Review

Synthesis of Co_3O_4 Nanoparticles through Solution Combustion Method and Their Applications: A Review

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Synthesis of Co_3O_4 Nanoparticles through Solution Combustion Method and Their Applications: A Review

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Abstract: Cobalt oxide nanoparticles are promising candidates for various kinds of practical application. The interest of researchers and scientists in these nanoparticles is due to their unique physical and chemical properties such as density, melting point, magnetic characteristics and band gap. The need to develop high performance and low-cost technologies for obtaining Co_3O_4 nanoparticles is a major reason in research in this area. The widespread commercial use of Co_3O_4 nanoparticles will open doors for numerous novel cost effective technologies, which are mostly dependent on the type of synthesis method and raw materials. A possible solution to this problem is to use Cobalt nitrates as a cost-effective precursor using the solution combustion method. Solution combustion synthesis method is one of the best candidate methods that have the potential for high performance and is also cost-effective. This review examines recent progress in the synthesis of Co_3O_4 nanoparticles by solution combustion method and underscores their significance across various fields, highlighting the need for further research and exploration of their multifaceted applications. In addition, the most recent advancements in the applications of Co_3O_4 nanoparticles in sensitive sensing, catalysis, supercapacitors/batteries and water treatment/pollutants removal are reviewed and described, focusing on current trends, challenges, and future outlooks.

Keywords: Co_3O_4 nanoparticles; Solution combustion method; Super capacitors; Li-ion batteries; Catalyst

1. Introduction

Co_3O_4 nanomaterials is one of the important nanoparticles that can provide valuable insights into the development of sensors for analytical chemistry. Recently, these nanoparticles have attracted a lot of interest because of their wide range of uses in sensors, energy storage, catalysis, environmental remediation, and among other areas. The chemical name for the inorganic compound Co_3O_4 is cobalt (II, III) oxide or Tri-cobalt-tetraoxide. It is one of the two well-defined cobalt oxides when mixed with cobalt oxide (CoO), Due to its mixed valence of Co(II) and Co(III), some cobalt atoms have a charge of +2, while others have a charge of +3. This can be shown by writing the formula as ($CoO \bullet Co_3O_4$). Cobalt oxide has a 6.11gr/cm^3 density and melts at 895C°, these particles are magnetic materials with a white tone. likewise, they have positive charge carriers considering they are P-type semiconductors [28]. The energy required to excite electrons from the valence band to the conduction band is known as the band gap and they have two of them. Abu-Zied et al. (2020) showcased the utility of Co_3O_4 nanoparticles as an efficient sensor for hydroquinone (HQ), describing

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its role in analytical chemistry applications for detecting chemical species. A major aspect of these applications is the synthesis of Co_3O_4 nanoparticles, and The solution combustion allows for the synthesis of a wide range of nanoscale materials, including metals, metal oxides, alloys, and sulfides. especially this approach has been proven to be a suitable and more effective way for obtaining these nanomaterials with specific properties [37, 28, 20]. Co_3O_4 nanoparticles synthesized by solution combustion approach, provide unique prospects for a variety of applications. due to the unique properties and many proses of these nanoparticles recently many scientists and researchers had focused to study Co_3O_4 nanoparticles in a wide range of fields, many researches and articles published as shown in (Figure 1).

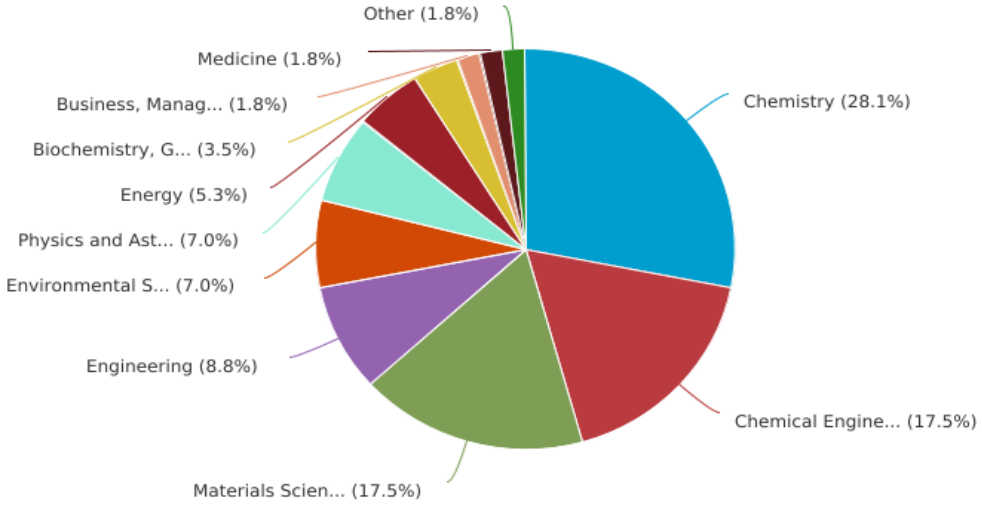

Figure 1. Recently publications of Co_3O_4 nanoparticles in a wide range of fields (taken from Scopus).

