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Case Report

Nano titanium oxide (nano-TiO_2): A review of synthesis methods, properties, and applications

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ABSTRACT

Nanoparticles have revolutioned materials secience and manufacturing industry thanks to their ultrafine scale. Nano-scale titanium oxide (nano-TiO_2) are key elements of a wide variety of sectors of advanced materials, devices, and systems in view of their versatility and extraordinary characetristics, mainly optical, electrical and catalytic properties. Thnaks to aforementioned features, they found a key position in different industries such as colors and pigments, photocatalysts, photovoltaic solar cells, adsorbents, cosmetics, electric and electronic devices. Nano-SiO_2 application gives rise to a wide range of properties and performance, which severely depends on particle size, particle size distribution, and agglomeration in the bulk of host materials or systems. When they are used as surface coating additive or even functionalized, nano- TiO_2 takes more roles, which are state-of-the-art depending on synthesis method. Therefore, review of synthesis, properties, surface- and bulk-functionalization/modification (respectively with function groups and doping) methods in achieving high-performance nano- TiO_2 seems essential. In this review, background information and developments from pure Titanium Oxide to chemically modified Titanium Oxide -based materials as photocatalysts were discussed in detail, Photocatalytic activity of Titanium oxide-based materials in nitrogen group pollutant decomposition. It also Titanium Oxide Nanoparticles as a Vehicle for Chemotherapeutics and Other Applications of Titanium Oxide Nanoparticles in Medicine and also an overview of the synthesis methods and factors affecting their properties in different synthesis methods have been reviewed.

1. Introduction

Nanotechnology and nanoparticles have changed our life in view of bringing the possibility of designing adsorbents for pollution removel and water purification [1], catalytic functions [2,3], energy devices [4,5], and biomedical applications [6,7]. It is possible to synthesize nanoparticles in different shapes and size [8], surface modification [9], bulk modification [10], or combination of both [11], to achieve a wide range of properties and performance in view of interaction with materials [12]. In this regard, using nanoparticles as additive for rubber

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industry [13,14], flame retardant [15,16], and photovoltanic solar cells are obviously appreciable. Titanium is the fourth most common metal in the world after aluminum, iron and magnesium and makes up about 60 % of the Earth's crust [17,18].

In the current review, studies focusing on titanium dioxide (titanium (IV) oxide, titania, TiO_2) nanoparticles, which belong to the category of metallic NPs are reviewed [19–21]. Notably, the evaluation of current Titanium Oxide functionalization methods accompanied by the biological and medical effects of these Nanoparticles were the driving force for this work. Mass production of Titanium Oxide began in the early twentieth century as a non-toxic substitute for a white dye for paints [22–24]. Nowadays, the annual production of Titanium Oxide exceeds four million tons per year, and this molecule has found numerous applications in everyday products (Fig. 1) as an excipient in the pharmaceutical industry, for sun cream production in the cosmetics industry, as a colorant in white plastics, and as a relatively cheap and nontoxic food pigment approved by the relevant European Union authorities for the safety of food additives [25–27]. Research on the possible applications of nanoparticles Titanium oxide dates back to 1985 when one of the first works on the subject of photocatalytic disinfection was published. Since that time, the use of nanoparticles Titanium oxide in photodynamic therapy studies has been constantly increasing. It concerns nanoparticles Titanium oxide' applications as photosensitizing agents in the treatment of cancer as well as in photodynamic inactivation of antibiotic-resistant bacteria [28–30]. Both nanoparticles Titanium oxide themselves, as well as their composites, combinations, or hybrids with other molecules, were successfully tested as photosensitizers in photodynamic therapy. Titanium (IV) oxide nanoparticles were applied inter alia in the synthesis of bioconjugates with cell-specific monoclonal antibodies for the treatment of malignant tumors or the preparation of black nanoparticles Titanium oxide for antimicrobial therapy of antibiotic-resistant bacteria [31].

1.1. Titanium oxide (TiO_2) crystal structures

Titanium oxide (TiO_2) is listed in Table 1. These structures can be described in terms of octahedral TiO_6 chains. In both anatase and rutile structures, each Ti^{+4} ion is surrounded with an octagon with 6 O^{2-} ions. In the anatase phase, the Ti-Ti atomic distance is larger than the rutile phase, but the O-Ti distance is smaller [32–35]. The anatase phase is more elongated along the axis. In the rutile structure, each octagon is in contact with 10 neighboring octahedrons (2 pairs of common oxygen atoms at the edges and 8 common oxygen atoms at the corners), while in the anatase structure, each octagon is associated with eight neighbors (4 common oxygen atoms at the edges, and 4 common atoms in the corners). These differences in network structure result in differences in phase density and electronic band structure [36–40].

Table 1
Physical properties of Titanium oxide (TiO_2) [34–36].

Property	Anatas	Rutile	Brookite
Crystal structure	Tetragonal	Tetragonal	Orthorhombic
Density(kg/m3)	3830	4240	4170
Molecular volume(°A3)	34.06	31.21	32.17
Refractive index	2.52	2.72	2.63
Hardness coefficient (Hs)	5.5–6	7–7.5	5.5–6
Electrical permeability	48	114	78

2. Most important properties of titanium oxide (TiO_2) related to its application

Titanium oxide (TiO_2) has a specific gravity of 3.9–4.2, a melting point of 1854 °C and a hardness of 5.5–6.5 is not soluble in water and organic acids and diluted alkaline solutions, but it's soluble in hot sulfuric acid and Hydrofluoric acid [41–44].

Titanium oxide (TiO_2) Semiconductor with large tape gap. Its anatas structure has a 3.2 eV optical gap with an absorption edge of 388 nm, located in the ultraviolet region of the spectrum (100–400 nm) [45–49]. Rutile has a smaller optical gap of 3.02 eV with an absorption edge of 410 nm in the visible region (400–700 nm), and the go-kite phase has an energy gap of 2.96 eV that absorbs near-visible light [50–53]. Titanium dioxide thin films have a high transparency in the visible wavelength range, but absorb ultraviolet light well [54–57]. The refractive index of titanium oxide thin films at $\lambda = 550$ nm is 2.49 for the anatase phase and 2.8 for the rutile. Fig. 1 shows the two structures of Titania (Rutile and Anatase) used in industry [58–62]. Titanium oxide (TiO_2) is electrically insulated and has a high dielectric coefficient, 50–60 for the anatase and 80–110 for the rutile phase. Its electrical breakdown voltage resistance is $4 kVmm^{-1}$. The surface electrical resistance of thin films for anatase and rutile structures is 1012 Ωcm, which has a high resistance compared to semiconductors such as SnO_2, with a resistance of 30 Ωcm [63–67].

The high dielectric coefficient results in many capabilities for this material, such as application in anti-reflection surfaces and as a dielectric gate material in metal-oxid-semiconductor field-effect transistors [68–72].

If a photon with an energy equal to or greater than the gap energy (more than 3 eV for Titanium oxide (TiO_2)) hits the semiconductor, it causes the electron to be excited from the valence band to the conduction band and an electron-hole pair is created [73–76]. These charge carriers can be recombined with irradiating (for direct-gap

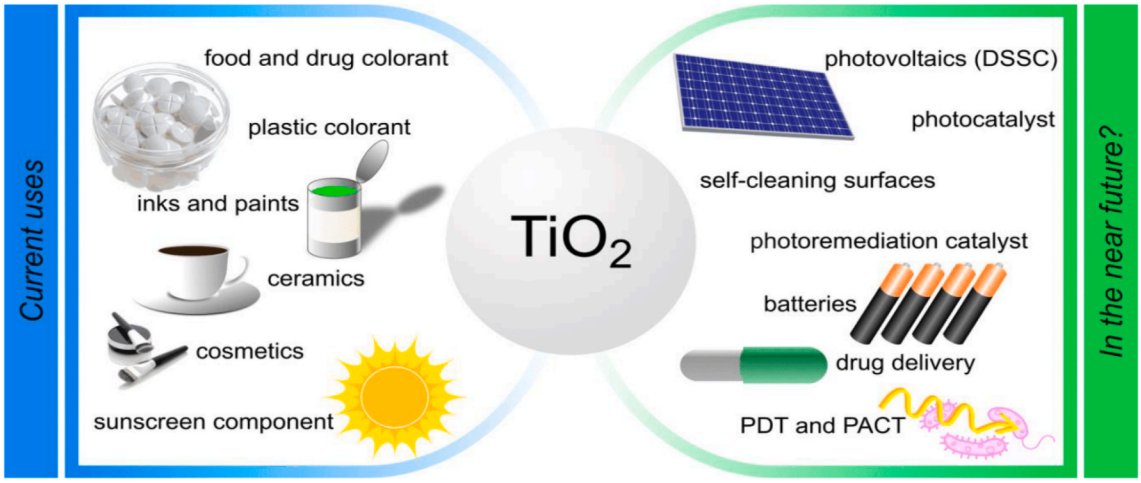


Fig. 1. Current applications and potential future use of Titanium Oxide. Photodynamic therapy; antimicrobial photodynamic therapy; dye-sensitized solar cell [31].

semiconductors) or without irradiating and dissipating energy as heat (in indirect-gap semiconductors), or can be trapped and react with an electron donor or acceptor elements [77–80].

2.1. Photocatalytic properties

In 1967, while Professor Fujishima and his colleague Honda [81–84] were experimenting, they encountered a strange phenomenon. They observed that when TiO_2 and Pt electrodes were placed in water, the formed circuit is capable of decomposing water into oxygen and hydrogen without an external electricity input, only when exposed to light [85–90]. Following this phenomenon, Honda discovered that Titanium oxide (TiO_2) has strong oxidizing properties, and focused his subsequent studies on the effect of this valuable substance on environmental phenomena such as sterilization, disinfection and pollution removal [91–95]. This important discovery, known as the photocatalytic or Honda-Fujishima effect, resulted in antibacterial products, being one of the most advanced tools for disinfection of spaces and one of the main branches studied in the materials industry [96–100].

