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Hydrothermal Synthesis of Cerium Oxide Nanostructures

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Abstract

The development of nanomaterials and nanocrystals in a lab-controlled environment has been found to be highly beneficial in the industrial and commercial settings. Past studies have assessed the growth mechanism of cerium oxides and how the nanocrystals can be prepared by hydrothermal synthesis. The hydrothermal synthesis of cerium oxide nanostructures is accomplished in two stages. In the first stage, the nucleation of cerium oxide nuclei is achieved. In the next stage, there is a ripening of the nuclei through hydrothermal synthesis. In the nucleation stage, the cations are precipitated and nanoparticles are developed. A transition to cerium oxide nuclei is accomplished through dehydration and oxidation processes. When the hydrothermal synthesis is executed, the ripening of nuclei results in the growth of nanocrystals. In this method, the dominant strategy is the oriented attachment. Afterward, there is a gradual addition of polyvinylpyrrolidone surfactant, which is followed by the adjustment of acidity in the solution. The resultant form accomplishes the nuclei dispersion. The collision mechanism aggregates the particles resulting in further grown nanocrystals. A key challenge in the hydrothermal synthesis is the conversion of assembly crystals to nanocrystals. The experimenter may also have to assess nanocrystals in the absence of well-defined edges. When it is accomplished, there is a further nuclei growth that eventually produces larger nanocrystals.

Keywords: *Hydrothermal synthesis, cerium oxide, nanoparticles, nanomaterials, nanostructures*

1. Introduction

Cerium is one among the rare metals on earth and its nanoparticles have exceptional properties. The particles are magnetic, optical and electronic. There are also unfilled 4f in its electronic structure. They have 4f2 6s2 with 2 common valence state Ce (III) and Ce (IV). Ce has thirty isotopes with mass numbers ranged from 123 up to 152. Ce metal oxidizes easily and associates quickly in air with tarnishing being apparent within an hour. There is also the formation of yellow Ce compound that simply separates from the surface throughout thirty-six hours of exposure to air. Ce compound is employed by the glass and ceramic industries for sprucing agent and to forestall the group action.

The addition of Ce (IV) compound to the glass helps to convert iron to the low visible absorption particle iron (II). The stability of pigments is additionally increased by the addition of Ce because it provides the pigments with color fastness and prevents clear polymers from darkening within the sun. Ce compound enhances stability as a result of its low absorption within the actinic ray; however, it is almost opaque within the actinic radiation. This protects the pigments employed in glass coloration as most of the loss elicited is because of ultraviolet illumination, UV actinic radiation, and actinic ray light exposure [1].

As such, it is being developed on an outsized scale phosphors supported group and magnetic materials, chemical element storage materials and high extent catalyst support. Most applications need the employment of non-agglomerated nanoparticles, as assembled nanoparticles cause combination of heterogeneous, poor sinterability and quantum properties [2]. However, nanocrystal with the initial particle size with five nm have a powerful tendency to agglomeration, that makes it troublesome to tackle. As such, the expected edges of high-crystalline nanoparticles square measure were simply overlooked throughout the manufacture of elements unless it will manufacture weak agglomerative nanoparticles [3].

Cerium compound has distinctive properties like a high index of refraction, a high stuff constant and a lattice constant almost like Si, creating it appropriate as associate insulation in Si device technology [4]. These properties build Ce compound helpful for applications in electronics and optics. Recently, ceria nanoparticles have attracted attention inside the medicine analysis community as a possible agent to inhibit cellular aging [5]. Mixed nerve cell cultures are shown to own associate enhanced period once an answer containing ceria nanoparticles is introduced into their surroundings.

CeO_2 is employed because the gas particle conductor in solid compound fuel cells, gas pumps and gas monitors are vulnerable to external influences owing to the high gas particle conduction [6-11]. Ceria additionally received lots of success within the oxidization and combustion catalysts as a result of its ability to change between the alter and reduced state as a result of a change within the concentration of gas [12]. As gas storage, Ceria is a buffer to produce gas underneath lean conditions and removes underneath conditions optimized for changing made in multilateral catalyst system [7, 8]. Underneath the conditions of labor, it is exposed to stimuli alternately O_2 deficient surroundings for O_2 excess. CeO_2, during this case, has the flexibility to get rid of CO and hydrocarbons through the O_2 imbalance within the cycle once the absorption and storage of gas O_2, NO and water through the surroundings O_2 is in excess [9]. This feature of ceria is termed gas storage capability. It derives from the flexibility to be simple and low productive for many CeO_2-X stoichiometries once exposed for O_2 atmosphere [9].

