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# Exploring the Potential of Cobalt ferrites in the Supercapacitors Applications

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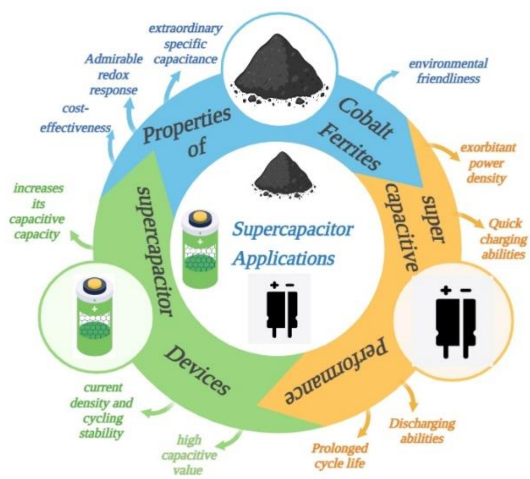
### Graphical abstract




**Abstract.** Supercapacitors have emerged as efficient energy storage devices for future autonomous gadgets due to their exorbitant power density, quick charging/discharging abilities, with prolonged cycle life. However, to meet demands such as high energy density and superior electrochemical performance, it is imperative to investigate different electrode materials. Primarily, electrode materials with a catholic potential range, low cost, and high specific capacitance are highly sought-after for supercapacitor applications. The cobalt ferrites ($CoFe_2O_4$) have emerged as materials with

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extraordinary specific capacitance, admirable redox response, are cost-effective, and are also environmentally friendly. In the present review article, we have discussed past reports where cobalt ferrites have been explored as potential candidates for supercapacitor applications.

## 1 Introduction

The advancements in technology have resulted in increased demand for efficient energy storage devices that exhibit high power, energy density, a long cycle life, and fast charging. These energy storage devices form an integral part of convenient electronic devices, electrically powered means of transportation, renewable energy storage structures, and other energy storage applications [1]. Supercapacitors and Li-ion-based energy storage devices are being explored in this field. However, Li-ion based energy storage devices suffer from limited energy density, degrade over time, are prone to thermal runaway, and pose a negative environmental impact, which limits their applications in certain fields [2]-[3]. Supercapacitors have emerged as promising alternatives to traditional energy storage devices as they exhibit long cycle life, have high power density, and offer quick charging. They store energy via an electrostatic pathway, which makes them ideal for applications where short bursts of high power are required [4]-[5]. Various electrode materials are being explored for supercapacitor applications. These include carbon-based materials (large surface area, better electrical conductivity), transition metal oxides (TMOs) (oxides of manganese, cobalt, nickel, and mixed metal oxides), polymers (polyaniline, polythiophene, and polypyrrole), nanomaterials, and hybrid materials (heterostructures of carbon-based structures with nanomaterials, which can be binary or ternary) [6][7,8]. The electrode material used on the surface of working electrode determines the performance characteristics like power and energy density, cycle life of cell. Researchers are trying combinations of different types of materials to improve the overall performance of supercapacitors [9]-[10]. In this regard, $CoFe_2O_4$-based materials have offered unique structural and electrochemical properties [11]. The $CoFe_2O_4$-based nanocomposites are environment-friendly, have unique magnetic properties, are cost-effective, and hence have manganese oxide, cobalt oxide, nickel oxide, over and above mixed metal oxides, polymers (polyaniline, polythiophene, and polypyrrole), nanomaterials ,and hybrid materials (heterostructures of carbon-based structures with nanomaterials, which can be binary or ternary) [6,12] They have been widely explored for various applications. Apart from this, $CoFe_2O_4$ can store large sums of energy and undergo charge-discharge at a fast rate without degradation, hence offering applications in supercapacitor applications [13]-[14].

In the present review, we have explored the cobalt ferrites ($CoFe_2O_4$) as a class of electrode material for supercapacitor applications. $CoFe_2O_4$ has drawn interest due to its unique magnetic, electrical, and structural characteristics. The hybrid composites of $CoFe_2O_4$ offer high specific capacitance with excellent stability after a large number of cycles, environmental friendliness, and low cost, making them apt candidates for supercapacitor applications. We have also reviewed the literature reports where these types of materials have been utilized for supercapacitor applications. Research in this field should be continued to improve performance and further understand their behaviour.