In general, photocatalysis is a catalytic reaction with the presence of photons. In other words, with irradiating photons to the surface, the substance is prepared to perform a chemical reaction [101–105]. Photocatalysts are semiconductors that absorb light when exposed to it (for Titania, the UV spectrum) and produce electron-hole pairs on the surface of matter [106–110]. The produced carriers are highly active and participate in oxidation and reduction reactions with oxygen and humidity. For example, in nature, chlorophyll in green plants, which is responsible for photosynthesis, is a photocatalyst [111–115]. Chlorophyll provides plants with oxygen and nutrients with absorbing light with water and carbon dioxide. Fig. 2 shows the Schematic diagram showing the TiO_2 photocatalysis [116]. Table 2 shown Photocatalytic activity of Titanium oxide-based materials in nitrogen group pollutant decomposition.

3. Applications of titanium oxide (TiO_2)

3.1. Antimicrobial, antiviral applications

Climate treatment and disinfection is necessary only for hospitals and medical equipment, but in other environments where the growth and multiplication of plants and animals takes place, making them susceptible to contamination, and involves microbes and harmfull organisms' eradication from water, air or surfaces [91].

Since microbial, viral, and fungal structures are gradually becoming resistant to the use of chemical disinfectants, and these compounds themselves are harmful and lethal to human life, a fundamental solution must be devised to eradicate these microorganisms [92]. All living structures are sensitive to DNA damage. Therefore, the synthesis of blocking and disabling proteins during a DNA cell division cycle can be a good way to eliminate them [93]. On the other hand, the increase in oxygen gas pressure is harmful and deadly for all types of life [94]. Thus, titanium surfaces, along with their photocatalytic properties, produce oxygen free radicals and create an oxygen poisoning for microorganisms [95].

3.2. Titanium oxide nanoparticles as a vehicle for chemotherapeutics

Cancer is considered one of the most significant challenges for modern medicine. Despite the continuous development of modern cancer treatment methods, the first line of therapy is the surgical removal of tumor and/or radiotherapy. Chemotherapy is usually a complementary therapy, but it is limited by many factors [135]. First of all, chemotherapeutics is extremely toxic to rapidly proliferating, both cancer and healthy, tissues in the human organism. Therefore, novel

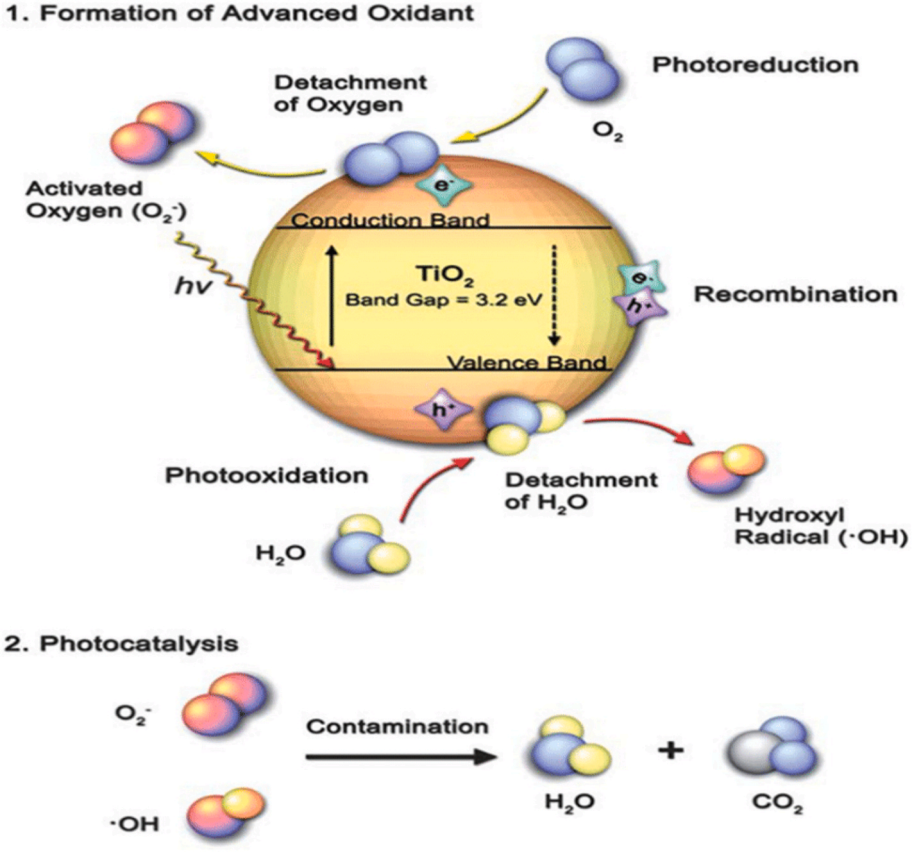


Fig. 2. Schematic diagram showing the TiO_2 photocatalysis [116].

Table 2
Photocatalytic activity of Titanium oxide-based materials in nitrogen group pollutant decomposition.

Catalysts	Light source	Target	Efficiency (%)	Ref
1 wt%Ag/Titanium oxide	UV/visible-light	NO	100	[117]
Titanium oxide/G-1 (0.01 %)	UV	NO/NO_2 mixture	35.40	[118]
Titanium oxide/G-1 (0.01 %)	Visible-light	NO/NO_2 mixture	22.75	[118]
Titanium oxide/rGO-2 (0.1 %)	UV	NO/NO_2 mixture	42.86	[118]
Titanium oxide/rGO-2 (0.1 %)	Visible-light	NO/NO_2 mixture	22.34	[118]
MTi5	UV	NO/NO_2 mixture	22.5	[119]
MTi5	Visible-light	NO/NO_2 mixture	18	[119]
TTIP- Titanium oxide	UV	NO_2	60	[120]
Titanium oxide/FGO	UV	NO/NO_2 mixture	51	[121]
M400	UV	NO/NO_2 mixture	38	[122]
M400	Visible-light	NO/NO_2 mixture	27	[122]
Pd/IL- Titanium oxide	UV	NOx mixture	88	[123]
N-Zr-Ni- Titanium oxide	Vis-PCO	NO	56.8	[124]
TAS	UV	NO	31	[125]
Titanium oxide	UV-A	NO/NO_2 mixture	97	[126]
P25	UV-A	NO/NO_2 mixture	99	[126]
Ti- Titanium oxide mesocrystal	Visible-light	NO	55	[127]
Pt- Titanium oxide	UV-PCO	NO	86	[128]
g + Titanium oxide/N, C-300-20 %	UV	NO/NO_2 mixture	20	[129]
(0.3/1) Titanium oxide/ g-C_3N_4	UV	N_2O	57	[130]
Titanium oxide/g-C_3N_4 (1:2)	UV-A	N_2O	68	[131]
Titanium oxide/g-C_3N_4 (1:2)	UV-A	N_2O	68	[131]
Titanium oxide	UV	NO	50	[132]
Titanium oxide	UV	NO	67	[132]
Titanium oxide	UV-PSCO	NH_3	100	[133]
1 wt% Ag (hυ)/Titanium oxide	UV-PCO	NH_3	75	[134]
0.2 wt% Pt/Titanium oxide	UV-PCO	NH_3	58	[134]
0.01 wt% Fe_2O_3/ Titanium oxide	UV-PCO	NH_3	70	[134]
0.1 wt% Fe_2O_3/Titanium oxide	UV-PCO	NH_3	4	[134]
0.5 wt% CoO/Titanium oxide	UV-PCO	NH_3	74	[134]
0.05 wt% MoO_3/ Titanium oxide	UV-PCO	NH_3	38	[134]
0.05 wt% V_2O_5/ Titanium oxide	UV-PCO	NH_3	55	[134]
1 wt% NiO/Titanium oxide	UV-PCO	NH_3	97	[134]
Titanium oxide	UV-PCO	NH_3	71	[134]
4 M H_2SO_4/Titanium oxide	UV-PCO	NH_3	65	[134]

delivery systems that would increase the tissue specificity of the therapy and reduce the systemic effects are still being sought. Many chemotherapeutic agents are also ineffective because of the multidrug resistance (MDR) mechanism displayed by cancer cells and related to the overexpression of some members of the ABC superfamily of efflux transporters that treat the drug as a poison and remove it from the matrix. Currently, one of the most commonly studied chemotherapeutic drug is doxorubicin (DOX). Although it provides many advantages for the therapy of various cancers, the use of doxorubicin is associated with adverse effects, out of which, the cardiotoxicity is the most severe and dangerous [136,137]. Potential solution to both problems may be the use of nanoparticles and the combination of chemotherapy with photodynamic therapy or photothermal therapy (Fig. 3). Titania nanoparticles offer significant advantages in this field, enabling efficient delivery of the drug molecules, and thus better pharmacokinetics, and their targeted delivery.

Inorganic photosensitizers, including Titanium Oxide Nanoparticles, similarly to organic photosensitizers, can be used for photodynamic therapy, which was presented above. Titanium Oxide Nanoparticles were investigated for photodynamic therapy under the excitation of UV or visible light after doping with organic photosensitizers. Considering some limitations of UV light mainly related to harmful effects for human body accompanied by low penetration to tissues, it is worth exploring NIR-triggered inorganic photosensitizers for the non-invasive photodynamic therapy in deep tissues. The rare-earth-doped nanoparticles converting NIR into UV light, NIR-triggered photodynamic therapy of Titanium Oxide inorganic photosensitizers can be obtained by coupling two different Nanoparticles, including up-conversion Nanoparticles (UC NPs) and Titanium Oxide Nanoparticles. UC Nanoparticles can be coated by Titanium Oxide inorganic photosensitizers to form a core-shell structure or combined to form UC/Titanium Oxide nanocomposite with a non-core-shell structure. The construction of nanocomposite seems to be more beneficial as such a system can be applied for the chemotherapy and NIR-triggered inorganic photodynamic therapy. Improvement of the DOX targeting to the cancer cells may be achieved by selective release of the drug in the desired site of action. This would then result not only in lowered toxicity of the anticancer agent, but also in increased concentration of the drug in cancer cells, enabling lower doses to be used and reducing the occurrence of adverse effects. Selected Titanium Oxide Nanoparticles combined with doxorubicin discussed in this chapter are summarized in Table 3.