Solution combustion synthesis can be classified according to the chemical composition of fuel, oxidizer, and solvent, different types of organic fuels or their mixtures are typically dissolved in a solvent with cobalt nitrate hydrates [37]. The solution combustion method involves the exothermic reaction between cobalt cantaining precusor and a fuel, the kinetics of a reaction, describes the rate at which the system moves to equilibrium, is important from a practical point of view, and defines the characteristic temperature and synthesis processing time, which in turn controls the formation of the products with desired properties. Solution combustion synthesis of Co_3O_4 nanoparticles has proven to be a robust method, offering tailored properties for diverse applications, ranging from energy storage to environmental remediation [37]. Numerous studies from different countries and universities as shown in (Figure 2) have explored the potential of Co_3O_4 nanoparticles synthesized via the solution combustion method across diverse fields. The aim of this review is to present a thorough overview of the synthesis of Co_3O_4 nanoparticles using the solution combustion method, exploring their properties, components, synthesis process, applications, characterization methods and a comprehencive comparison of the previous work releated to Co_3O_4 nanoparticles performance and production. Many investigations have studied the synthesis of Co_3O_4 nanoparticles using solution combustion, examining crucial factors, such as the ratio of fuel to oxide, precursor materials, and reaction conditions. For instance, Michalska et al. (2021) demonstrated the application of nanometer-scale Co_3O_4 as an anode material for Li-ion batteries, showcasing its promise in energy storage applications. Acedera et al. (2020) investigated the use of porous Co_3O_4 nanoparticles as electrocatalysts for the oxygen evolution reaction (OER) in an alkaline medium, highlighting their potential in renewable energy technologies and emphasizing the vital role of these nano materials in energy conversion technologies. Kumar et al. (2021) investigated how the structural and physical properties of nanocrystalline Co_3O_4 were affected by the fuel-to-oxidizer ratio. Murayama et al. (2019) investigated two methods for low-temperature synthesis; the solution combustion method and the metal-organic framework-decomposition approach, recognizing the features of Co_3O_4 nanoparticles

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is essential in customizing their abilities for certain uses. Singhal et al. (2016), concentrated on the electrochemical characteristics of Co_3O_4 and its quick, one-pot production in several electrolytes. Deng et al. (2014) focused on Co_3O_4 nanoparticles as supercapacitor electrode materials. Co_3O_4 nanoparticles produced by the solution combustion process have a wide range of uses.

To emphasize the adaptability of these nanoparticles in energy storage devices, it is essential to understand the structure of Co_3O_4 nanoparticles in order to maximize their effectiveness, by concentrating on morphological characteristics. Keneshbekova et al. (2023) explored the Morphological features of Co_3O_4 nanoparticles obtained by the solution combustion method, providing valuable insights into their structural characteristics and the finer points of particle creation. Beyond energy storage and electrocatalysis, Co_3O_4 nanoparticles have found applications in environmental remediation. El-Shafie et al. (2022) investigated the synthesis and application of Co_3O_4-impregnated biochar for the removal of pharmaceutical contaminants, highlighting its potential in water treatment. Farhadi et al. (2016) characterized cobalt oxide nanoparticles prepared via the thermal decomposition of a complex and explored their photocatalytic activity, showcasing their multifunctional applications. Jahani et al. (2020) investigated the impact of Co_3O_4 nanoparticles on Brassica napus L., and focused on ion leakage, total phenol, antioxidant enzyme activities, and cobalt accumulation. Furthermore, research by Pagar et al. (2019) described how Co_3O_4 nanoparticles impacted plants and investigated Co_3O_4 nanoparticles that were biosynthesized using plant extracts, respectively.

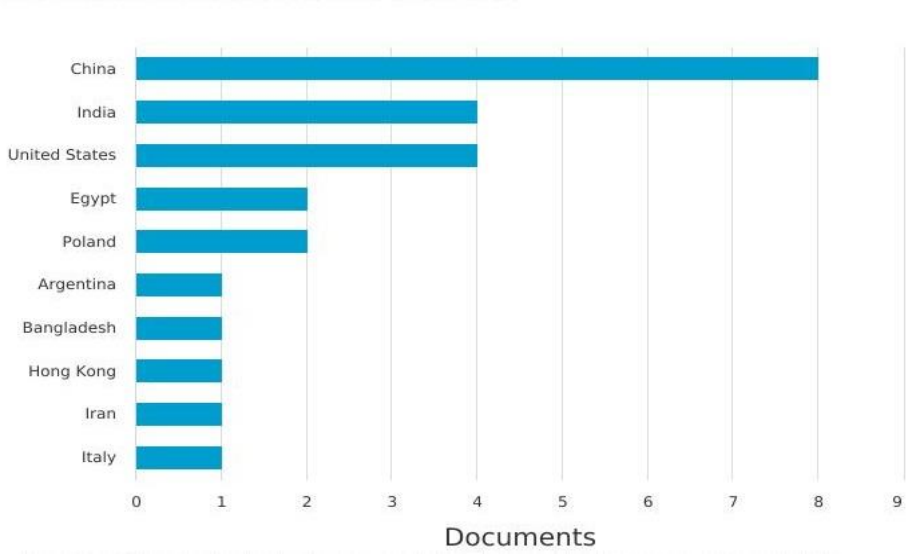

Figure 2. Recently publications of Co_3O_4 nanoparticles from different countries (taken from Scopus).

Our work includes a comparison of previous investigations on the synthesis of Co_3O_4 nanoparticles using the solution combustion method, examining their properties, synthesis processes, applications, and characterization. A comprehensive understanding of the developments and possible future directions in the field of Co_3O_4 nanoparticles can be obtained by examining these publications.

2. Synthesis of Co_3O_4 Nanoparticles by Solution Combustion Method

The solution combustion method is a widely employed technique for synthesizing Co_3O_4 nanoparticles due to its simplicity and scalability. Initial precursors are solid powders of different oxidizers (typically metal nitrites) and fuels (e.g., glycine, citric acid, and urea). These powders have high solubility in solvents (e.g., water). The reactive solution is the oxidizer and fuel dissolved in a desired ratio in a solvent [34]. Synthesized nanoparticles by solution combustion method have highly magnetic characteristics and are useful for different bio-applications [15]. Using cobalt nitrate as an initial precursor results in the formation of nanoscale Co_3O_4 particles [28, 20].