Past studies focused on the hydrothermal treatment for assortment ceria nanoparticles, morphology and crystal structure. The pH scale of the reaction medium may be an important parameter for the character and type of the nanoparticles, and the implications of acidity were reported on [13].

This work isn't solely aimed to hydrothermal synthesis of the nanostructured CeO_2 employing however additionally to review its properties. The synthesized CeO_2 and their structure were evaluated with focused measurement and differential thermal analysis (TG-DTA), diffuse reflectance-UV visible (DR-UVis) spectrographic analysis, X-ray difractometry (XRD), Fourier remodel infrared spectrographic analysis (FTIR), and transmission microscopy (TEM).

2. Background

Nanomaterials are of crucial significance in different science domains including physics and material sciences. Nanoparticles are integral components of nanomaterials and they have numerous applications in cosmetics and medicine. Their size is limited and reduced and therefore nanocrystals are capable of exhibiting electrical, optical, and magnetic properties [14]. The reduced size also enables them to show higher surface to volume ratios. As a result, they fine-tune the properties of materials by capitalizing on their morphologies, shapes, and surface/volume ratios. Although nanoparticles are highly useful and beneficial in their raw form, scientists and researchers have also endeavored to produce nanoparticles in which their shapes, size, and morphologies are controlled to optimize their output. These are called synthesis routes and various synthesis routes have been indicated by the researchers.

Hydrothermal synthesis is regarded as the most popular among these approaches because it provides the benefits of reliability, eco-friendliness, and cost-efficiency [15]. When nanoparticles and nanocrystals are produced in a lab-controlled environment, their effectiveness from their native state can improve significantly. It is because the process of synthesis considers the strengths and limitations of nanoparticles. The areas in the cell of nuclei that can prove significant are enlarged by applying high level of temperature and pressure. The process enables the expansion of those areas of the cell that are beneficial and that can improve the overall output and productivity of nanoparticles.

Nanoparticles of various materials have been developed by the scientists including ferrites, metal oxides, and rare-earth oxides. This study focuses on a material Cerium (Ce) that belongs to the family of rare-earth oxides [16]. There is a high abundance of this material in the nature due to which the material has extensive applications. The material is used as glass-polishing agent, water-gas shift reactor, catalyst, oxygen sensor, and in other applications [16]. However, there are still significant areas and applications where Cerium (Ce) can be useful. The basic premise of this study is that the potential impacts of cerium oxide have been underestimated, and the development of nanoparticles of cerium oxides in a lab-controlled environment can increase its usefulness. Cerium is found in the form of different oxides such as cerium dioxide and cerium sesquioxide. However, most of the benefits of cerium are associated with cerium dioxide [16]. Therefore, hydrothermal synthesis determines the useful applications of cerium dioxide. A critical factor in the case of nanoparticles is that although the reduced particle sizes are beneficial, they originate at higher interface densities. Therefore, the outcomes may produce non-stoichiometry levels [15]. Hence, there is a need for a detailed analysis of cerium oxide reactions and properties.

3. Literature Review

Hydrothermal synthesis is considered as the widely-recognized method for developing nanomaterials in a controlled environment. The method follows a reaction-based approach [17]. The objective of developing nanomaterials is accomplished at room temperatures as well as extremely high temperatures. The synthesis of crystal is reliant on the minerals' solubility in hot water [17]. The crystals grow in an autoclave vessel. The treatment method exposes the material to a high level of moisture after which bulk water is removed from the material's structure. Different methods are used for preparing nanomaterials and the selection of any material is dependent on the size and shape of the particle and the environmental factors. The most common methods that are usually employed include photochemical method, gamma irradiation, microwave irradiation, and thermal decomposition [18]. The usual strategy in all these methods is to derive nanoparticles from larger molecules. These nanoparticles are then synthesized using the bottom-up strategies. Another method of synthesis is to use functionalization in which there is a conjugation to bioactive molecules [18].