3.3. Other Applications of titanium oxide nanoparticles in medicine

Applications of titanium dioxide in medicine are going further than the design of drug delivery systems or applications as vehicles for chemotherapeutics. Titanium Oxide Nanoparticles have been applied in pharmacy, especially in pharmaceutical chemistry and technology, as well as medicine, including growing areas related to dentistry and surgery [143]. The selected Titanium Oxide forms of potential applications in dentistry, surgery, and pharmacy discussed in this chapter are summarized in Table 4.

In dentistry, the photochemical activity of titanium dioxide was utilized for the improvement of tooth personal care and teeth whitening. This property was demonstrated by Cuppini et al. who studied Titanium Oxide gel bearing H_2O_2 and methylene blue They noticed that the combination of Titanium Oxide with H_2O_2 allows for reducing the time necessary for tooth bleaching by 30 min of gel-tooth direct contact significantly. Importantly, Kurzmann et al. reported initial toxicity studies of Titanium Oxide based gels for tooth bleaching. They observed that diluted gel formulations tested against L-929 cells, 3T3 cells, and gingival fibroblasts did not reveal any noticeable reduction in cell viability [144]. The authors suggested additional experiments aiming to assess the Titanium Oxide gel toxicity. Sodagar et al. solved the problem of caries next to brackets in orthodontic treatment. They proposed the addition of Titanium Oxide nanoparticles at the concentration up to 10 % into the orthodontic bond. The presence of Titanium Oxide in the composite decreased the colony counts of Streptococcus mutans and S. sanguinis. Unfortunately, the presence of Titanium Oxide nanoparticles resulted also in loss in the shear bond strength in comparison to unmodified composite [145]. Finally, the addition of up to 5 % of Titanium Oxide helped to achieve a compromise between bacterial growth reduction and loss in the shear bonding strength. During the orthodontic treatment with a fixed appliance, the caries lesions are commonly spotted, especially next to orthodontic brackets. It is a result of difficult

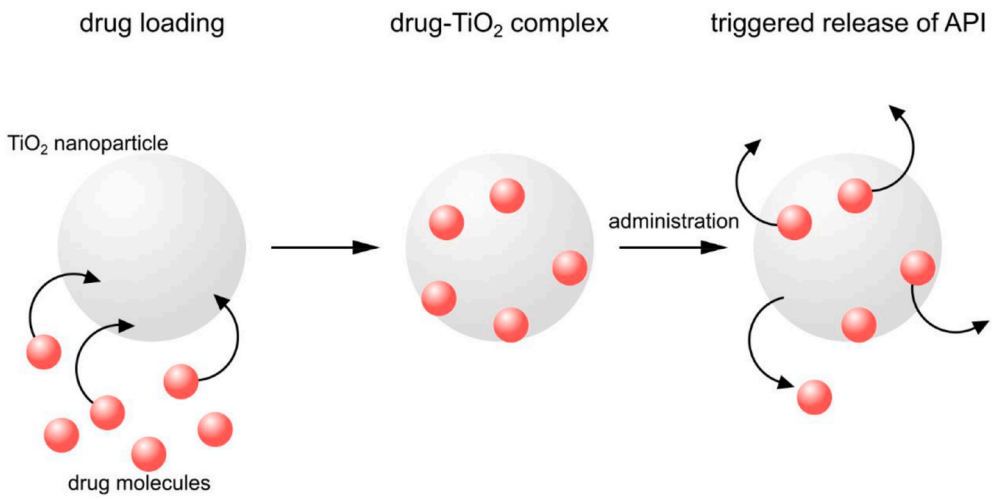


Fig. 3. Simplified mechanism of titanium (IV) oxide as drug delivery vehicle [136,137].

Table 3
Synthesis, physicochemical characteristics, and medical applications of selected Titanium Oxide Nanoparticles in combination with doxorubicin.

Characteristics	Method	Application	Ref
ZnPc@ Titanium Oxide _CHCl3 (20 nm) ZnPc@ Titanium Oxide _THF (125 nm) ZnPc@ Titanium Oxide _CHCl3/THF (13 nm)	Nanoparticles —commercially; nanotubes—from titanium (IV) isopropoxide in a sol-gel method followed by hydrothermal treatment; deposition of ZnPc in CHCl3, THF or 1:1 v/v CHCl3/THF	photodynamic therapy, bioimaging and doxorubicin delivery (tested on HeLa cells)	[138]
UCNPs@SiO2@ Titanium Oxide (Titanium Oxide shell thickness—5–6 nm)	Titanium Oxide was grown on UCNPs@SiO2-NH2 NPs from titanium diisopropoxide bis (acetylacetonate); further hydrothermal treatment yielded crystalline structure	PDT in cancer treatment mixed with doxorubicin (tested on HeLa cells)	[139]
diamond-shaped mesoporous Titanium Oxide (220 nm in width, 250 nm in length, 40 nm thick, pore size—4.1 nm)	from Ti (IV) isopropoxide at 28 °C, followed by silylation and PEGylation	pH-responsive drug delivery vehicles for cancer therapy	[140]
Titanium Oxide nanowhiskers (width 80 nm, length range—200–5000 nm)	K2CO3 with Titanium Oxide heated at 810 °C, soaked in distilled water for about 7 days, dried, and calcinated	photodynamic therapy with daunorubicin delivery against hepatocarcinoma cells	[141]
0.3 μm Titanium Oxide nanotube array (single nanotube diameter—90 nm)	growth of Titanium Oxide nanotubes in a glycerol/water/NH4F mixture, then annealing to form anatase	Visible-light-triggered release of ampicillin	[142]

Table 4
Synthesis, physicochemical characteristics and applications of selected Titanium Oxide nanoparticles in dentistry, surgery and pharmacy.

Characteristics	Method	Application	Ref
Titanium Oxide (anatase, 25 nm) Titanium Oxide/Ag nanoparticles	commercial distribution of Titanium Oxide anatase powder was mixed with silver nitrate, reduced and heated at 300 °C	toxicity reduction of teeth whitening gels	[143]
Titanium Oxide (anatase, ≤15 μm) Eggshell- Titanium Oxide composite (irregular, spherical shape particles, ≤13 nm)	undefined/ commercial distribution of Titanium Oxide, eggshell powder with Titanium Oxide was ground in ball mill	occluding opened dentine tubules	[144]
Titanium Oxide (anatase, 10 nm)	undefined/ commercial distribution	improving of endoprotheses biocompatibility	[145]
P25 (anatase/rutile 8:2, 21 nm)	commercial distribution	photocatalytic degradation of phenol	[146]
Titanium Oxide (anatase, 20–50 nm) Titanium Oxide (rutile, 50–100 nm) Titanium Oxide mixed phase (anatase/rutile 83:17, 20–50 nm)	commercial distribution	photocatalytic degradation of atenolol	[147]

access to these areas in daily personal care. Therefore, the development of a new class of orthodontic bonds with bactericidal activity is very desirable. Sharma et al. reported the necessary shear bond strength for orthodontic treatment as 5.9–8 MPa. The Titanium Oxide modified composite developed by Sodagar et al. with shear bond strength 13.9 MPa seems to be a promising material. It should be analyzed whether it is suitable for safe debonding of orthodontic brackets. In another study, Sun et al. prepared Titanium Oxide nanotubes and loaded them with tetracycline. They carried out several tests against Porphyromonas gingivalis. Pure Titanium Oxide and loaded nanotubes showed great adhesion potential and antibacterial properties [146]. Also, tetracycline was released quickly within 15 min of the experiment and the material was stabilized in 90 min. Titanium Oxide nanoparticles have not only antibacterial but also antifungal properties. Huang et al. prepared Co-Cr alloy, on which they deposited a thin layer of Titanium Oxide. Several tests under UV-irradiation revealed that the prepared material exhibited significant antifungal activity and that it can be considered in the future against denture stomatitis [147].

4. Nanoparticle titanium oxide (TiO_2) and thin film synthesis methods

The properties and applications of Nanostructures Titanium oxide

(TiO_2) are highly dependent on the particle size, structure, effective surface area, and surface properties. Since these properties are in turn influenced with synthesis methods, in this section we will have an overview of different methods of synthesis of nanoparticles Titanium oxide (TiO_2) thin films [148–152]. Chemical reactions for the synthesis of substances can take place in gaseous, liquid or solid forms. The rate of penetration of reactants in the gas or liquid phase is several times faster than in the solid phase. Therefore, the methods of synthesis of nanostructures can be divided into two general categories, methods of synthesis from the liquid phase) and synthesis from the vapor phase [153–158].

4.1. Synthesis methods from the liquid phase

During the deposition process from the liquid or solution phase, the material is solidified with condensation. This approach is commonly used to synthesize high purity thin films and powders [159–162].

4.1.1. Sol-gel method

The sol-gel process was first discovered in the late nineteenth century and has been widely used since the early 1940s. Sol-gel is a more chemical method for making ' thin films ', powders and membranes. Synthesis of materials in this method, oxides with different physical and chemical properties are obtained [163–166]. The sol-gel method has advantages over other methods, which makes it a suitable method, with great care in the preparation of nanoparticles and thin films. Among the advantages of this method are: simplicity of the method, controllability of the synthesis steps, purity and homogeneity of the product, control of elemental proportions, high chemical reactivity, low reaction temperature and preparation of coatings on a large scale [167–171].

Here we need to first describe the sol-gel method and then the steps to achieve the final product.

The sol-gel process is common in both alkoxide and non-alkoxide pathways. In the non-alkoxide method, inorganic salts (such as nitrates, chlorides, acetates, carbonates, acetyl-acetates, etc.) [156–158] are used as raw material. Non-alkoxide synthesis requires additional materials to remove inorganic anions. Because in this way, most halides remain in the final oxides and it is very difficult to remove them.

The most important and common method of sol-gel process in the preparation of minerals including glass, catalyst bases and ceramics is the alkoxide pathway. In this method, metallic organic compounds such as metal alkoxides are used as starting material [172–175]. In general, the sol-gel process is the systemic transition from a liquid sol phase to a solid gel phase.