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For sure preparation of precursors, weighed a calculated amount of cobalt nitrate hexahydrate ($Co(NO_3)_2{\cdot}6H_2O$) in different ratios, φ (0.5, 1.0 and 1.5) based on the desired Co_3O_4 nanoparticle size to Synthesize the Co_3O_4 nanoparticles by the solution combustion method [21, 82]. Dissolved the oxidizor in deionized water to form a clear solution. When the precursor is prepared then in fuel Addition term, a calculated amount of the fuel to the cobalt nitrate solution is added. The solution vigorously Stired to ensure complete dissolution of the fuel and the crucible containing precursor solution placed on a hotplate for placing the solution combustion,. When the resulting gel precursor is heated within a temperature range of 300 to 900 ^oC for 1-2h in air. The exothermic reaction results in the formation of Co_3O_4 nanoparticles [21]. Once the combustion reaction is complete, quenched the reaction by adding ethanol to the hot solution. Collected the precipitated Co_3O_4 nanoparticles by centrifugation or filtration. Washed the obtained nanoparticles with ethanol and deionized water to remove residual reactants. Then dried the collected nanoparticles at a moderate temperature. Optionally, anneal the dried nanoparticles to enhance crystallinity and structural stability [21]. The combustion reaction involves decomposition of precursors, fuel oxidation, combustion reaction and cobalt oxide formation steps, such as Cobalt nitrate hexahydrate decomposes upon heating to produce cobalt oxide species (2). The citric acid fuel acts as a reducing agent and gets oxidized (3). The generated carbo monoxide (CO) from the fuel reacts with the oxygen released during the decomposition of cobalt nitrate, resulting in the combustion of the fuel (4). The high-temperature environment facilitates the formation of Co_3O_4 nanoparticles (5).

Michalska et al. (2021) successfully utilized this method to produce Co_3O_4 anode materials for Li-ion batteries, emphasizing the nanoscale precision achieved through this approach. As shown in (Figure 3), Powder X-ray diffraction (XRD) and Raman spectroscopy (RS) are used to characterize the structural properties of the Co_3O_4 nanoparticles. First, the Co_3O_4 nanoparticles have been found to have a crystalline nature by XRD pattern. For the observation of their surface morphology and particle size scanning electron microscopy (SEM) and transmission electron microscopy (TEM) were used. it may be concluded that the cobalt oxide consists of particles measuring 12-60 nm, with an average size of about 36 nm and loose arrangement featuring several empty spaces from the SEM and TEM imaging results [28].

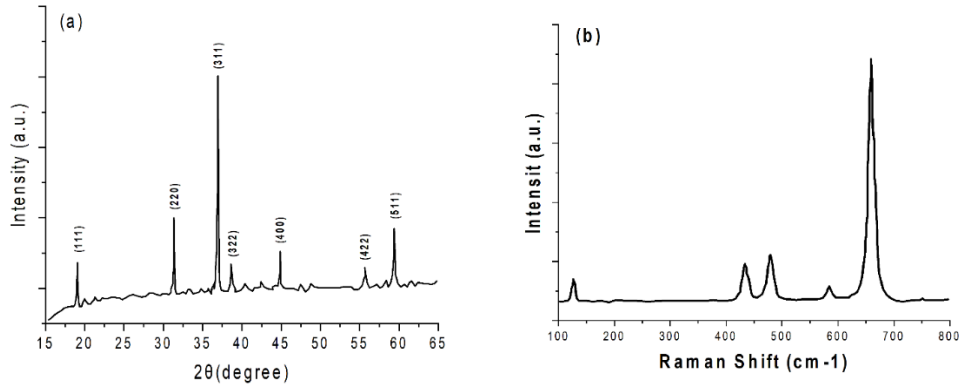

Figure 3. (a) XRD pattern; diffractogram of Co_3O_4 obtained by solution combustion method from cobalt nitrate- glycine mixture at φ=1.5 and (b) Raman spectrum for Co_3O_4 powder. Adapted from [28].

Solution combustion synthesis is best method to produce high quality Co_3O_4 nanoparticles that have great electrochemical activity used as the electrodes in lithium-ion battery. Obtained Co_3O_4 nanoparticles has specific capacity of 1060 $mAhg^{-1}$ (which is achieved in 100 cycles on the current density 100 mAg^{-1}) as shown in (Figure 4 a, b). Besides, they exhibit impressive cyclability at the respective present densities between 50 and 5kmA g^{-1} [28].

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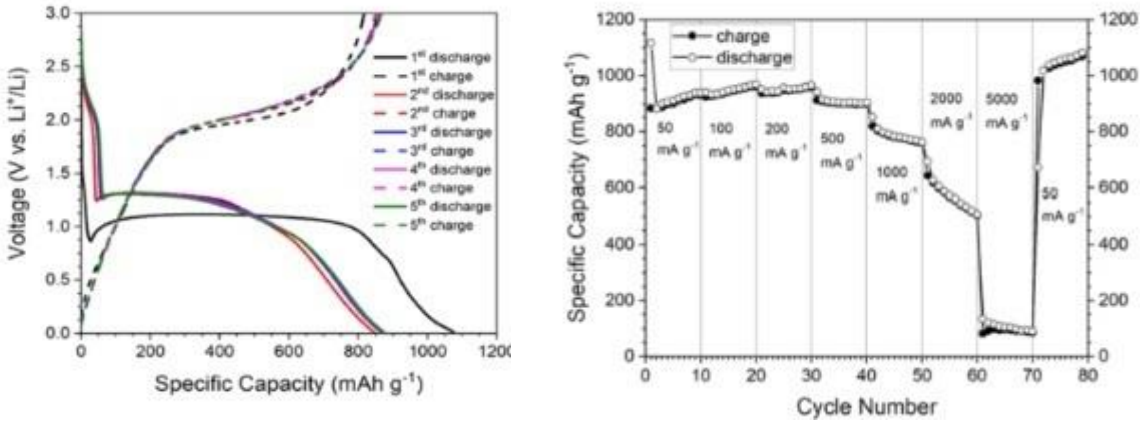

(**a**) (**b**)

Figure 4. Electrochemical characteristics for Co_3O_4 electrodes. (a) from first - fifth cycle profiles tested at current density of 100 mA·g^{-1}, (b) at current density rates of 100 and 500 mA·g^{-1} [28]. Adapted from [28].