The widely-used hydrothermal synthesis processes are gasification, liquefaction, and carbonization [19]. Out of these processes, carbonization is considered as the mildest process [19]. The autoclave reactor is also developed, which is a cylindrical reactor and withstands high temperatures and pressures. The reactor is used for the evaluation of pressure reactions, temperature kinetics, and the specialty of chemicals. Hydrothermal synthesis results in the production of two types of deposits. First is the accumulation of high-temperature Mn deposits. These are formed when the fluids enter fissures and faults. Second is the bedded Mn deposits. These are formed when the cooling floods migrate on the bedding [19]. Hydrothermal solutions are essentially representations of water, where there is a deep heating of water above ambient surface temperature. The solutions may also contain solids and dissolved gases.

The synthesis of cerium oxide nanoparticles is accomplished by different methods. The differences in methods make a significant impact on the overall quality of produced nanoparticles. The developed nanostructures vary in their morphological, physical, and chemical properties [20]. Hence, there is a sharp contrast in the efficiency of the developed nanoparticles based on the type of synthesis used. This study highlights the significance of hydrothermal synthesis because it results in a rapid and substantial increase in nuclei that eventually increases the size of nanoparticles. The synthesis method should be applied in a way that the final features meet the requirements of the synthesis. Cerium oxide is majorly used in industrial applications. However, the precise development of final features is particularly significant in the medical applications because the chemical properties directly deal with the biological interface.

3.1. Electronic Structure

In the cerium family, cerium dioxide is the most stable oxide. According to the electronic structure, cerium dioxide is electropositive. There is also another oxide known as cerium sesquioxide; however, still dioxide is a preferred option because it has higher stability during chemical reactions and hydrothermal synthesis [14]. Cerium oxide nanoparticles are preferred because of their cost-efficiency. These particles are also the preferred choice because their catalytic properties are preserved even if the environmental conditions are not favorable.

3.2. Crystal Structure

The crystal structure of cerium dioxide is a fluorite structure. The structure also carries an oxygen sub-lattice [14]. The arrangement of this lattice is such that cerium ions are located alternately in cerium ions structure. The whole structure is classified as a tetrahedron with oxygen atoms at the corners and cerium at the center.

3.3. Microstructure

When the microstructure of cerium dioxide is evaluated, it becomes evident that the thin films can have different shapes based on the deposition method, substrate material, composition contents, and deposition attributes. When polycrystalline films are evaluated, a number of grains are seen. These grains play a pivotal role in the process of electrical conduction [20]. The process is carried out in thin films and depletion layers are formed by ensuring low levels of conductivity.

The size of nanoparticles is highly significant because it enables the delivery of therapeutic benefits [21]. This should be accomplished without any compromise on the integrity of the membrane. When there are significant changes in the size of nanoparticles, there are corresponding changes in the behavior and characteristics of those particles. It is because the changes affect the biological attributes such as diffusivity, half-life, and immunogenicity [21]. When there is a decrease in nanoparticles' size, there is a corresponding increase in surface/volume ratio. The larger value of this ratio makes an impact on the catalytic properties. Moreover, the larger value makes it possible for the nanoparticles to entrap free radicals.

3.4. Characteristics of Cerium

Cerium possesses the atomic number 58, and it is a chemical element mentioned in the periodic table. It is from the family of soft metals, and there is a tarnishing of the material when there is a higher exposure to air. In the lanthanide series, cerium ranks second and carries either a +3 or +4 oxidation state [22]. Researchers are particularly interested in the cerium metal with a +4 state because it is considered as the stable state of the metal and there is an extremely low risk of oxidization with water.

Another distinction of cerium is that it is from the family of rare-earth metals [21]. The uniqueness of these family of metals is that all members of the family demonstrate similar chemical properties, but they are unique and different concerning magnetic and electronic properties. When cerium is observed in its pure form, it can tarnish even at the room temperature. The metal can react with cold water that can result in the formation of hydroxides. The metal can also react with steam that can result in the formation of oxides. Those compounds of cerium that are soluble in water may prove toxic. Therefore, the researchers focus on insoluble compounds to reduce its toxic nature [21].