Sol is the distribution of solid discrete particles measuring 1–100 nm in a liquid, which remain suspended due to their small size due to Brownian motion in solution, and the Gel is also a colloidal solid containing both solid and liquid components [159].

In a typical gel cell process, the alkoxide precursor is subjected to a series of hydrolysis and polymerization reactions to form a colloidal suspension or sol. During the synthesis process, complete polymerization and solvent removal leads to the transition from liquid sol to a solid gel phase. Finally, with calcination of the gel, the desired powder can be produced [176,177].

The following equations show the basic reactions that make it possible to convert an alkoxide precursor into a gel and eventually into a mineral network.

$$1)M-OR+HOH\rightarrow M-OH+R-OH$$
$$2)M-OH+M-OR\rightarrow M-O-M+R-OH$$
$$3)M-OH+M-OH\rightarrow M-O-M+H-OH$$

Reaction (1) shows the hydrolysis of a metal alkoxide that M can be a metal such as Si, Ti, Zr, Al, etc., and R can be an alkyl group such as methyl, ethyl, isopropyl, butyl, etc. Reactions (2) and (3) show the polymerization and gel formation reactions [160]. In the sol-gel method, the raw materials are first dissolved in a suitable solvent, which is called solute.

A gel-forming agent which contains a complexing agent and an electrolytic binding agent is subsequently added to the Sol. The complexing agent forms a complex with forming weak hydrocarbon bonds with cations. The electrolytic agent then polarizes the end heads of the complexes with polarizing them, so that colloidal clusters grow. These colloidal clusters help the cations to be connected to each other and randomly adjacent to each other on a regular basis to form a colloidal solid or gel. In other words, in the gel state, the bonds of the complex chains are established together in the sol, and with gentle heating of the primary sol, usually carried out over a long period of time, the bonds strengthen and slowly, due to the loss of solvent, the sol turns into a gel with. After performing the heating step at relatively low temperatures, the hydrocarbon bonds are released as gas and the cations with a suitable ionic radius remain together, resulting in a very homogeneous powder of the desired material, with very fine grains.

Preparing various materials from alkoxy precursors with the sol-gel process encompasses several successive stages. Each stage acts as a bridge between the previous and next stage, as follows**:**

✓ Mixing Primary materials

It involves mixing the precursor with water, solvent, and other additives to prepare the initial Sol at a suitable pH to prevent scale formation. The initial Sol is usually transparent, because having a homogeneous mixture increases the reaction rate and decreases the reaction temperature, thus creating the conditions for the production of fine-grained powder [161]. Additives can include complexing agent, polymerizing agent and catalysts. In the mixing step, with adding water (O-H group), hydrolysis and polymerization occur according to reactions 1 to 3. Mixing conditions can change the rate of hydrolysis and polymerization reactions and the size of Sol particles. These conditions can include molar ratio of raw materials (such as alkoxide/water ratio), Sol pH, material flux rate, type and concentration of catalyst, type and concentration of complexing agent and polymerizing agent.

✓ **Shaping**

One of the advantages of the sol-gel method is that from a certain composition, it is possible to make different shapes of materials such as layers, fibers and powders only with changing the test conditions. One of these important and controllable parameters for preparing different products is the viscosity of sol and gel [162]. For example, according to experimental research, the optimum viscosity of Sol for fiber preparation is more than 1 Pa. The viscosity of the solution is affected with hydrolysis reactions, polymerization and Sol particle size. In the process of forming the sol-gel process, the sol, which is a low-viscosity solution, can be formed with changing the viscosity to a certain mold.

Fig. 4 shows the different pathways of the sol-gel process to achieve different products.

✓ Gelation

At this stage, the hydrolysis and polymerization reactions convert the molecules of the primary homogeneous solution (Sol) into an infinitely heavy three-dimensional polymer molecule called gel. During the sol-gel process in a period, the viscosity of the sol increases sharply, which is called the gel point or teel time. In fact, the resulting elastic solid fills the volume of the solution.

✓ Dehydration or chemical stabilization

It involves the removal of surface hydroxyl groups from the pore network, which results in the preparation of a solid with high porosity. The vibrational energy of these hydroxyl bonds, which is approximately in the range Wavelengths between ultraviolet and infrared reduce

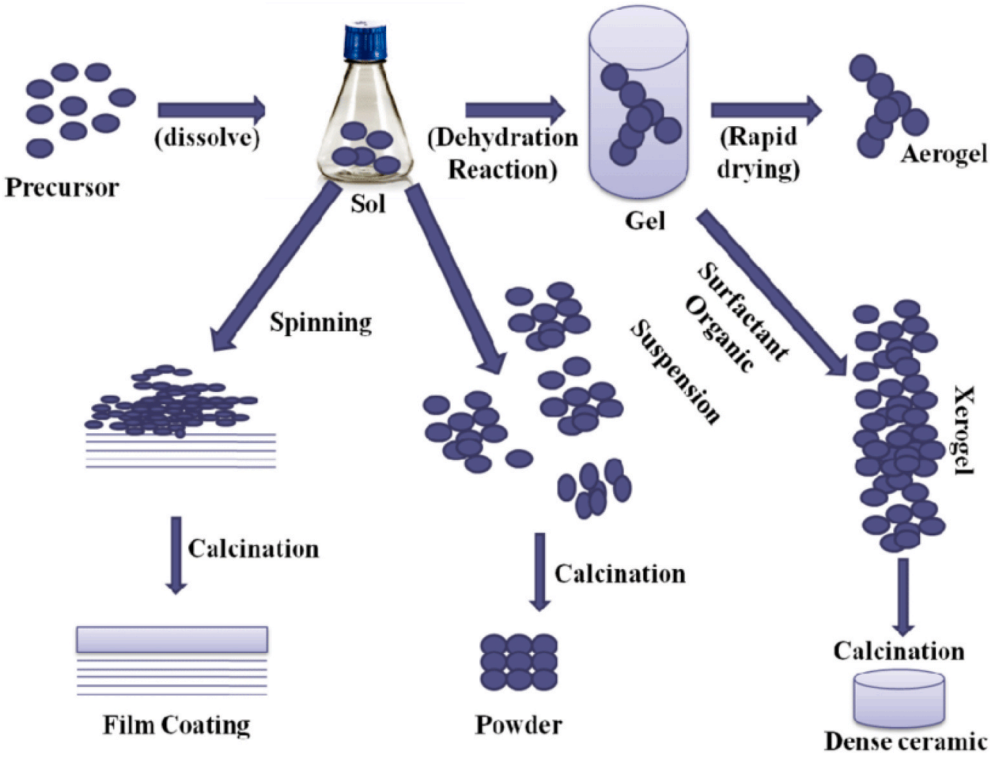


Fig. 4. Different stages, routes and products of the sol-gel processing illustrating its versatility [163].

optical applications. For this reason, the dehydration step is necessary to achieve optical performance. For dehydration, it is necessary to know that water is absorbed in two ways: one freely in the pores of the gel structure (physical absorption of water) and the other as hydroxyl groups in relation to the gel surface (chemical absorption of water). On the other hand, the amount of water physically absorbed depends directly on the number of hydroxyl groups present on the surface. The evaporation temperature of water can be different for the two shapes. Since the amount of hydroxyl group in the surface is very high, in order for the condensation process to be complete and the oxidation to be complete, the surface must be dehydrated before the pores are closed during the processes [166].

✓ Densification and sintering

Compaction is the last step in the synthesis of materials with the sol-gel method and involves heating the porous gel at high temperature. At this stage, the pores and pores are reduced and the density is increased. The compaction temperature is significantly dependent on the size of the pores, the pore relationship and the effective surface area. In alkoxide gels, the annealing temperature is usually below 1000 °C [168]. As the density temperature increases, the effective surface area decreases due to the reduction in the volume of pores. At this stage, all the fluid inside the cavities is released and a compact solid called Xerogel is formed. Fig. 5 shows the different states of the gel [166].

4.1.2. Synthesis of nanoparticles titanium oxide (TiO_2) with sol-gel method

Sol-gel, which involves the hydrolysis reactions and densification of alkoxide precursors, is a reliable method for the synthesis of very fine metal oxides [15]. Researchers have used the sol-gel method in different ways. Wang et al. [178] added tetra n-butyl titanate to deionized water and, with adding hydrochloric acid or ammonia, prepared a gel which, after drying, grinding, and calcination at various temperatures, produced nanopowder Titanium oxide (TiO_2) [179,180]. The spectra obtained from the annealed powders at different temperatures (Fig. 6) show that the phase transition from anatase to rotai started at 600 °C

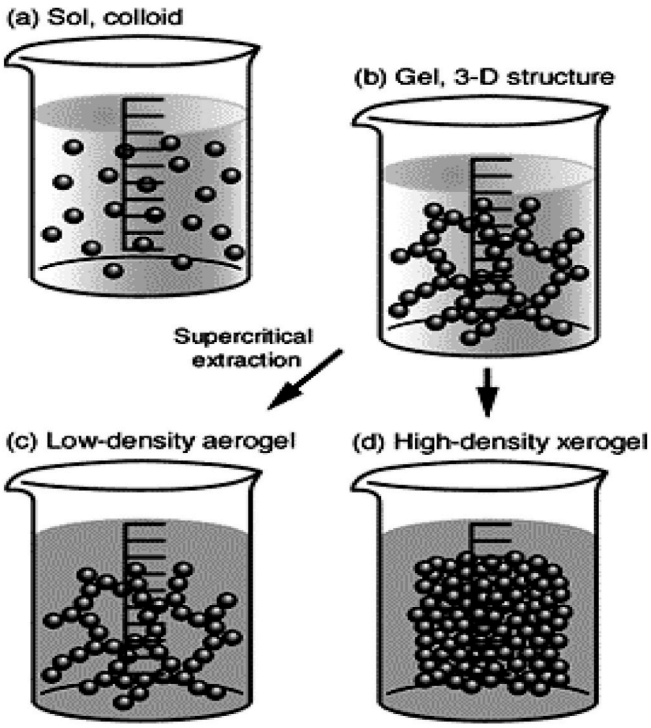


Fig. 5. Different stages of gel preparation (a) Cell (b) Wet gel (c) Aerogel (d) Exrogel [177].

temperature and was completed at about 800 °C.

