations,

caused by disrupted antiferromagnetic order and spin frustration, to ferrimagnetic and spiral magnetic ordering at higher Co concentrations, resembling the magnetic nature of $CoCr_2O_4$ [152]. Priyanka et al. prepared cerium-doped $ZnCr_2O_4$ nanoparticles by the solution combustion method using Aloe vera gel extract as a green fuel. Electrochemical properties were studied using cyclic voltammetry, and the supercapacitance values were observed to increase from 84.29 F/g to 123.41 F/g with higher Ce concentration, indicating strong sensitivity to the dopant amount [153]. Table (1) shows the comparison of dye degradation performance of different spinel chromite and their composite. Table (2) shows that chromite-based electrodes exhibit excellent supercapacitor performance, with composites, doped samples, and optimized synthesis methods significantly enhancing capacitance, energy density, and cycling stability.

Table 1. Comparison of Dye Degradation Performance of Spinel Chromites and their composite

Dye	System	Time	Light Source and Condition	Catalyst dose (g/l)	Dye Concentration (mg/l)	Percentage (%)	Ref.
Methylene blue	$CoCr_2O_4$	160 min.	UV–Vis (Xenon lamp 450 W)	-	20	100	[23]
	$CoCr_2O_4$ + 15% wt. g-C_3N_3	80 min.	UV–Vis (Xenon lamp 450 W)	-	20	100	[23]
	$CuCr_2O_4$	-	Solar irradiation + 30% H_2O_2 was mixed with 50 ml	0.10	10	80.6	[39]
	$CuCr_2O_4$	180 min.	Visible light source (150 W)	2	2	84	[46]
	$CuCr_2O_4$	90 min.	Sunlight at room temperature at pH 7	0.2	10	88	[47]
	$CuCr_2O_4$	-	LED light (λ=440nm)	0.6	10	98	[48]
	$NiCr_2O_4$	60 min.	-	-	-	89	[77]
	$ZnCr_2O_4$	70 min.	Sun light	0.4	10	96.5	[88]
	$ZnCr_2O_4$	120 min.	UV–Vis light (300 W medium-pressure Hg lamp)	0.4	100	87	[96]
	$ZnCr_2O_4$/ZnO	120 min.	UV light	-	-	93	[99]
	$Ni_{0.6}Mg_{0.4}Cr_2O_4$	90 min.	UV light (400 W)	0.05 g	0.05 g	60	[143]
Malachite Green	ZnO/$CoCr_2O_4$	-	Visible lamp (λ >420 nm, TForce Core 50 W)	0.12	5 μM	90.91	[5]
	$CoCr_2O_4$	-	Visible lamp (λ >420 nm,	0.12	5 μM	70	[5]

			TForce Core 50 W)				
	$CoCr_2O_4$	-	Sunlight	-	20 ppm	91.33	[21]
	$MgCr_2O_4$	120 min.	Sun light	0.5	5	70	[68]
	$NiCr_2O_4$	120 min.	Sun light	0.5	5	90	[68]
	$NiCr_2O_4/TiO_2$	240 min.	Sun light (pH 7, $NiCr_2O_4/TiO_2$ 50–50% weight ratio)	1	10	90	[79]
Congo Red	CCO@450	60 min.	Room light	0.8	20	90	[29]
	CCO@550	60 min.	Room light	0.8	20	87	[29]
	$CoCr_2O_4$	180 min.	Sun light	0.2	10	84.5	[30]
	$CoCr_2O_4+H_2O_2$	180 min.	Sun light	0.2	10	94	[30]
Methyl Orange	$CuCr_2O_4$	-	Solar irradiation + 30% H_2O_2 was mixed with 50 ml	0.10	10	92.3	[39]
	$CuCr_2O_4$	180 min.	Visible light source (150 W)	2	2	45	[46]
	$CuCr_2O_4$	-	LED light (λ=440nm)	0.6	10	87	[48]
Rhodamine B	$CuCr_2O_4$	-	Solar irradiation + 30% H_2O_2 was mixed with 50 ml	0.10	10	93.6	[39]
	$MgCr_2O_4$	60 min.	UV lamp (400 W, pH 7)	1.25	10	70	[56]
CV	$MgCr_2O_4$	120 min.	Sun light	0.5	5	85	[68]
	$NiCr_2O_4$	120 min.	Sun light	0.5	5	95	[68]
Phenol Red	$ZnO/NiCr_2O_4$	90 min.	Visible light source (50 W LED lamp, λ = 450-650 nm)	1	5	81.4	[18]
	$ZnCr_2O_4$	30 min.	UV light (400 W)	-	-	13.42	[87]
Azo dye	$CuCr_2O_4$	-	Visible radiation. (125W high-pressure mercury lamp)	0.5	50	99.6	[53]
Azo dye RB5	$ZnCr_2O_4$	20 min.	Mercury lamp (Max=365nm, 300W)	1	50	96	[89]