In Afrooze et al. (2024) investigation the electrical tests revealed that the capacitance of the Co_3O_4 nanoparticles was 603 Fg^{-1} (1 mVs^{-1}), and the cyclic stability of Co_3O_4 nanoparticles evaluated 97.6 % at 10 mVs^{-1} scan rate for 5000 cycles. Electrochemical characteristics of cobalt oxide (Co_3O_4) nanoparticles could provide high-performance and longer-lasting Li-ion batteries [16]. It can reversibly store eight lithium ions according to the following conversion reaction (1). The number of studies that have been revealed that they are excellent electrocatalysts [6] as they are abundant, cheap, sensitive to the environment, and in some cases equal activity exactly like the noble metal-based catalyst. They have significant influences or can say critical effects of calcination temperature, pH, and fuel-to-oxidizer ratio on the morphology, phase composition, crystalline structure and OER function of the synthesized nanoparticles [2]. Co_3O_4 nanoparticles prepared with an optimized amount of precursor (i.e., when the ratio of cobalt nitrate and ascorbic acid is 1:1) have increased activity towards oxygen evolution reaction. Maurya et al. (2023) employed a synthesis of Co_3O_4 nanoparticles involving the introduction of a copper interlayer to tune the reactivity of Co_3O_4 towards the OER. The controlled synthesis procedure aimed at enhancing the electrochemical performance of Co_3O_4 in oxygen evolution. The samples with lower/higher amounts of precursors described the detriment in activity with copper interlayer. This effect is due to the presence of Co^{+3} at the surface. The solution combustion synthesis approach has several advantages, including its low cost and the use of a less toxic reducing component. Furthermore, compared to the produced nanoparticles exceeding earlier reported, Co_3O_4 nanostructures tested as anode coating materials in terms of electrochemical efficiency, exhibit better electrochemical performance [28].

$$Co_3O_4 + 8Li+ + 8e- \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftharpoons}} 3Co + 4Li_2O \quad (1)$$

Synthesized Co_3O_4 nanoparticles include a porous structure with a high specific surface area and a spinel-type crystal structure with a cubic shape. It also has a foam-like shape with pores that are micro- and nano-sized, that exhibit several beneficial characteristics for electrocatalytic applications. Due to their specific surface area, crystallinity, and porosity these nanoparticles have exceptional catalytic activity for the oxygen evolution reaction [2, 6]. Vennela et al. (2019) has been studied the crystallite size of the Co_3O_4 nanoparticles. The lattice parameters of Co_3O_4 are calculated to be in good agreement with the theoretical value for spinel Co_3O_4 nanoparticles, indicating the stability of the crystal structure [2]. Additionally, high-resolution transmission electron microscopy (HRTEM) images show well-resolved lattice fringes, confirming the crystallinity of Co_3O_4 nanoparticles. The catalytic performance is attributed to factors, such as the specific surface area, crystallinity and porosity of the nanoparticles [43].

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$$2Co(NO_3)_2{\cdot}6H_2O \xrightarrow{\text{Heat}} 2CoO + 4NO_2 + 12H_2O + O_2 \quad (2)$$

$$2C_6H_8O_7 + 6O_2 \xrightarrow{\text{Combustion}} 6CO_2 + 8H_2O + 6CO \quad (3)$$

$$6CO + 6NO_2 \xrightarrow{\text{Heat}} 6CO2 + 3N_2 + 3O_2 \quad (4)$$

$$6CoO + 4O_2 \xrightarrow{\text{High Temperature}} 2Co_3O_4 \quad (5)$$

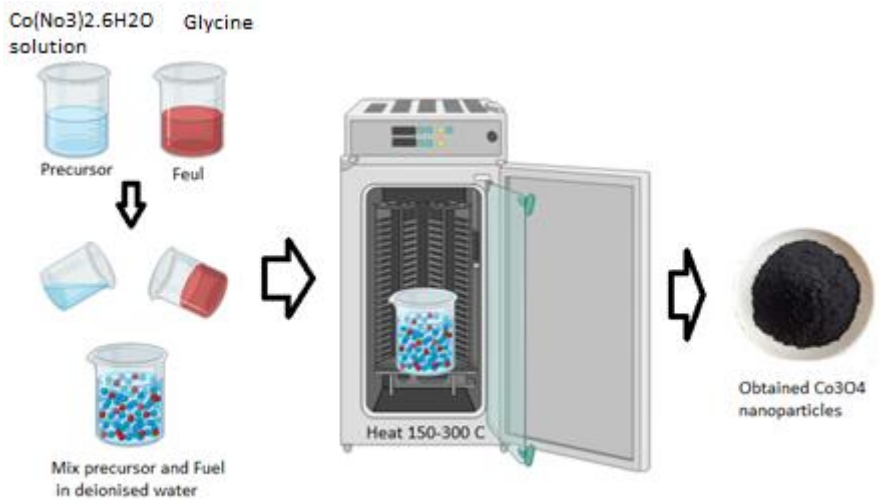

Figure 5. Procedure of the Co_3O_4 nanoparticles synthesis by SCS.