As the annealing temperature increases from 350 °C to 600 °C, the nanoparticle size increases from 6 nm to 36 nm. According to Fig. 7, the growth rate of particles at low annealing temperatures is slow, but at high temperatures, the increase in nanoparticle diameter accelerates.

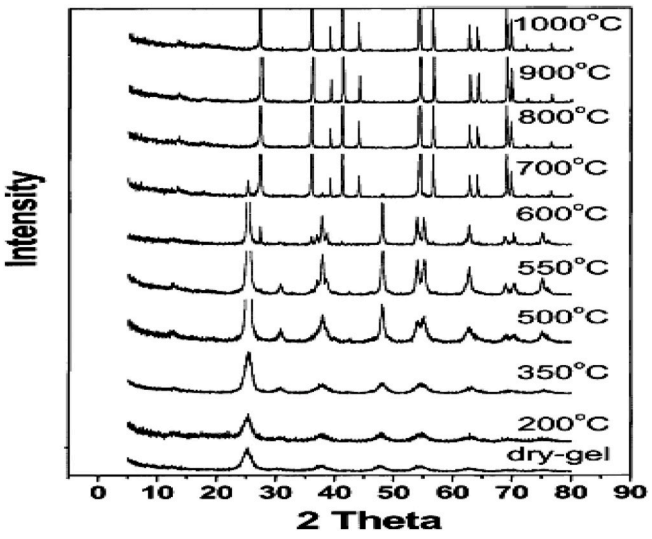


Fig. 6. XRD spectra of nanoparticles Titanium oxide (TiO_2) at different annealing temperatures for 2 hours [178].

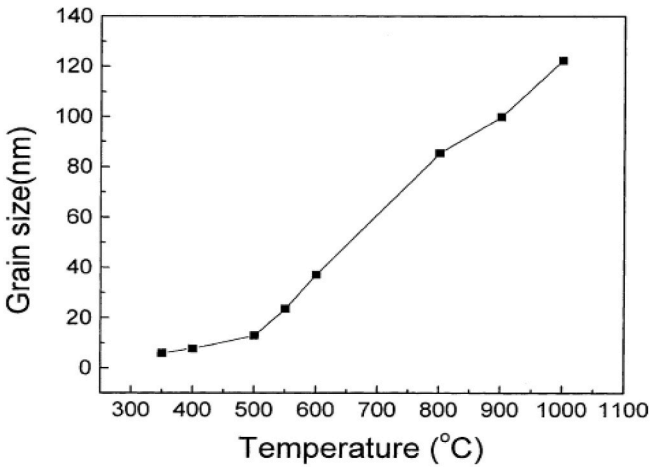


Fig. 7. Nanoparticle size change curve with increasing annealing temperature [178].

Since the production of catalytic compounds, electrodes and other Titanium oxide (TiO_2) equipment on polymer substrates and some special metals is not possible at high temperatures, the synthesis of nanoparticles at low temperatures will be of particular importance. In a study by Li et al. [15], titanium oxide nanoparticles were synthesized with sol-gel method at temperatures below 100 °C. After preparing the dry gel from the initial solution containing tetrabutyl titanate and ethanol, it was left in the medium for 12 hours at a temperature of 100 °C (shelf life). Not only has persistence been observed to help eliminate organic compounds, but it also crystallizes the anatase phase. Fig. 8 shows the synthesis methods of Titanium oxide (TiO_2) thin film.

4.1.3. Co-sedimentation method

The method of preparing colloidal materials from the liquid phase is called co-precipitation and involves preparing the precipitate with adding a base solution (NaOH, NH_4OH) to the starting material and hydrolyzing them [171]. with sintering the resulting precipitate, the desired oxide is prepared. The deposition reaction is relatively fast, therefore, lack of control over particle size and distribution is one of the disadvantages of this method. In the co-precipitation method, $TiCl_4$ [172,173] or $TiCl_3$ [174] are usually used as raw material to prepare nanoparticles Titanium oxide (TiO_2).

4.1.4. The hydrothermal and solothermal method

In this method, chemical reactions in an aqueous solution (hydrothermal) or in a non-aqueous solution (solothermal method) with several organic substances such as methanol, 1 and 4 butanol and toluene [175,176], under high pressure and low temperatures (usually less than 25 °C) are involved. Depending on the reaction required to obtain the final material, it is usually necessary to bake the material below the melting point to crystallize the final material. If aqueous solutions are used as solvents, the hydrothermal technology is used. The hydrothermal process is more suitable for the preparation of hydroxides, oxyhydroxides or oxides due to the use of water as a solvent. To prepare non-oxidizing materials (especially nitrides, collagenides, etc.) processes that use non-aqueous solvents are involved [177]. Temperature and pressure improve solubility in most cases. Increasing these factors induces an increase in the concentration of the precursor in the solvent, which in turn contributes to the growth process (especially micro or nanocrystals).

The term hydrothermal mainly refers to any heterogeneous reaction in the presence of an aqueous solvent at temperatures above the critical temperature and at high pressures. In other words, hydrothermal refers

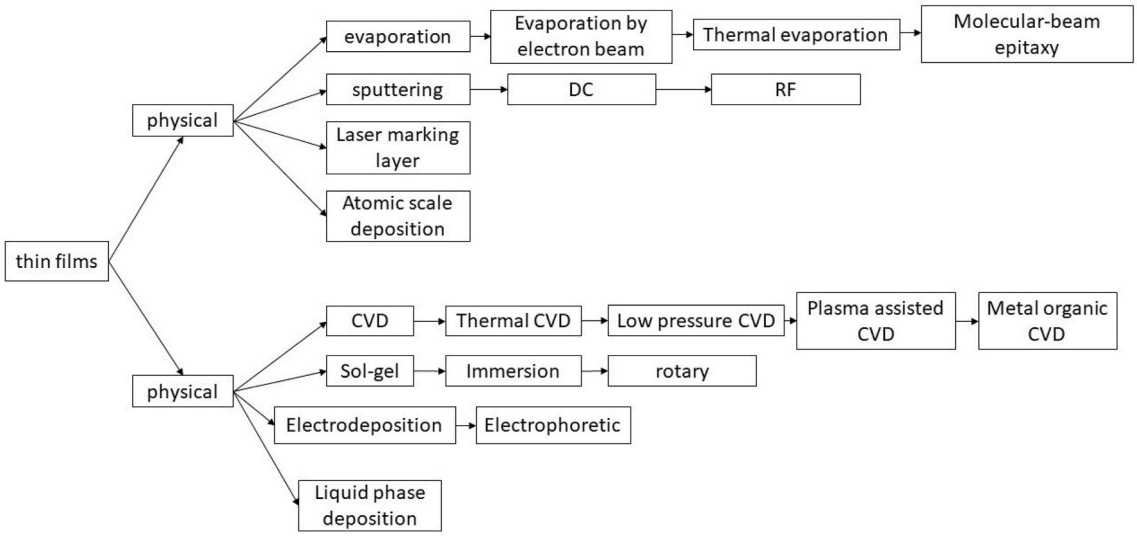


Fig. 8. he synthesis methods of Titanium oxide (TiO_2) thin film [178].

to aqueous solvent reactions that take place at temperatures above 100 °C and pressures above 1 atm [177]. In this type of process, the reactants are completely dissolved together with the solvent in two separate containers with a specific concentration that depends on the elemental fit coefficients of the reaction in question. Crystal growth takes place in a device that consists of a pressure steel tube, namely an autoclave, in which the raw material is mixed with water. At the two opposite ends of the growth chamber, a temperature gradient is applied to dissolve the warmer end of the material and the colder end to cause increased grain growth. After applying a certain pressure and temperature, the sample is removed from the autoclave chamber and dried [13, 178]. The advantage of the hydrothermal method over other synthesis methods is the ability to create crystalline phases that are not stable at the melting point. Due to its good control power over the composition steps, the method is also suitable for the growth of large crystals with the desired quality. Materials that have high vapor pressure, close to their melting point can also be prepared with the hydrothermal method. The disadvantages of this method are the high cost of autoclaves and grains with good quality and suitable size, and the impossibility of observing the crystal during its growth [177].

This method has been widely used in the ceramic industry, for the synthesis of simple and mixed oxide powders with controlled morphology at relatively low temperatures (150–350 °C), and in the preparation of nanoparticles (especially Titanium oxide (TiO_2)) [178].

Due to the various parameters involved in the hydrothermal process (temperature, pressure, reactant concentration and solution pH [178]) and the involvement of a heating step, different hybrid models have been used, in various hydrothermal methods, for the synthesis of nanoparticles Titanium oxide (TiO_2).

Ivanov et al. [181] used the hydrothermal process with ultrasonic waves to synthesize Titania nanoparticles. Amorphous Titanium oxide (TiO_2). H_2O gels were prepared with mixing a solution of $TiCl_4$ in concentrated hydrochloric acid (molar ratio 1:2) with aqueous ammonia solution (5 M) under constant stirring. The obtained sediments were separated from the liquid using a funnel equipped with a strainer and washed thoroughly with distilled water. In this process, the agglomerated nanoparticles are broken down with sound waves. On the other hand, the acoustic reaction of solutions has led to a significant increase in the decomposition rate of waste organic matter. According to Transmission Electron Microscope (TEM) images (Fig. 9), both powders, obtained with conventional hydrothermal method and hydrothermal method with ultrasonic waves have an average size between 25 and 30nm. The acoustic reaction dramatically increases the crystallization rate of nanoparticles and thus leads to a decrease in the temperature and synthesis time.