Due to the abundant availability of cerium, the studies and experiments were conducted to know the utility of cerium because it can be extracted easily from the ores. Contrary to other metals from lanthanides, the oxidization of cerium can be enabled to the +4 oxidation state [22] that makes it highly useful for various applications. Initially, the isolation of cerium was accomplished and it was made available in the form of the oxides that are popularly known as ceria.

3.5. Applications of Cerium Oxide

Cerium oxides were first used in gas mantles. However, in the later stages, the greatest application of cerium oxide was found as a polishing compound and as a catalyst in self-cleaning appliances [22]. Its use was found highly effective in the creation of high-standard optical surfaces. It is also used as an oxidizing agent when quantitative analysis is required in various experiments and medical research. A good aspect of cerium is that it has no biological impact in humans, and it can be used safely at a wider scale in the commercial and factory settings [22]. Not only that there is no harm incurred by cerium in human body, recent applications have also found the effectiveness of cerium in producing good health outcomes such as lowering blood pressure and cholesterol, assistance in metabolism, and managing the appetite. Cerium has also been found useful in providing relief when a person suffers from third-degree burns [23].

The abundance of cerium can be realized from the fact that it covers 0.0046% of the Earth's crust from the view of its weight [24]. Moreover, it is the only rare earth material that has the potential of exhibiting the oxidation state of +4 when it is found in solutions. However, when cerium is used in its oxidation state of +3, it becomes a typical rare earth metal and its significance is reduced. Cerium can be obtained through the process of ion exchange. It should be noted that the abundance of cerium is declared in relation to other rare earth elements. It does have an extremely higher availability in nature. However, compared to other rare earth elements, it has a higher abundance in the crust of the earth.

The most significant compound of cerium is cerium oxide and it is present in different minerals such as monazite and bastnaesite [25]. When the ore of bastnaesite is heated followed by its treatment with hydrochloric acid, cerium oxide is formed. Cerium has a unique smell that possesses both smoky and metallic qualities. Ce3+ is considered as the basic and elementary form compared to Ce4+. It is because when there is a need for extracting four electrons from an atom, there is a requirement of extremely higher amount of energy compared to Ce3+. When the calcination of cerium axalate is carried out with cerium hydroxide, an unstable state is generated, and eventually, there is an oxidation to Ce4 oxide. The oxidation states and isotopes of cerium are described in Figure 1 below:

Common oxidation states	4, 3				
Isotopes	Isotope	Atomic mass	Natural abundance (%)	Half life	Mode of decay
	^{136}Ce	135.907	0.185	> 0.7 x 10^{14} y	EC EC
				> 4.2 x 10^{15} y	β- β-
	^{138}Ce	137.906	0.251	>3.7 x 10^{14} y	EC EC
	^{140}Ce	139.905	88.45	-	-
	^{142}Ce	141.909	11.114	> 1.6 x 10^{17} y	β-β-

Figure 1: Oxidation States and Isotopes of Cerium [22]

4. Methodology

This study was focused on hydrothermal synthesis of cerium oxide nanostructures. Various properties of cerium oxide were reviewed for its potential application. The study was based on the review of secondary data [26], for which, the researcher searched and analyzed books and journal articles. The researcher preferred the analysis of secondary data because there is an extensive literature available on hydrothermal analysis and its potential applications in the development of nanoparticles and nanocrystals. Studies have demonstrated the benefits of hydrothermal analysis in different chemical structures and reactions. However, there was a need for consolidating the findings regarding cerium oxide due to its abundance in nature and usefulness in glass materials as well as therapeutic interventions. This formed the rationale of this study and the researcher reviewed and consolidated secondary data regarding the hydrothermal synthesis of cerium oxide nanoparticles and why hydrothermal synthesis is the preferred approach over other methods of synthesis.

The analysis was qualitative [27] because the researcher was interested in finding new and emerging patterns from the existing data. The researcher was particularly interested in the 'why' of the phenomenon as to why certain methods such as hydrothermal analysis is highly effective in the context of developing nanocrystals and how the current benefits of cerium oxides can be extended to further applications in the engineering and medical disciplines.