In the literature, there are various reports where ferrites are listed as efficient storage devices for supercapacitor applications. Ferrite-based nanomaterials that have been studied include nickel-based ferrites, cobalt -created ferrites, manganese-based ferrites, and copper ferrites. However, cobalt ferrites ($CoFe_2O_4$) have been extensively employed due to their environmental friendliness and low cost. Sherief *et al.* [15] studied the role of cobalt and ferrites in supercapacitor applications. The composite was found to exhibit a specific capacitance of 458 $Fg^{-1}$, current density $1Ag^{-1}$, with a scan rate of 5 $mVs^{-1}$ and excellent stability of 85.15% after 3000 cycles. Rajeev Gandhi and co-workers [16] have explored $CdCoFe_2O_4$ nanoparticles with a size of 20-40 nm synthesized via the co-precipitation route. The synthesized material exhibited a high specific capacitance of 395 $Fg^{-1}$ with current density 1 $Ag^{-1}$ with scan rate 2 $mVs^{-1}$. Sanjeev *et al.* [17] have explored graphene-based cobalt-ferrite (GR-$CoFe_2O_4$) hybrid composite using polymerization technique. The composite exhibited 781.27 $Fg^{-1}$ at a current density of 0.5 $Ag^{-1}$ with a scan rate of 1 $mVs^{-1}$. The composite has resulted in enhanced supercapacitive performance due to synergistic interactions between the two. Later on, Jeevanantham *et al.* [18] investigated the role of strontium-doped $CoFe_2O_4$-based nanoparticles in supercapacitive performance synthesized using a sol-gel approach. The doped $CoFe_2O_4$ material exhibited a specific capacitance of 637 $Fg^{-1}$ at a current density of 0.5 $Ag^{-1}$ using a 6 M KOH solution with high thermal stability (98.4% at 500 ˚C). The excellent coulombic efficieny (98.79%) was attributed to the presence of $CoFe_2O_4$ providing good electrochemical performance. Kiey *et al.* [15] put forward the synthesis of $CoFe_2O_4$ using citrate and exploited them for supercapacitor applications. The spherical-shaped nanoparticles (30-50 nm) displayed a specific capacitance of 893 $Fg^{-1}$ with a current density of 1 $Ag^{-1}$ at a scan rate of 2 $mVs^{-1}$ with 1 M KOH solution as an electrolytic medium. The capacitive retention for prepared electrodes was 90% at the end of 3000 cycles using current density 1 $Ag^{-1}$. Majumda*et al.*[19] investigated the role of silver-decorated Manganese-$CoFe_2O_4$ (Ag-decorated $MnCoFe_2O_4$) for the study of a hybrid solid-state supercapacitor. The incorporation of Ag-decorated $MnCoFe_2O_4$ resulted in enhanced specific capacitance to 291 $Fg^{-1}$ when anchored onto GO sheets which was 2.5 times better than $MnCoFe_2O_4$. In a research work, $CoFe_2O_4$ was anchored to cellulose nanocrystals (CNCs) which resulted in helical nanocomposites. The $CoFe_2O_4$@CNC resulted in enhanced specific capacitance 629 $Fg^{-1}$ at 0.5 $Ag^{-1}$ with coulombic efficiency of 95.8% at the end of 5000 cycles. Also, after accolementing of CNCs in the nanocomposite improved the number of electrocatalytic sites and hence electrochemical storage capacity [20]. Saira and co-workers study heterostructured GO, $CoFe_2O_4$ and polypyrrolenanocomposites for energy storage applications. They utilized a one-step methodology for the synthesis of the binary composite while a two-step approach was developed for ternary composite (RGO/$CoFe_2O_4$) with urea. The heterostructures offered synergistic interactions and thus offered high energy and power density with excellent specific capacitance [21]. Amani *et al.* conducted another study in which they used an $MnCoFeO_4$ based electrode for supercapacitor applications. In this, they used the co-precipitation method. For this, they used 1M $H_2SO_4$ electrolyte and showed excellent specific capacitance of 380 $Fg^{-1}$ at 1 $Ag^{-1}$ current density. The stability of this electrode is 96% after 5000 cycles. This GO helps to improve its supercapacitive property [22][9]. Another piece of research has been published by Suganay *et al.* in this journal. In this, they used a B-doped $CoFe_{11}O_9$ electrode for supercapacitor applications. A $BaCoFe_{11}O_{19}$-based electrode exhibits 314.6 $Fg^{-1}$ capacity with a current density of 0.5 $Ag^{-1}$ and exhibits stability of 94.3% after 10,000 cycles. These composites showed outstanding cycling performances and are suitable materials for improving the supercapacitor capacity of electrodes [23]. Mayakkannan*et al.*[24] designed Nickel $CoFe_2O_4$ composites via the microwave method. The system exhibited extraordinary specific capacitance 314.97 $Fg^{-1}$ at current density 3 $Ag^{-1}$ with scan rate 5 $mVs^{-1}$ in electrolytic media (3 M KOH solution). The

$NiCoFe_2O_4$ composite offered excellent cyclic stability of 94% at the end of 5000 cycles. The $NiCoFe_2O_4$ electrode displayed admirable electrochemical enactment with great potency for supercapacitor applications. Thus, there are various reports where $CoFe_2O_4$ has been explored for supercapacitor applications. We need to explore different composites of $CoFe_2O_4$ for enhanced supercapacitor applications.