Solothermal reactions include oxidation-reduction, hydrolysis, heat-capping, and complex formation. Solothermal reactions have been developed in the production of functional materials, crystal growth at low temperatures (method for single crystals with minimum density of crystal defects), and preparation of nanocrystals of different sizes and morphologies. Solothermal method for oxide nanostructures such as barium titanate (due to application in dielectric ceramics) [181], Titanium oxide (TiO_2), Fe_2O_3-α as pigment and catalyst [182] and one-dimensional magnetic oxides (optical applications), ZnO (due to electrical, optical properties and piezoelectric) is used [183].

4.1.5. Reverse micelle or microemulsion method

This method is one of the newest liquid phase ones and is used to obtain nanocrystalline materials. Research emphasizes that this method is a suitable option for the synthesis of nanocrystalline metal oxide powders with controlled properties. with applying a precise control to the reaction parameters, this technique is able to produce particles with precise shapes and dimensions.

Surfactants are substances with molecules consisting of hydrophilic and hydrophobic hydrocarbons which are being dissolved with organic solvents. Spherical aggregates form what are known as inverted or reversible micelles (Fig. 10) [184]. The property of inverse micelle formation in organic solutions can be used to control particle growth [185]. In the presence of water, the polar head groups of surfactant molecules arrange themselves around the water droplets, dispersing the aqueous phase into the oil phase. Due to the small environment inside the micelles, an aqueous solution of raw material can be a suitable environment for the formation of nanoparticles. Reactions such as hydrolysis of reactive raw materials (such as alkoxides) and deposition reactions of metal salts in micelles can lead to the production of nanoparticles in the micellar medium. The final product is obtained following solvent removal and calcination. In this process, various surfactants such as pentadoxy ethylene nonyl ether, poly (oxyethylene) nonyl phenol ether can be used. Particle raw material concentrations (including dimensions, reactive distribution, and weight percentage of the aqueous phase in the microemulsion can affect the dimensional properties and phases of the final oxide powders.

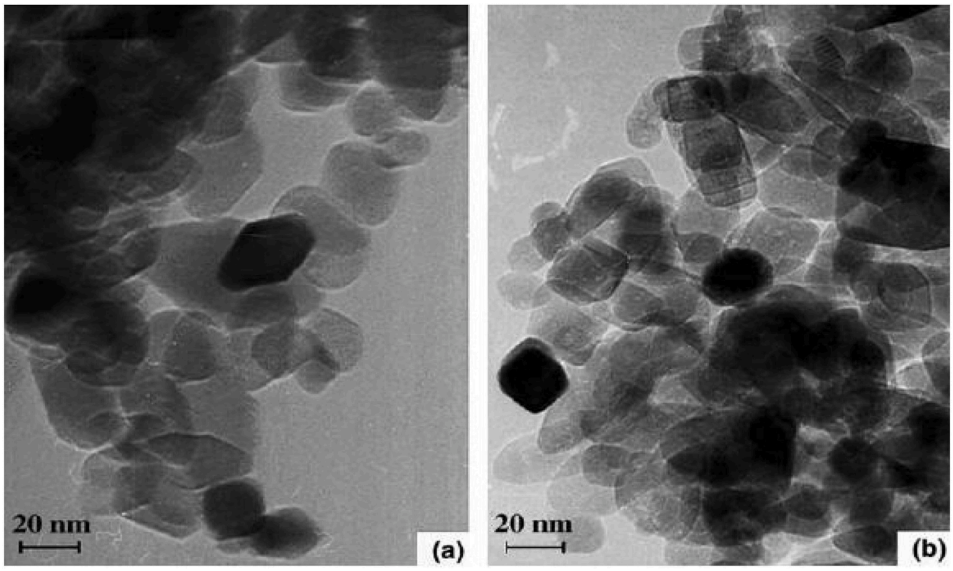


Fig. 9. TEM images of Titanium oxide (TiO_2) powders prepared with (a) hydrothermal method (b) with the help of conventional ultrasonic waves [181].

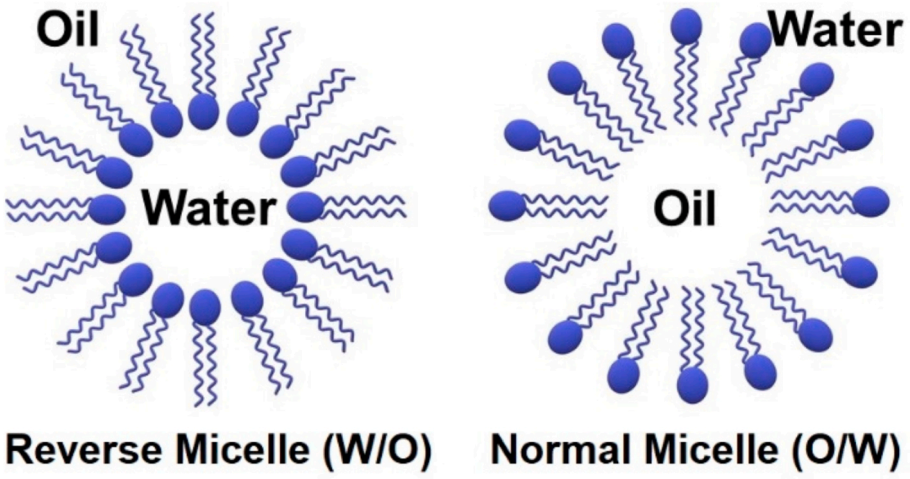


Fig. 10. Schematic structure of a reverse and normal micelle [185].

4.1.6. The combustion method

The combustion method is a cost-effective one and produces high purity powders with high effective surface, but obtaining nano-structured materials [186] is quite difficult. The combustion synthesis process is based on the property of exothermic reactions. The initial composition, which usually consists of an oxidizer with an organic fuel (reducing agent), undergo combustion and expands spontaneously during the mixing process [187]. The reason why the reaction proceeds spontaneously is the difference in the enthalpy of raw materials and products. In this method, the reactants can be gaseous, liquid or solid. Due to the high reaction speed, the production efficiency of this method is high and, due to the high temperature of the combustion front (up to 65 °C), many impurities evaporate and therefore leave the environment, resulting in a final product with a higher degree of purity than other methods [188].

4.1.7. The electrochemical method (electrodeposition)

This method of chemical synthesis is commonly used to prepare advanced thin films such as epoxy growths, superlattices, quantum dots, and porous coatings [35]. This method has also been used for metal coatings such as Titanium oxide (TiO_2) [35]. The deposition layer is usually done with performing a reduction reaction on the cathode. The substrate is placed as a cathode in a bath of metal salt, and, as the current passes, the metal ions are absorbed with the cathode and reduced. In this way, a coating of the desired material is formed on the cathode. Although the preparation of Titanium oxide (TiO_2) layers from various compounds of $TiCl_3$, $Ti(SO_4)$ [188], $(NH4)_2TiO(C_2O_4)_2$ [194] has been reported, due to the high tendency of salts to be hydrolyzed, the use of inorganic titanium salts in aqueous solution has always been associated with issues. Using a non-aqueous solution can be a good option to solve this problem [187].

4.2. Synthesis methods from the gas phase

Gas phase synthesis methods, either physical or chemical, are usually used to prepare coatings. The most important methods used in the preparation of Titanium oxide (TiO_2) thin films are as follows:

4.2.1. Chemical vapor deposition (CVD)

The chemical vapor deposition (CVD) process is one of the most important and widely used methods for the production of layers, coatings and particles. There are over ten types of CVD methods. This method can be used in various conditions for coating, thin film production and powder synthesis, especially nanoparticles. If the germination operation in the steam phase is heterogeneous and adjacent to a substrate, the product is a thin layer. But if homogeneous germination occurs in the system, powder will be produced. Unlike the Physical Vapor Deposition (PVD) method, in which atoms deposit directly on the surface, in the CVD method, the atoms sit uniformly at all angles and in different parts of the substrate [187,188].

In this method, the substrate is affected with one or more volatile raw materials (in the gas phase), the coating layer being applied with means of a chemical reaction at high temperature (usually above 500 °C), resulting in the desired pattern. The waste gas products are removed from the reaction medium with the carrier gas stream. The device consists of a horizontal cylindrical reactor chamber, equipped with several inlet channels, aimed for the entry of material vapor. The samples or substrate is placed inside this chamber and a thin layer is deposited on the substrate, with passing the material at high temperature. shows a simple design of this device. Materials such monocrystalline, amorphous and woven materials, silicon, carbon fiber, carbon nanotubes, SiO_2, germanium, tungsten, silicon carbide (SiC), silicon nitride, silicon oxy-nitride, titanium nitride, high dielectric constant dielectrics and various semiconductor and magnetic compounds allow prepation with different manufacturing methods using the CVD technique [169–174]. Table 5 presents a brief list of CVD processes and their conditions for polymetals and semiconductors [189].

4.2.2. Physical vapor deposition (PVD) layer

The PVD includes several methods which involve the physical deposition of thin films or nanostructures. It's carried out on various surfaces (such as semiconductor substrates) and consists of three stages: evaporation of the solid source, vapor phase transport from the source to the substrates, and vapor condensation. In other words, without any chemical reaction, the precursor becomes a product [189].

PVD involves vacuum deposition processes in which one or more of the depositing species are evaporated or otherwise atomized from a solid source in the coating chamber but CVD involves deposition processes in which the depositing species are inlet into the coating chamber in a gaseous or vapor form [180].

In the Physical vapor deposition (PVD) the source materials are transformed into a vapor or plasma using a physical process (typically heating or bombardment.) The vapor then moves towards a substrate where it condenses on the surface. Main advantages of physical vapor deposition: It does not require the use of chemical reagents or cleaning post-treatments, so it has a very low environmental impact. PVD can be applied to any type of inorganic material. The coatings obtained with PVD have great adhesion, resistance and durability. The advantage of PVD over CVD: This process is relatively more expensive, but is worth the added cost for applications that demand higher precision. Sputtering

Table 5
CVD process conditions for metal deposition and semiconductors [189].