Qualitative synthesis in this study was presented in the form of thematic analysis [28]. The themes were based on the literature on hydrothermal synthesis of cerium oxide nanostructures. Thematic analysis is a highly recommended method for qualitative analysis because it enabled the researcher for collecting and reviewing the themes regarding the topic of the study in a systematic manner. The researcher built themes that emerged from the data and consolidated the findings from each study under the relevant theme. The review process ended when the data saturation was reached and there were no further themes emerging from the studies based on hydrothermal synthesis of cerium oxide nanostructures.

5. Findings and Discussion

5.1. Cerium Dioxide

Cerium dioxide appears as a pale yellow-white powder with a chemical formula of CeO_2. It is not only a polishing and cleaning agent but also assists in purifying the elements when they are extracted from their ores. A unique feature of cerium dioxide is that when its conversion is enabled to a non-stoichiometric oxide, the conversion process remains reversible. The structure of cerium oxide is fluorite, and when it is exposed to high temperature, there is a gradual release of oxygen. However, even in this deficient form, the fluorite lattice of CeO_2 is preserved. The equilibrium state of cerium oxide is predicted by Equation 1 below [22]:

$$\frac{x}{0.35 - x} = \left(\frac{106\,000\ \mathrm{Pa}}{P_{O_2}}\right)^{0.217} \exp\left(\frac{-195.6\ \mathrm{kJ/mol}}{RT}\right)$$

In the above equation, the value of x is reliant on different factors such as oxygen partial pressure, surface termination, and temperature.

There are four main applications of cerium oxide that include 1) polishing 2) optics 3) conduction and 4) medical applications [21]. In the case of 1) polishing, there is a wide-scale, industrial use of cerium oxide that is accomplished through Chemical-Mechanical Planarization (CMP). As a polishing agent, cerium oxide is preferred over many other oxides such as zirconia and iron oxide. For 2) optics, cerium dioxide is used for the de-colorization of the glass. When cerium dioxide is applied, green-tinted impurities are transformed to colorless oxides. For 3) conduction, cerium dioxide was found highly useful due to the electronic and ionic conduction properties. It also has a key role in the development and research of fuel cell. In the case of 4) medical applications, the nanoparticles of cerium dioxide have got huge attention of the researchers for the antioxidant and antibacterial applications.

5.2. Hydrothermal Synthesis

Hydrothermal synthesis is one of the fundamental methods in nucleation and crystal structure. It involves different techniques and strategies in which nanocrystals are developed from aqueous solutions having high pressure and temperature. In this method, single crystals are synthesized and the accuracy of the synthesis depends on how well the minerals are soluble in water when they are exposed to high temperature and pressure. A lab setting in a controlled environment is arranged to ensure the crystal growth. In this setting, an apparatus is used that is known as autoclave and that enables a steel pressure [29]. During the process of synthesis, a nutrient is used and water is supplied to the nutrient. Temperature is also controlled in this lab environment. The outcomes are observed at both the hotter and cooler ends. When the end is hotter, it is observed that the nutrient solute is being dissolved. When the end is cooler, deposits are formed at the seed crystal. This outcome is highly significant because it results in the growth of the required crystal.

Hydrothermal synthesis is far superior to other methods that are used for the growth of nanocrystals and nanomaterials. The method has the potential of developing crystalline phases that cannot retain their stable state at the point of melting. The method also enables the growth of those nanomaterials that are associated with a high vapor pressure when they reach the points of melting. The method is highly relevant when there is a requirement of growing good-quality nanocrystals in large amount and it is also needed to maintain a precise control on the composition of developed crystals. There are also some drawbacks of using the method of hydrothermal synthesis [29]. Autoclaves used in this method are highly expensive, and if the experimenters are not able to obtain the crystals with the ideal composition, the cost may outweigh the benefits. Moreover, if an experimenter uses a steel tube in hydrothermal synthesis, it will not be possible for them to observe the progressive growth of the crystals.

The main equipment used in hydrothermal synthesis is autoclaves [30]. These steel cylinders have thick walls and they are supported by a hermetic seal. The seal should be precise and accurate because it is the seal that has to bear high pressures and temperature for an extended time. The seal that is highly recommended in the current context is the Bridgman seal [20]. The solutions that are used in hydrothermal synthesis are mostly those solutions that are steel-corroding. Therefore, there should be some mechanism in the autoclave for the prevention of corrosion. The corrosion prevention should be available for autoclave’s internal cavity. It is always recommended to use protective inserts for this purpose. Another consideration is regarding the material of the autoclave [30]. The material should demonstrate inertness concerning the solvent that is utilized. Another design consideration in the case of autoclave is its closure.