Synthesis of Co_3O_4 nanoparticles by solution combustion method can be done in different conditions as shown in (Table 1). For instance, control over the average particle size range was achieved by tuning the reaction ignition temperature between 300°C and 800°C. Transmission electron microscopy (TEM) studies revealed an increase in the size range from 5–8 nm to 200–400 nm for Co_3O_4 nanoparticles synthesized at 300°C and 800°C, respectively. Magnetic susceptibility measurements revealed a dominant antiferromagnetic (AFM) ordering and the temperature decreases with a decreasing average particle size range from (200–400 nm) to (5–18 nm) [32]. In a further low-temperature oxidation (190−240°C) step, very small Co_3O_4 particle size (2.3−7.4 nm) could be achieved for high loadings of Co_3O_4 (up to 59%) in the carbon network [46], the pyrolysis and oxidation temperature increase led to an increase of nanoparticle size, porosity and electronic conductivity. both the crystallite size and the lattice parameter nanocrystalline Co_3O_4 increase with increasing the molar ratio of fuel(F)/oxidizer(O) as well as the calcination temperature [27]. At high temperature the combustion of cobalt nitrate hexahydrate ($Co(NO_3)_2{\cdot}6H_2O$) with citric acid ($C_6H_8O_7$) fuel leads to the formation of nanometer-scale Co_3O_4 particles, which are proposed as an anode material for Li-ion batteries [28]. In solution combustion synthesis the change of the molar ratio of F/O, calcination temperature effects on the production of composite's components, size morphology and specific surface area of the obtained Co_3O_4 nanoparticles [27, 45]. In alkaline medium, the combustion synthesis is performed using cobalt nitrate hexahydrate and citric acid, the reaction takes place in an alkaline medium [2, 44], such as the solution combustion method results in the formation of porous Co_3O_4 nanoparticles, designed for use as oxygen evolution reaction (OER) electrocatalysts in alkaline environments. Synthesis and application of cobalt oxide-impregnated olive stones biochar for the removal of rifampicin and tigecycline with multivariate controlled performance [12, 13].

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Table 1. Synthesis of Co_3O_4 nanoparticle by solution combustion method in different conditions.

No	Used precursors and fuel solution	Electrolyte	Specific capacitance, Fg^{-1}	Surface area/m^2g^{-1}	Pure volume/cm^3g^{-1}	T_A, °C	Reaction T, °C	Particle size/diameter, nm	Proposed applications	References
1	Cobalt nitrate hexahydrate and 2-imidazolidinone hemihydrate (ethylenurea)					500		26.0	Sensitive sensors for the safety of environmental and healthcare	[1]
2	$(Co(NO_3)_2{\cdot}6H_2O)$ and glycine, NH_2CH_2COOH	1M KOH		10.45		25	300	13.1	Best-performing electrode obtaining	[2]
3	$Co(NO_3)_2{\cdot}6H_2O$ and urea, NH_2CONH_2 with 100 mL deionized water	3M KOH	212	69.34	0.0431	600		13.64	High performance electrodes for supercapacitors	[4]
4	$(CoCl_2.6H_2O)$, $(AgNO_3)$ and (NH_3), in deionized water	0.1M KOH	992.7	407.33	0.1155			12.98	Super capacitores applications	[7]
5	$(CoCl_2.6H_2O)$, $(AgNO_3)$ and (NH_3), in deionized water	0.1M KOH		53.06	0.07425			19.37	Super capacitores applications	[7]
6	$(Co(CH_3\text{-}CO_2)_2\_6H_2O)$ and citric acid monohydrate($C_6H_8O_7{\cdot}H_2O$),and ammonium nitrate (NH_4NO_3) were used as fuel,		362.8	17.9	0.095	350	550	26.1	Supercapacitors electrode materials	[10]

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7	3M($Co(NO_3)_2{\cdot}6H_2O$), 6M glycine ($C_2H_5NO_2$), 10% by weight of cobalt nitrate (nitric acid) and 50ml deionized water		700	90	292.66	260	1200	20-65	Gas sensors	[20]
8	($Co(CH_3\text{-}CO_2)_2$ $4H_2O$) and urea (CH_4N_2O) As fuel.					500		70	Catalysis and energy storage applications	[21]
9	($Co(NO_3)_2{\cdot}6H_2O$) and ($CO(NH_2)_2$) as fuel	Alkaline	5000	3	0.02	600		36	As the anode material for Li-ion batteries	[28]
10	($Co(NO_3)_2{\cdot}6H_2O$) and methanol as feul	1M KOH	3560			500			electrode for electrochemical applications	[29]
11	5g($Co(CH_3\text{-}CO_2)_2\_6H_2O$) and 1.72g urea ($CH_4N_2O$) As fuel. And 15 ml deionized water	KOH				400	900	50	Active for oxygen evolution reaction (OER)	[33]
12	Cobalt nitrate, urea as fuel and deionized water			1.4	0.016	400		200	In catalysts as coatings	[44]
13	($Cocl_2$ $6H_2O$), D-glucose, fructose, maltose, sucrose.	1M KOH				600			Non-enzyme glucose detection	[45]

Brunauer Emmett Teller (BET) is performed to evaluate the specific surface area and porosity of Co_3O_4 nanoparticles [2]. According to the (Table 2), synthesis methods, raw materials and temperature are effectiveness on the porosity and specific surface area of the obtained nanocatalyst. In Acedera et al. (2020) investigation mentioned the Synthesis of foam-like Co_3O_4 nanoparticles through SCS that process parameters, such as fuel type and fuel-to-oxidizer ratio, have been correlated with the resulting morphological, structural, optical, and capacitive properties of Co_3O_4. On the other hand, utilizing ethylene di amine tetra acetic acid (EDTA) as fuel produced Co_3O_4 with BET surface area of 23 m^2g^{-1} [2].

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Table 2. Specific surface area and corresponding preparation temperature of several nano Co_3O_4 structures.