Deposited material	Substrate	Inputreactant	Deposition Temperature	Crystallinity
Si	Single-crystal Si	$SiCl_2H_2$, $SiCl_3H$ or $SiCl_4$+H_2	1050–1200	E
Si		SiH_4+H_2	600–700	P
Ge	Single-crystal Ge	$GeCl_4$ or GeH_4+H_2	600–900	E
GaAs	Single-crystal GaAs	$(CH_3)_3Ga$ + AsH_5	650–750	E
InP	Single-crystal InP	$(CH3)_3In$ + PH3	725	E
SiC	Single-crystal SiC	$SiCl_4$, toluene, H_2	1100	P
AlN	Sapphire	$AlCl_3$. NH_3 .H_2	1000	E
In_2O_3:Sn	Glass	In-chelate, $(C4H9)_2Sn$ $(OOCH_3)_2$, H_2O, O_2,H_2	500	A
ZnS	GaAs, GaP	Zn, H_2S, H_2	825	E
CdS	GaAs, Sapphire	Cd, H_2S, H_2	690	E
Al2O_3	Si, cemented carbide	$Al(CK_3)_3$+O_2	275–475	A
		$AlCl_3$, CO_2, H_2	850–1100	A
SiO_2	Si	SiH_4+O_2, $SiCl_2H_2$+N_2O	450	A
Si_3N_4	SiO2	$SiCl_2H_2$+NH_3	750	A
TiO_2	Quartz	$Ti(OC_2H_5)_4$+O_2	450	A
TiC	Steel	$TiCl_4$, CH_4, N_2	1000	P
TiN	Steel	$TiCl_4$, N_2, H_2	1000	P
BN	Steel	BCl_3, NH_3, H_2	1000	P
TiB_2	Steel	$TiCl_4$, BCl_3, H_2	⟩800	P

Note: E = epitaxial; P= Polycrystalline; A = amorphous.

(PVD process) does not require the use of specialized precursor materials as used in CVD. Sputtering has a wider range of materials readily available for deposition [181].

5. Parameters which influence the properties of nanostructures titanium oxide (TiO_2) prepared with sol-gel method

The sol-gel method can be used in the process of making ceramics as a molding material and can be used as an intermediate between thin films of metal oxides in various applications.

The sol-gel process is a more chemical method (wet chemical method) for the synthesis of various nanostructures, especially metal oxide nanoparticles. In this method, the molecular precursor (usually metal alkoxide) is dissolved in water or alcohol and converted to gel with heating and stirring with hydrolysis/alcoholysis [177].

5.1. Effect of pH

In research conducted with Pookmanee, the effect of initial solution pH on phase composition, particle size and growth mechanism of particles synthesized with sol-gel method was investigated [177]. To prepare Titanium oxide (TiO_2) powder, a 1 M solution of ammonium hydroxide and nitric acid was added to titanium isopropoxide at a temperature of 10 °C. Then, to adjust the pH at 2, 4 and 6, a solution containing deionized water, 1 M ammonium hydroxide and 0.3 mol citric acid was added to the cell. The obtained white colloidal cell was placed in an oven at 80 °C for 24 hours. The final product was annealed at temperatures of 400 °C and 800 °C with a rate of 5 °C.min^{-1} and a duration of 2 hours. In the X-ray diffraction spectra of Titanium oxide (TiO_2) powder annealed at 400 °C for different pH, only anatase phase is observed. With increasing pH, a slight decrease in the width and intensity of the diffraction peaks is observed (Fig. 11).

The SEM images show the agglomeration of particles and the

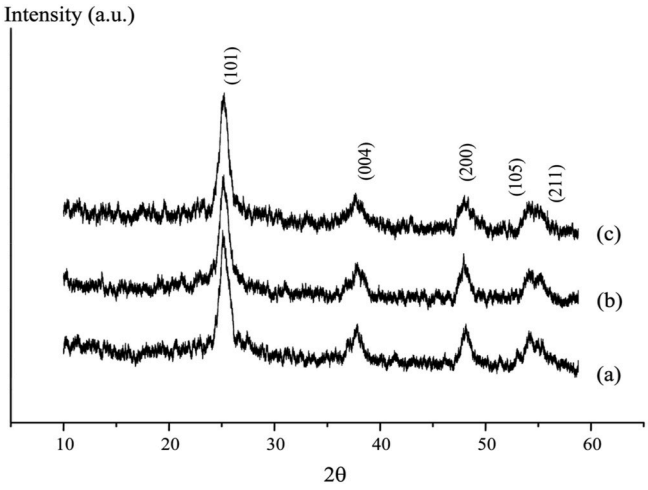


Fig. 11. X-ray diffraction patterns of Titanium oxide (TiO_2) powder calcined at 400°C for 2 h at pH (a) 2, (b) 4, and (c) 6 [177].

increase in particle size with increasing pH of the solution. The size of nanoparticles at pH 2, 4 and 6 was measured as 0.1, 0.2 and 0.4 μm (Fig. 12).

On the other hand, with the increase in pH, the size of the particles increases, confirmed with the SEM images. The particle sizes at pH 2, 4 and 6 at 800 °C are measured as 0.4, 0.2 and 0.5 μm (Fig. 13).

6. Conclusion and prospective and further works

1. Titanium with the formula Titanium oxide (TiO_2) has a specific gravity of 4.2–3.9, a melting point of 1854 °C and a hardness of 5.5–6.5. Titanium oxide (TiO_2) is not soluble in water and organic acids and dilute alkaline solutions, but is soluble in hot sulfuric acid and HF. Titanium oxide (TiO_2) can be crystallized in three structural forms: anatase (tetragonal), rutile (cubic) and brookite (orthorectic). There are several methods for the synthesis of nanoparticles Titanium oxide (TiO_2), such as sol-gel, microwave chemical precipitation. Applications of this oxide in the medical branch of dentistry - color and pigment, photocatalysts, sensors.
2. As the annealing temperature increases due to the increase in the crystal order, the intensity of the peaks in the XRD spectra increases and the size of the crystals increases due to the connection and welding of the particles to each other.
3. TEM and FT-IR studies show that with the increase of annealing temperature, the amorphous background caused with the removal of additives, ethanol, acetyl acetone, etc. is reduced and the purity of the product increases. With observing the TEM images, the suitable heating temperature to achieve the anatase phase is about 400 °C and to achieve the rutile phase is about 700 °C, within 1 h because with increasing annealing time, the size of nanoparticles becomes larger.
4. The phase transition from anatase to rutile for the complexing agent acetylene and citric acid occurs at a temperature of about 500 °C, but for ethylene glycol, which is used with the same molar concentration as acetylene, the phase transformation takes place at a higher temperature. Therefore, the use of acetyl acetone and citric acid as a complexing agent makes it possible to achieve the anatase phase at a lower temperature.
5. The phase transition temperature from anatase to rutile strongly depends on the type and concentration of the complexing agent.
6. Increasing the annealing temperature increases the size of nanoparticles and decreases their effective surface area. The use of acetyl acetone complexing agent and citric acid in the synthesis of TiO_2 nanoparticles leads to the synthesis of smaller nanoparticles with

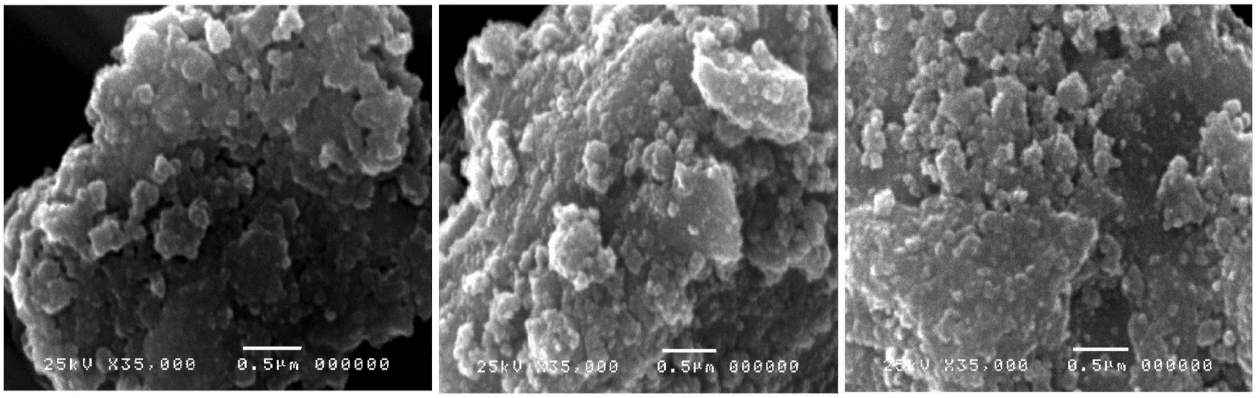


Fig. 12. SEM micrographs of Titanium oxide (TiO_2) powder calcined at 400°C for 2 h at pH (a) 2, (b) 4, and (c) 6 [177].

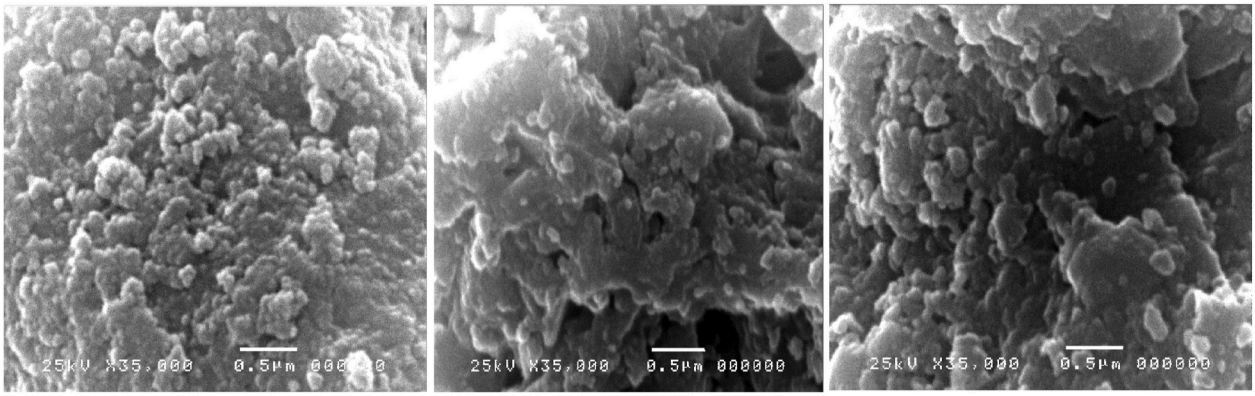


Fig. 13. SEM micrographs of Titanium oxide (TiO_2) powder calcined at 800 °C for 2 h at pH (a) 2, (b) 4, and (c) 6 [177].

more effective surface, which are suitable for photocatalytic and sensing applications.