Different methods used for hydrothermal synthesis are based on temperature difference, temperature reduction, and metastable phase [31]. The most widely-used method is the one that is based on temperature difference. In this method, the primary objective is to reach the level of super-saturation. The temperature is reduced and it is aimed at the main zone of the crystal growth. Eventually, the supersaturation of the solution is achieved at the upper part. The second technique is based on temperature reduction. The key difference in this technique is that crystallization is accomplished without a temperature gradient between the zones of dissolution and the zone of crystal growth. The drawback of this strategy is that complexities are observed in introducing seed crystals and managing the growth process in a controlled manner. Due to these limitations, this strategy, despite its intuitive appeal, is not used frequently. The third method is based on the exploitation of metastable phase. In this technique, the differences in solubility parameters are assessed. Those nutrients are used in this method that are unstable thermodynamically [31]. Their instability in the growth conditions enables the successful growth of the required crystals. When the solution reaches the metastable phase, the solubility level of the solution is far greater than the stable phase. In the later stages, crystallization is achieved smoothly because the metastable phase enables the dissolution. The objectives in this technique are highly difficult to accomplish. Therefore, this technique is employed in conjunction with other techniques.

5.3. Hydrothermal Synthesis – Cerium Oxide Nanostructures

When nanocrystals of cerium oxide are synthesized with PVP (PolyVinylPyrrolidone), different conditions are observed at different intervals of time as shown in Table 1 below [20]:

Table 1. Size and Morphology of CeO_2 Nanocrystals Synthesized with PVP (30 g/L) at Different Experimental Conditions

Ce^{3+}/OH^-	1:1	3:3	1:3	1:4	1:5	1:10
size (nm, XRD)	8.74		11.89	13.38	8.23	7.25
size (nm, TEM)	8.4	16.5	14.3	17.2	15.0	7.8
pH (before hydrothermal)	4−5	5	9	12	12	14
pH (after hydrothermal)	4	5	6−7	10	12	14
shape	regular octahedron	regular octahedron with pores	irregular octahedron with pores	irregular octahedron with pores	irregular shape with pores	small particles with more surface steps
level of agglomeration	well dispersed	dispersed	dispersed	dispersed	agglomerated	heavily agglomerated

These morphologies have been examined by TEM images. The synthesized crystals show different size and shape and achieve the target of desired crystal growth. This aspect is of critical consideration because the benefits of cerium oxide are achieved at an optimum level when the desired level of crystal growth is accomplished and the nanoparticles grow at the cell portions where the experimenters have set the expansion.

Table 1 also highlights that the synthesis process receives the optimum results when PVP is added. In the absence of PVP, the required level of expansion is not accomplished and the investment may prove counterproductive. Table 2 highlights the effects when addition of PVP is not considered [20]:

Table 2. Size and Morphology of CeO_2 Nanocrystals Synthesized without Addition of PVP

Ce^{3+}/OH^-	1:1	3:3	1:2.5	1:3	1:4	1:10
size (nm, TEM)	7.3	7.9	5.4	3.4	4.0	3.7
pH (before hydrothermal)	5	5	5	10	12	14
pH (after hydrothermal)	1	1	2	6	12	13
shape	regular octahedron with pores	regular octahedron with pores	porous octahedron with surface steps	small and fused particles	small and fused particles	small and fused particles
level of agglomeration	well dispersed	agglomerated	agglomerated	heavily agglomerated	heavily agglomerated	heavily agglomerated

Table 2 highlights that the results have significant differences when they are compared with PVP added (as in Table 1). The differences are observed in all aspects including the size, shape, and agglomeration level of the crystals.

The CeO_2 nanocrystals are formed by a systematic process in hydrothermal synthesis. In the first step, nucleation of the cells is carried out that produces clusters. These clusters then go through the process of dehydration and oxidation. As a result, expanded CeO_2 nuclei is formed. The hydrothermal synthesis performs oriented attachment and agglomeration. The output is dissolution and precipitation that eventually forms CeO_2 nanocrystals.