**Table 1.** Various types of electrode materials comprising of $CoFe_2O_4$ and its composites with other nanostructures displaying specific capacitance with stability duration

| Electrode Material | Electrolyte | Method | Specific Capactance, current density | Stability, Number of cycles | Ref |
|---|---|---|---|---|---|
| *GO/PANI/$CoFe_2O_4$* | *1M KOH* | *Combustion* | *781.27 $Fg^{-1}$, 1 $mVs^{-1}$* | *79.03%, 5000 cycles* | [17] |
| *$NiCoFeO_4$* | *6M KOH* | *Microwave* | *1263 $Fg^{-1}$, 1 $Ag^{-1}$* | *94%, 2000 cycles* | [25] |
| *$NiCoFeO_4$* | *1M KOH* | *Sol-Gel* | *50 $Fg^{-1}$, 1 $Ag^{-1}$* | ---- | [26] |
| *$CoFe_2O_4$-MNPs* | *6M KOH* | *Co-precipitation* | *429 $Fg^{-1}$, 0.5 $Ag^{-1}$* | *98.8%, 6000 cycles* | [27] |
| *$CoFe_2O_4$/CNTs* | *2M KOH* | *Hydrothermal* | *1240 $Fg^{-1}$, 0.5 $Ag^{-1}$* | *85.6%, 1000 cycles* | [28] |
| *$CoFe_2O_4$ (QDs)* | ---- | *Solvothemal* | *1269 $Fg^{-1}$, 12 $Ag^{-1}$* | *91.1%, 10000 cycles* | [29] |

| | | | | | |
|---|---|---|---|---|---|
| *$CoFe_2O_4$/MWCNTs* | *2M KOH* | *Sonochemical* | *390 $Fg^{-1}$, --* | *93%, 2000 cycles* | [30] |
| *$CoFe_2O_4$@MC* | *6M KOH* | *Aerogel* | *433.3 $Fg^{-1}$, --* | *89%, 2000 cycles* | [31] |
| *$CoFe_2O_4$/$SiO_2$* | *1M KOH* | *Sol-Gel* | *316.1 $Fg^{-1}$, 0.5 $Ag^{-1}$* | *95.4%, 5000 cycles* | [32] |
| *$CoFe_2O_4$/Ni foam* | *2M KOH* | *Hydrothermal* | *9.7$Ccm^{-2}$, 10 mA $cm^{-2}$* | *89.7%, 5000 cycles* | [33] |
| *$CoFe_2O_4$ porous* | *3M KOH* | *Hydrothermal* | *933.6 $Fg^{-1}$, 1 $Ag^{-1}$* | *92.1%, 4000 cycles* | [19] |
| *$CoFe_2O_4$@CNC* | *1M KOH* | *Hydrothermal* | *629 $Fg^{-1}$, 0.5 $Ag^{-1}$* | *95.8%, 5000 cycles* | [20] |

| | | | | | |
|---|---|---|---|---|---|
| *$CoFe_2O_4$/PEDOT* | *EDOT* | *Solvothermal* | *299.2 $mAhg^{-1}$, 1 $Ag^{-1}$* | *91%, 2000 cycle* | [34] |

## 2 Supercapcitor Devices/Cell/Half cell

Isidorio *et al.* also conducted research on Co-$Fe_3O_4$NS@NG for a two-electrode-based supercapacitor. In this study, they utilized 2032 half-coin cells. For this, they made fine slurry Co-$Fe_3O_4$ NS@NG and coated it on Ni foil, drying it at 60°C for 12 hrs with 6M KOH aqueous electrolyte which showed 8.52 $Fg^{-1}$ at the lowest current density (0.75 $Ag^{-1}$). $CoFe_2O_4$/AC materials exhibited good candidates for supercapacitors. This supercapacitor revealed outstanding capacitance and coulombic efficiency [35]. Halder *et al.* studied $NiCoFe_2O_4$based devices for supercapacitor application with potential window -1 V to 0 V. In this device, $NiCoFe_2O_4$ is used as the electrode for positive terminal, and graphene is used as the electrode for negative terminal, which showed a high capacitive value of 169.5 $Fg^{-1}$ at 1 $Ag^{-1}$ current density and cycling stability of 100% after 1000 cycles, which indicated suitable material for supercapacitor applications [36].