No	Synthesis method	Raw materials	Catalyst	Temp, °C	BET, surface area m^2g^{-1}	References
1	Co-precipitation method	($CoCl_2$. $6H_2O$), ($AgNO_3$) and (NH_3), in deionized water	single-cubic Co_3O_4 nanostructure Ag doped.		407.33	[7]
2	Solution combustion	$(Co(NO_3)_2{\cdot}6H_2O$ and urea $((NH_2)_2CO)$	Co_3O_4 nanoparticles	300-800	39-2	[32]
3	Solution combustion	$(C_4H_6O_4Co{\cdot}4H_2O)$ and D-(+)($C_6H_{12}O_6$)	Spinel-structured Co_3O_4 powder	700	3	[28]
4	Solution combustion	($Co(NO_3)_2{\cdot}6H_2O$) and urea ($CO(NH_2)_2$) in deionized water	Nano-crystalline Co_3O_4	600	10	[33]
5	Sol-gel method	($Co(NO_3)_2{\cdot}6H_2O$) and PEG in deionized water	Co_3O_4 nanorod	90-350-700	170.2-48-20.9	[35]
6	Reactive calcination route	($Co(NO_3)_2{\cdot}6H_2O$) and ($Mn(NO_3)_2{\cdot}4H_2O$) in deionized water	Mn promoted Co_3O_4 spinel (Cat-R)	340-380-420	127.94-94.5-57.43	[36]
7	Hydro thermal method	($Co(NO_3)_2{\cdot}6H_2O$) and urea ($CO(NH_2)_2$) in deionized water	Co_3O_4 nanoplate	325	45.5	[39]
8	Hydro thermal method	($Co(NO_3)_2{\cdot}6H_2O$) and urea ($CO(NH_2)_2$) in deionized water	Co_3O_4 nanorod	325	111.4	[39]
9	Hydro thermal method	($Co(NO_3)_2{\cdot}6H_2O$) and urea ($CO(NH_2)_2$) in deionized water	Co_3O_4 NPs	325	112.6	[39]
10	Sol-gel method	($Co(NO_3)_2{\cdot}6H_2O$) and (C_2H_5-OH)	Co_3O_4 NPs	150	15	[41]
11	Sol-gel method	($Co(NO_3)_2{\cdot}6H_2O$) and ethanol (C_2H_5-OH)	Co_3O_4 NPs	550-650	46-42	[41]

TGA is employed to study the thermal stability and composition changes of Co_3O_4, [12] Two samples were examined in El-Shafie et al. (2022) investigation using the TGA. As shown in (Figure 7) the results reveal that both samples are thermally stable in the (100–450°C) temperature for OSBC and Co-OSBC The weight loss between (50-100°C) was (7.09%-9.69%), it may be ascribed to free water vaporization. Otherwise, a loss of 31.06% and 38.02% was observed for OSBC and Co-OSBC between (550–800°C), which might be attributed to the loss of carbonization of polymeric material or other organic content [12].

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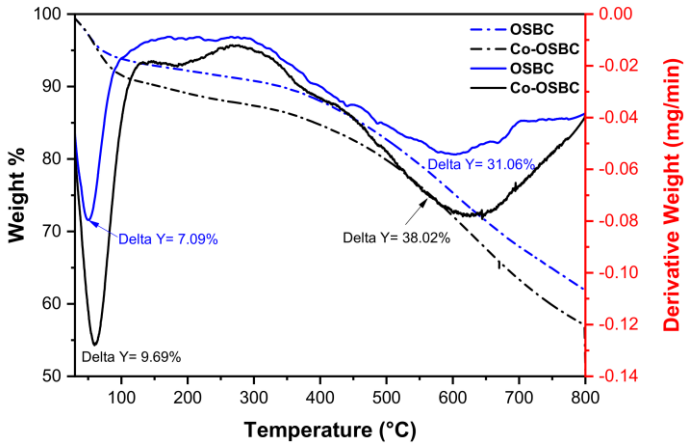

Figure 7. TGA/dTA analysis of OSBC and Co-OSBC [12].

Co_3O_4 gives best performance for Electrochemical Characterization that can be used Cyclic Voltammetry (CV) and Galvanostatic Charge-Discharge (GCD), Used to evaluate the electrochemical properties, such as capacitance and charge-discharge behavior, for supercapacitor applications [10, 16]. Deng et al. (2014) investigation in agreement with the CV results, the GCD data determined that specific capacitances of sample-I, -II, -III and -IV were 73.1 $F{\cdot}g^{-1}$, 179.7 $F{\cdot}g^{-1}$, 141.6 $F{\cdot}g^{-1}$ and 130.5 $F{\cdot}g^{-1}$ at a current density of 0.2 Ag^{-1}, respectively. As shown in (Figure 8) both measurements indicated that sample II showed the best capacitor performance among samples.

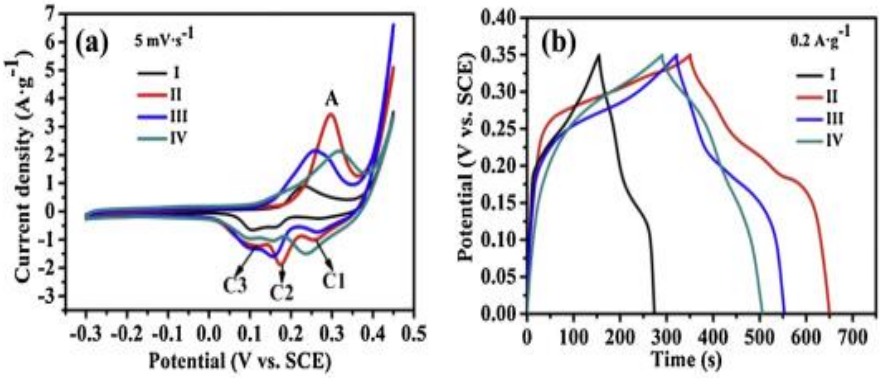

Figure 8. (a) CV curves of sample-I, -II, -III and -IV at the scan rate of 5 mVs^{-1}. (b) galvanostatic charge-discharge curves of Sample-I, -II, -III, and -IV at a constant discharge. current density of 0.2 Ag^{-1} [10]. This figure is reprinted from [10], with permission from Elsevier B.V., 2014;.