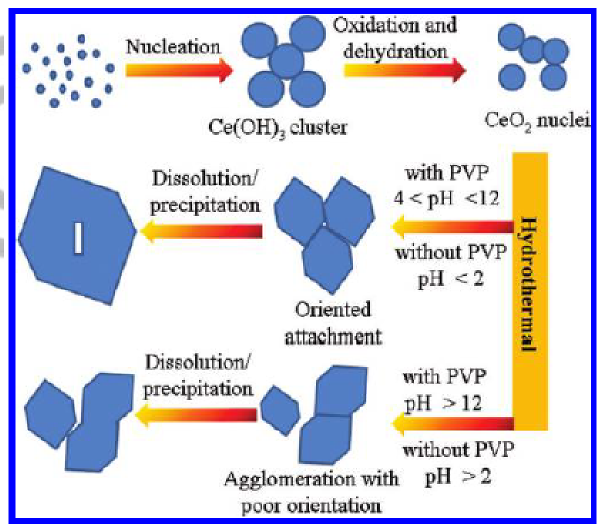

Figure 2: Formation of CeO_2 Nanocrystals

As shown in Figure 2 [20], the hydrothermal synthesis begins with the nucleation process. When the ripening of the nuclei occurs, there is a corresponding growth of nanocrystals. The dominant stage in this whole process is the oriented attachment. The process relies on the collision mechanism that takes place among nuclei. The ripening process follows the Ostwald methodology in which there is a dissolution as well as re-precipitation. The process controls the low solubility aspect of the crystals and clusters are transformed into nanocrystals. This is one of the most appealing method for growing nanocrystals and objectives can be achieved at different temperature levels.

6. Conclusion and Recommendations

This study analyzed the effectiveness and role of hydrothermal synthesis of cerium oxide nanostructures. Nanomaterials are highly effective in industrial and commercial applications and rare-earth metals are particularly studied by the researchers. This study focused on the nanostructures of cerium oxide. The study found that the metal cerium possesses higher level of abundance than other rare-earth metals. However, its true potential has yet to be tapped in the commercial and healthcare sectors. So far, cerium oxides have been used mainly as polishing agents but its oxidization potential can give rise to other applications as well.

Cerium oxide is often used in +3 oxidation state. However, real benefits of the oxide are found in the +4 oxidation state. This aspect is the unique feature of cerium, and other rare earth metals have not been able to acquire +4 oxidation state. Cerium oxides are used in their native forms. However, different processes of synthesis have also been developed that can produce and form nanocrystals in a controlled lab environment.

Hydrothermal synthesis is one of the widely-used method for enabling the formation and growth of nanocrystals. This study found that this method of synthesis is also relevant and significant in the case of cerium oxide nanostructures. Any process of synthesis is considered better when the crystals are formed precisely based on the initial criteria. Hydrothermal synthesis has the potential of developing nanocrystals in the exact required formation. It is a significant finding of this study because the scope of the benefits of cerium oxide can be expanded if the nanocrystals can be formed in the exact requirements in the lab. The resultant products can then be highly effective and improve the usefulness of cerium oxide.

The abundance of cerium oxide in relation to other rare-earth metals should be capitalized and researchers should focus on the development of nanocrystals that could improve the outcomes wherever cerium oxide is used. Cerium does not produce any biological impact and its toxicity is also at the mild level. This provides a potential opportunity for its usage in the medicine field as well. The increased solubility is an area of consideration that can be accomplished by hydrothermal synthesis. The higher oxidation state of +4 is also a critical factor that increases the efficacy. These factors suggest that when there is a development of cerium oxide nanostructures in a controlled environment, the benefits are far better than using cerium oxide in the raw form. The controlled environment should be properly managed by the experimenters because inaccuracies can affect the nuclei expansion and the expansion of the overall cell cannot be achieved at the desired level and area.

Future studies can expand on these findings and implement the strategies of hydrothermal synthesis for cerium oxide. This study analyzed the method of nucleation of the cells and how the strategy of oriented attachment can be followed. Future studies can use other methods and compare the effectiveness of other methods with the methodologies mentioned in this study.

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