Another study was also conducted by Verma *et al.*, who have made supercapacitor devices by using GO, PANI, and $CoFe_2O_4$ materials. In this study, they have utilized a two-electrode system to study its capacitive applications. For this, they made a fine slurry of GO, PANI, or $CoFe_2O_4$ dropcasted it on paper made of carbon and attached it with wire made of copper. The other electrode was activated carbon material, and used 1M KOH electrolyte. The fabricated device's supercapacitive value was 346.92 $Fg^{-1}$ at 1 $Ag^{-1}$ current density, and cyclic stability was 79.5% after 5000 cycles. GO has helped to increase its charge transformation rate, so it is a preferable material for supercapacitor applications [17]. S. Martinez-Vargas and his coworkers have studied cobalt ferrite nanoparticles (NPs) for flexible supercapacitor applications. The device showed supercapacitive value 77.8–337.1 $Fg^{-1}$ at 1 $Ag^{-1}$ but also excellent discharge times of 1650–4957 s. This cobalt ferrite nanoparticle not only increases its capacitive capacity but also increases its surface area, which helps to increase its ion storage mechanism [37].

Another research paper has been published by Yang *et al.*, who also prepared a flexible supercapacitor and made a 3D composite of Cu@$CoFe_2O_4$ on iron foam. This is a porous material with a large surface to volume ratio. Its cyclic stability was 87% after 2000 cycles. Due to its porous structure, it has a high ion storage capacity, which increases its supercapacitor value [38]. AnirbanMaitra *et al.* also study the $CoFe_2O_4$ structure. In this, they made cells by growing $CoFe_2O_4$ on stained steel fabric, which was used as the positive electrode, and for the negative electrode, they used a composite of iron oxide nanoparticles and GO sheets, which are grown on stain-less steel fabric by using 3M KOH electrolyte. This cell was charged at 1.6 V for 31 minutes, which was the maximum charging time. Its capacitive value was 155.8 $Fg^{-1}$ at 1 $Ag^{-1}$, and its stability was 97.1% after 2000 cycles [39].

**Table 2.** Different types of device materials comprising of $CoFe_2O_4$ and its composites with other nanostructures displaying specific capacitance with stability duration

| Electrode | Voltage window | Electrolyte | Specific Capacity, Current density | Stability, Number of cycles | Ref |
|---|---|---|---|---|---|
| *Co-$Fe_3O_4$ NS@NG* | *0-1 V* | *3M KOH* | *775 $Fg^{-1}$, 1 $Ag^{-1}$ for Halfcell* | *97.1%, 1000 cycles* | [36] |
| *G/Co/F-NCs* | *0-1 V* | *2M KOH* | *184 $Fg^{-1}$, 1 $Ag^{-1}$ for Full cell* | *99.0%,10000 cycles* | [35] |
| *CoNiBiFe$O_4$* | *0 - 1.5 V* | *1M $Na_2SO_4$* | *127.9 $Fg^{-1}$, 0.2 $Ag^{-1}$* | *87%,10000 cycle* | [23] |
| *Porous $CoFe_2O_4$* | *0 - 1.5 V* | *3M KOH* | *73.12 $Fg^{-1}$,1.2 $Ag^{-1}$* | *98%,5000 cycles* | [40] |
| *$CoFe_2O_4$* | *0-1 V* | *1M $H_2SO_4$* | *115 $Fg^{-1}$, 1 $Ag^{-1}$* | *92%,6000 cycles* | [41] |
| *$CoFe_2O_4$/C (NCFC)* | *-0.3 to - 0.4 V* | *5 M KOH* | *94 $Fg^{-1}$, 5 $mVs^{-1}$* | ----- | [42] |

Thus, by employing Cobalt ferrites ($CoFe_2O_4$) as electrode materials for supercapacitor, scientists are able to achieve high stability after 10,000 cycles and good specific capacities making them apt candidates for energy storage applications.

## 3 Conclusion

Cobalt ferrites ($CoFe_2O_4$) exhibited significant potential for supercapacitor applications as they are cost-effective, exhibit high electrical conductivity and are stable towards redox reactions. They have been utilized in supercapacitors for enhanced specific capacitance, energy density and excellent cyclic stability. Various synthetic routes have been put forward for synthesis of $CoFe_2O_4$ with different morphology, shape, size and crystal structure which is chosen on the basis of desired property. Through this review, we aim to present most recent literature where $CoFe_2O_4$ have been employed for energy storage applications. The composites of $CoFe_2O_4$ with other nanomaterials exhibit great potential which can store and deliver energy more efficiently, hence the research in this field must be expanded. Hence, there is need to develop $CoFe_2O_4$ based nanocomposites for enhanced electrochemical performance in supercapacitor applications. These composites offer high specific capacitance, excellent stability after a large number of cycles, environmental friendliness, and low cost, making them apt candidates for supercapacitor applications. This review contain insights for future endeavours in the field of supercapacitor applications utilzing $CoFe_2O_4$ as an electrode material.

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