The rate performance of Co_3O_4 has been investigated by recording GCD curves at different current densities at the potential range between (0-0.35 v), the results are shown in (Figure 10, c). The nonlinearity in the discharge curves shows the pseudo capacitance behavior of Co_3O_4, which corresponds well with the CV test as shown in (Figure 10 a, b), for sample II-350. At the current densities between 0.2-4 Ag^{-1}, the specific capacitances of sample-II-350 Co_3O_4 electrode ranged from 362.8 - 285.7 Fg^{-1} (Figure 10, d). It is also found that even at a high current density of 4 Ag^{-1}, nearly 78.7% of the initial capacitance value remains, demonstrating excellent rate performance of the sample-II-350 Co_3O_4 electrode as shown in (Figure 9).

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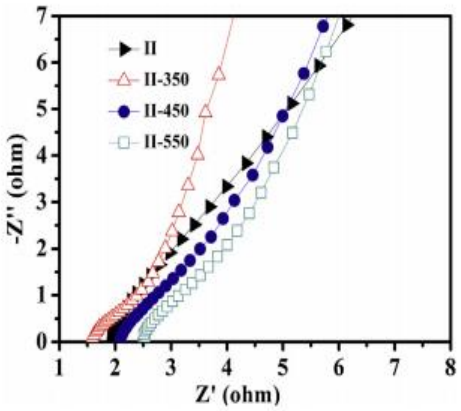

Figure 9. Nyquist plots of experimental impedance data for sample-II, -II-350, -II- 450 and -II-550 electrodes [10]. This figure is reprinted from [10], with permission from Elsevier B.V., 2014;.

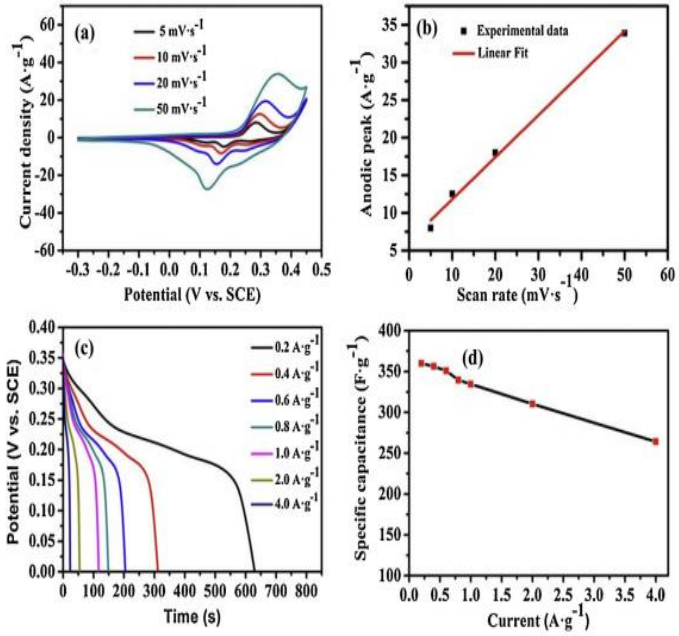

Figure 10. (a) CV curves of sample-II-350 at various scan rates, (b) the linearity of anodic current density with scan rates, (c) GCD curves of sample-II-350 at different current densities, (d) the specific capacitances of sample-II-350 calculated from GCD curves at different current densities [10]. This figure is reprinted from [10], with permission from Elsevier B.V., 2014;.

These comprehensive characterization processes integrate various analytical techniques, provided a thorough understanding of the structural, morphological, chemical, and functional properties of Co_3O_4 nanoparticles synthesized through the solution combustion method.

3. Application

Cobalt oxide nanoparticles have a wide range of applications, such as a few examples of these nanoparticles are applications in biomedical science (antibacterial, antifungal, antiviral, antileishmanial, medications, anticancer, and drug delivery), gas sensors, solar specific absorbing materials, anode materials in lithium-ion batteries, energy storage, pigments and dyes, electromagnetic field-emitting materials, capacitors, diverse catalysis, magneto-resistive devices, and electronic lightweight films [42, 5, 16]. These applications underscore the versatility and significance of Co_3O_4 nanoparticles in various scientific and technological fields. Such as, Co_3O_4 nanoparticles exhibit promising capabilities in environmental remediation. Their application in wastewater

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treatment and pollutant removal displays their potential for addressing environmental challenges [31, 8]. Co_3O_4 nanoparticles exhibit sensitivity to various analyst, making them suitable for sensor applications. Integration of Co_3O_4 nanoparticles into sensor devices enhances detection capabilities in environmental monitoring and healthcare fields. Also exhibiting magnetic properties make them suitable for applications in magnetic resonance imaging, allow to enhance the contrast and diagnostic capabilities of MRI techniques [31]. Because of their distinctive properties like Co_3O_4 is a p-type antiferromagnetic semiconductor with a direct optical band gap that is between (1.48-2.19 eV). Cobalt, [9] and cobalt oxide (Co_3O_4) nanoparticles have attracted the most attention in many areas as shown in (Figure 11), are abounding in nature. Only Co_3O_4 and CoO are stable, with having highest stability, Catalytic and Photocatalytic properties. Farhadi et al. (2016) investigated the photocatalytic activity of cobalt oxide nanoparticles produced by the thermal decomposition of a complex, exhibiting potential uses in catalysis. Also, Zhao et al. (2021) used laser-induced graphene to incorporate with Co_3O_4 nanoparticles for a flexible and highly sensitive enzyme-free glucose biosensor, highlighting their versatility in sensing applications.