SY Dye	$CuCr_2O_4$	240 min.	Tungsten bulb (200 W, pH 4)	0.8	10	97	[12]
TC	$ZnO/NiCr_2O_4$	20 min.	Visible light (50W LED lamp, λ = 450-650 nm)	1	20	98	[18]
Eriochrome Black T	$CoCr_2O_4$	90 min.	Visible light (90 W lamp, λ>400nm)	0.80	20	93	[22]
Reactive Blue 222	$CoCr_2O_4$	10 min.	Visible light (Fluorescent lamp, λ > 400, 90 W,)	0.80	40	93	[27]
BB41	$CoCr_2O_4$	180 min.	Visible light (Tungsten filament, 200 W, pH 9)	0.5	10	99	[33]
Fuchsin Dye	$CoCr_2O_4$	60 min.	UV–visible light	0.5	5	100	[37]
Xylenol Orange	$MgCr_2O_4$	10 min.	UV–visible mercury vapor lamp (125 W, pH 7)	1	0.479	92	[58]
Rh-G6	$MgCr_2O_4$	150 min.	UV–visible mercury vapor lamp (125 W, pH 7)	1	0.479	92.5	[58]
Red 88	$NiCr_2O_4$	150 min.	Mercury lamp (250 W, pH 7)	0.8	2	99	[73]
Orange (II)	ZnO/(60%) $NiCr_2O_4$	23 min.	Sun light (pH 7)	-	20	68	[81]
Eosin -Y	$ZnCr_2O_4$	30 min.	UV light (400 W)	-	-	95.26	[87]
DB122	$MgFeCr_2O_4$	60 sec.	Visible light (90W lamp, λ > 400nm)	0.8	10	96	[124]
Acid Red	$NiCr_2O_4$	90 min.	UV light (400 W)	0.05 g	0.05 g	62	[143]

Table 2. Comparison of electrochemical performance parameters of various chromite-based electrodes.

No.	**Sample**	**Specific Capacitance C_s (F g^{-1})**	**Current density (A g^{-1})**	**Voltage window (V)**	**Energy density (Wh kg^{-1})**	**Power density (W kg^{-1})**	**Retention (%)**	**Electrolyte**	**Ref.**
1	$0.5CoCr_2O_4$ -0.5rGo	226	0.0118	-1 to 0	31.4	-	-	3.0 M KOH	[7]
2	$CoCr_2O_4$/ GO	574.8	-	-	14.88	2489	95 % (after 100 cycles)	1 M KOH	[24]

3	$CuCr_2O_4$/ GO	370.5	-	-	-	-	-	0.1M H_2SO_4	[13]
4	$CuCr_2O_4$ /MXene	445.5	-	-0.5 to 0.6 mV	-	-	100% (after 500 cycles)	0.1M H_2SO_4	[14]
5	$CuCr_2O_4$ (Sol-gel)	2427	-	-0.6 to 0.6	-	-	-	3 M KOH	[38]
6	$CuCr_2O_4$ (Green)	1503	-	-0.6 to 0.6	-	-	-	3 M KOH	[38]
7	Nitrogen-doped graphene/ $CuCr_2O_4$	530.6	0.5	-0.2 to 0.45	-	-	98.3% (after 5000 cycles)	1M H_2SO_4	[43]
8	Ppy/ $CuCr_2O_4$	725	2.2	-	-	-	-	0.1M H_2SO_4	[52]
9	$MgCr_2O_4$	17	0.25	0.754 to 0.854	11	275	84.24 % (after 1000 cycles)	1 M H_2SO_4	[10]
10	$MgCr_2O_4$	21	0.5	0.754 to 0.854	14	550	85.63 % (after 1000 cycles)	1M $NaClO_4$	[10]
11	$CoCr_2O_4$/ NF	550	1	-	-	-	94.15% (after 5000 cycles)	3 M KOH	[16]
12	$NiCr_2O_4$/NF	442	1	-	-	-	90.82% (after 5000 cycles)	3 M KOH	[16]
13	$CoCr_2O_4$/ NF//AC/NF	114.12	1	0 to 1.7	45.8	849.9	89.4% (after 5000 cycles)	3 M KOH	[16]
14	$ZnCr_2O_4$: Sm (9%)	130.92	0.2	-1 to 1	-	-	-	0.1 M HCl	[150]
15	$ZnCr_2O_4$: Ce(9%)	123.41	0.2	-1 to 1	-	-	-	0.1 M HCl	[153]

4 Conclusion

Our review found that no earlier paper had discussed pure and doped chromites together or compared how different synthesis methods affect their properties. Most previous reviews talked only about photocatalysis or only about supercapacitors, which did not give a complete picture. In our work, we compared pure and doped chromites made by sol–gel, co-precipitation, combustion, hydrothermal, and green methods, and explained how their structure controls their photocatalytic, magnetic, antibacterial, and electrochemical behaviour. Chromite nanoparticles are important because they have useful structural,

optical, magnetic, and catalytic features, and tools like XRD, FTIR, SEM, TEM, UV–Vis, and XPS help confirm their phase and cation distribution. Doping changes the arrangement of ions and the band structure, which improves their performance in photocatalysis, sensing, magnetism, and energy storage. Overall, our review gives a clear and complete understanding of how synthesis, structure, and doping influence the properties and applications of chromite nanomaterials.

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