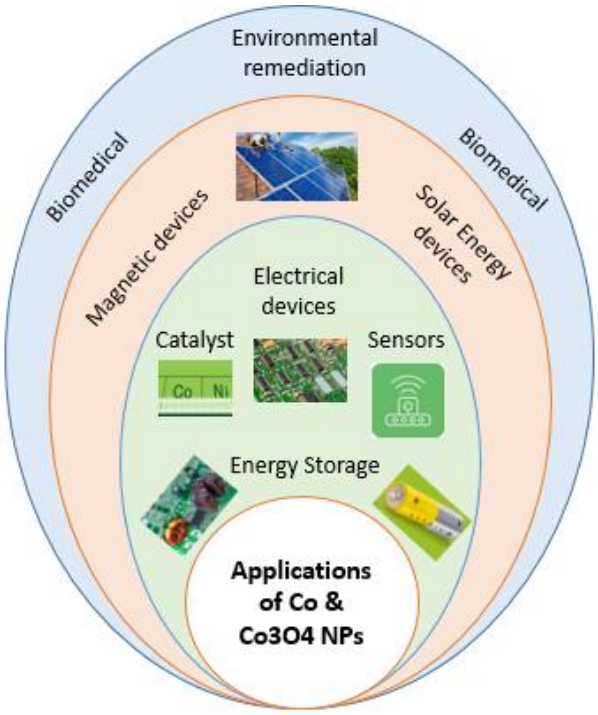

Figure 11. Applications of cobalt and cobalt oxide nanoparticles in different fields.

According to the recently publications Co_3O_4 nanoparticles shows better performance in batteries as shown in (Table 3). Mahmood et al. (2022) investigated Co_3O_4 nanoparticles as anodes in Li-ion batteries, these particles has a higher capacity about 890 mAg^{-1} than graphite 370 Ag^{-1}. One of the usage problems of Co_3O_4 as an anode is large volume changes during repeated lithiation and delithiation processes. To solve this problem various nanostructures, such as nanoring, mesoporous, 3D nanofiber, and nanofilms of Co_3O_4 have been prepared and studied extensively. Mesoporous Co_3O_4 networks were synthesized via thermal decomposition and showed a maximum capacity of 587 $mAhg^{-1}$ after 500 cycles.

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Table 3. Capacitive performance of synthesized Co_3O_4 nanoparticles as electrode materials.

№	Material	Method of preparation	Electrolyte	Specific capacitance, Fg^{-1}	Scan rate/ Current density, $A\ g^{-1}$	Retention	Cycles	Ref.
1	Co_3O_4 nanospheres	Solution combustion	1 M KOH	182	0.5	71%	2000	[3]
2	Marigold 3D flower like Co_3O_4 nanoparticles	Solution combustion	3 M KOH	603		97.6%	5000	[4]
3	Co_3O_4 nanospheres	One pot hydrothermal		182	1	93.75 %	8000	[5]
4	Co_3O_4@C NPs	Simple thermolysis	2 MKOH	642	1			[11]
5	Pure Co_3O_4 nanoparticles and Co_3O_4 /graphite nanocomposite	Co-precipitation method	6M KOH	239.5 for pure 395.04 for Co_3O_4/ graphite	0.5	2.68%	1000	[14]
6	Cobalt oxide	Electrodeposition	PH 12	504			600	[18]
7	Co_3O_4 nanoflakes	Cathodic potential step method		598.9	6.25			[19]
8	Hexagonal Co_3O_4	Solution combustion	6 M KOH	227	1	95%	1000	[22]
9	Co_3O_4 thin films	Electrodeposition	KOH	235				[23]
10	Co_3O_4 nanoparticles	Solid-state calcination		100	1.1		50	[24]
11	Cobalt oxide	Solution combustion	2 M KOH	351	0.85	98.6%	1000	[25]
12	Spinel-nanostructured Co_3O_4 powder	Solution combustion		100	0.05-5	75%	100	[28]
13	Cobalt oxide flakes	Potentiodynamic approach	0.1 M Na_2SO_4	396.67		better cyclic	1600	[30]

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						retention		
14	Cobalt oxide thin film	Heating of an alkaline bath of cobalt salt	KOH 0.25 to 2.0 M	118				[33]
15	Cobalt oxide	Solution combustion	2 M KOH	54	10	82%	10000	[46]
16	Co_3O_4 nanoflake	Hydrothermal	2 M KOH	351		good	4000	[47]

There are many kinds of catalysts for CO combustion especially, when include metal oxides, metal oxide's compounds, and a variety of supported noble metal catalysts. To decrease the production CO and remove it from H_2-rich syngas specially, to make it more ideal when applied to fuel cells the catalytic combustion of CO at low temperature is the most effective way for elimination of CO toxic gas. In Wang, X et al. (2023) investigation, it has proven that Among all the oxides studied Co_3O_4 is the best catalyst support, both the catalytic activity and stability of Au@CuxO/ Co_3O_4 are high. The Au content in the catalysts is only 0.11 wt% and the 90% CO conversion temperature is 132 ^oC. CO can even combust on Au@CuxO/ Co_3O_4 at room temperature with 51% conversion and without loss after a 72 h reaction. Furthermore, Anele et al. (2022) discussed recent trends in the environmental remediation of bacteria in waste water using Co_3O_4 nanoparticles.

4. Conclusions

Many synthesis methods are used to obtain Co_3O_4 nanoparticles with increased morphology and properties, which can enhance the potential application, however Synthesis of Co_3O_4 nanoparticles with more enhanced properties and cost-effectiveness are possible by using solution combustion method. The solution combustion method is cost affective and offers a straightforward route for synthesizing Co_3O_4 nanoparticles with efficiency and controlled sizes. The use of cobalt salts which are inexpensive precursors and a fuel like glycine, glucose, and urea. To produce Co_3O_4 nanoparticles in various conditions, will make it possible to use these nanoparticles not only for sustainable energy efficiency, and storage, but also for sensitive gas sensors, water treatment duo to its high adsorption activity, surface area and porosity. Solution combustion synthesis is aimed at enhancing the morphology, porosity and structural purity to improve their physical and chemical properties. despite active research in this area, there still exist problems, such as large amount of impurities that significantly affect the morphology of Co_3O_4 nanoparticles. The tasks for solving these problems are the obtaining conditions in solution combustion synthesis. Literature analysis has shown that, these nanoparticles can be effectively used in diverse fields, including energy storage, environmental remediation, and biomedical applications, [42] and have great potential for commercialization of low-cost applications in the global economy.

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