7. with increasing the annealing temperature from 400 °C to 700 °C for all samples, the energy gap of TiO_2 nanoparticles decreases with the increase in the size of nanoparticles.
8. According to X-ray diffraction spectra at low deposition temperatures, the growth of layers is amorphous. with increasing the temperature of the bed up to 400, the crystalline shape of the layers improves and the optical transparency of the layer's decreases, and the optical gap of the layers increases due to the improvement in the formation of the anatase crystalline phase and the increase in the size of the grains. But as the temperature increases further and the crystal order is disturbed, the intensity of the peaks decreases and it approaches the amorphous structure.

Data availability

All data generated or analyzed during this study are included in this published article.

Ethics approval and consent to participate

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] V. Vatanpour, S.S.M. Khadem, A. Dehqan, M.A. Al-Naqshabandi, M.R. Ganjali, S. S. Hassani, N. Dizge, Efficient removal of dyes and proteins by nitrogen-doped porous graphene blended polyethersulfone nanocomposite membranes, Chemosphere 263 (2021) 127892.

[2] M. Jouyandeh, S.S.M. Khadem, S. Habibzadeh, A. Esmaeili, O. Abida, V. Vatanpour, R.S. Varma, Quantum dots for photocatalysis: synthesis and environmental applications, Green Chem. 23 (14) (2021) 4931–4954.

[3] D. Bazrgari, F. Moztarzadeh, A.A. Sabbagh-Alvani, M. Rasoulianboroujeni, M. Tahriri, L. Tayebi, Mechanical properties and tribological performance of epoxy/Al2O3 nanocomposite, Ceram. Int. 44 (1) (2018) 1220–1224.

[4] R. Salimi, A.S. Alvani, N. Naseri, S.F. Du, D. Poelman, Visible-enhanced photocatalytic performance of CuWO 4/WO 3 hetero-structures: incorporation of plasmonic Ag nanostructures, New J. Chem. 42 (13) (2018) 11109–11116.

[5] R. Salimi, A.S. Alvani, B.T. Mei, N. Naseri, S.F. Du, G. Mul, Ag-Functionalized CuWO 4/WO 3 nanocomposites for solar water splitting, New J. Chem. 43 (5) (2019) 2196–2203.

[6] M.H. Norahan, M. Pourmokhtari, M.R. Saeb, B. Bakhshi, M.S. Zomorrod, N. Baheiraei, Electroactive cardiac patch containing reduced graphene oxide with potential antibacterial properties, Mater. Sci. Eng. C 104 (2019) 109921.

[7] N. Rabiee, M. Bagherzadeh, M. Jouyandeh, P. Zarrintaj, M.R. Saeb, M. Mozafari, R.S. Varma, Natural polymers decorated MOF-MXene nanocarriers for co-delivery of doxorubicin/pCRISPR, ACS Appl. Bio Mater. 4 (6) (2021) 5106–5121.

[8] M. Saeedi, O. Vahidi, M.R. Moghbeli, S. Ahmadi, M. Asadnia, O. Akhavan, N. Rabiee, Customizing nano-chitosan for sustainable drug delivery, J. Contr. Release 350 (2022) 175–192.

[9] S. Ahmadi, Y. Fatahi, M.R. Saeb, D. Kim, M. Shokouhimehr, S. Iravani, R. S. Varma, Metal-organic frameworks (MOFs) and their applications in detection, conversion, and depletion of nitroaromatic pollutants, Inorg. Chem. Commun. (2023) 111982.

[10] M. Jouyandeh, M.R. Ganjali, F. Seidi, H. Xiao, M.R. Saeb, Nonisothermal cure kinetics of epoxy/polyvinylpyrrolidone functionalized superparamagnetic nano-Fe3O4 composites: effect of Zn and Mn doping, Journal of Composites Science 4 (2) (2020) 55.

[11] M. Jouyandeh, M.R. Ganjali, M. Mehrpooya, O. Abida, K. Jabbour, N. Rabiee, M. R. Saeb, Cure kinetics of samarium-doped Fe3O4/epoxy nanocomposites, Journal of Composites Science 6 (1) (2022) 29.

[12] M. Jouyandeh, M.R. Ganjali, M. Aghazadeh, S. Habibzadeh, K. Formela, M. R. Saeb, Bulk-surface modification of nanoparticles for developing highly-crosslinked polymer nanocomposites, Polymers 12 (8) (2020) 1820.

[13] A.E. Jahromi, H.R.E. Jahromi, F. Hemmati, M.R. Saeb, V. Goodarzi, K. Formela, Morphology and mechanical properties of polyamide/clay nanocomposites toughened with NBR/NBR-g-GMA: a comparative study, Compos. B Eng. 90 (2016) 478–484.

[14] S.M.R. Paran, G. Naderi, H. Mosallanezhad, E. Movahedifar, K. Formela, M. R. Saeb, Microstructure and mechanical properties of carboxylated nitrile butadiene rubber/epoxy/XNBR-grafted halloysite nanotubes nanocomposites, Polymers 12 (5) (2020) 1192.

[15] E. Movahedifar, H. Vahabi, M.R. Saeb, S. Thomas, Flame retardant epoxy composites on the road of innovation: an analysis with flame retardancy index for future development, Molecules 24 (21) (2019) 3964.

[16] G. Moradkhani, M. Fasihi, L. Brison, F. Laoutid, H. Vahabi, M.R. Saeb, Flame retardancy effect of phosphorus graphite nanoplatelets on ethylene-vinyl acetate copolymer: physical blending versus chemical modification, Polym. Adv. Technol. 32 (11) (2021) 4296–4305.

[17] A. Falanga, P. Laheurte, H. Vahabi, N. Tran, S. Khamseh, H. Saeidi, M. Mozafari, Niobium-treated titanium implants with improved cellular and molecular activities at the tissue–implant interface, Materials 12 (23) (2019) 3861.

[18] M. Karbassi, P. Zarrintaj, A. Ghafarinazari, M.R. Saeb, M.R. Mohammadi, A. Yazdanpanah, M.J.M.C. Mozafari, Microemulsion-based synthesis of a visible-light-responsive Si-doped TiO2 photocatalyst and its photodegradation efficiency potential, Mater. Chem. Phys. 220 (2018) 374–382.

[19] M. Sajjadnejad, S. Karkon, S.M.S. Haghshenas, Corrosion characteristics of Zn-TiO2 nanocomposite coatings fabricated by electro-codeposition process, Advanced Journal of Chemistry, Section A 7 (2) (2024) 209–226, https://doi.org/10.48309/ajca.2024.418391.1425.

[20] M. Ahmadlouydarab, S. Javadi, F. Adel Alijan Darab, Evaluation of thermal stability of TiO2 applied on the surface of a ceramic tile to eliminate methylene blue using silica-based doping materials, Advanced Journal of Chemistry, Section A 6 (4) (2023) 352–365, https://doi.org/10.22034/ajca.2023.405496.1379.

[21] F. Arjomandi Rad, J. Talat Mehrabad, M. Dizaji Esrafili, A communal experimental and DFT study on structural and photocatalytic properties of nitrogen-doped TiO2, Advanced Journal of Chemistry, Section A 6 (3) (2023) 244–252, https://doi.org/10.22034/ajca.2023.391772.1358.

[22] S. Janitabar Darzi, H. Bastami, Au decorated mesoporous TiO2 as a high performance photocatalyst towards crystal violet dye, Advanced Journal of Chemistry, Section A 5 (1) (2022) 22–30, https://doi.org/10.22034/ajca.2022.305643.1281.

[23] S. Mowlazadeh Haghighi, A. Purkhosrow, A. Khalafi-Nezhad, S. Oftadehgan, One pot synthesis of heterocyclic dihydroquinoline analogs incorporating quinoline and pyrimidine fused rings in condensation reaction using NCTDSS as a catalyst, Asian Journal of Green Chemistry 6 (3) (2022) 203–222, https://doi.org/10.22034/ajgc.2022.3.3.

[24] Z. Zaid Almarbd, N. Mutter Abbass, Recycling of plastic waste made of polystyrene and its transformation into nanocomposites by green methods, Chemical Methodologies 6 (12) (2022) 940–952, https://doi.org/10.22034/chemm.2022.359620.1603.

[25] M.B. Al Taee, B.M. Al Shabander, Study the effect of ZnO concentrations on the photocatalytic activity of TiO2/cement nanocomposites, Chemical Methodologies 6 (11) (2022) 831–841, https://doi.org/10.22034/chemm.2022.352379.1578.

[26] S.O. Malumi, T. Malumi, M.O. Osiele, A. Ekpekpo, I.L. Ikhioya, Enhance and performance evolution of silver-doped titanium dioxide dye-sensitized solar cells using different dyes, Journal of Engineering in Industrial Research (2023) 189–200, https://doi.org/10.48309/jeires.2023.4.1.

[27] S.S. Moayeripour, R. Behzadi, Experimental investigation of the effect of titanium nano-particles on the properties of hydrophobic self-cleaning film, Journal of Medicinal and Pharmaceutical Chemistry Research 5 (4) (2023) 303–316.

[28] Z. Almarbd, N. Mutter Abbass, 'Synthesis and characterization of TiO2, Ag2O, and graphene oxide nanoparticles with polystyrene as a nonocomposites and some of their applications', Journal of Medicinal and Pharmaceutical Chemistry Research 4 (10) (2022) 1033–1043.

[29] .

[30] M. Mohammed, K. Mahmood, Study of some physicochemical, microbial and sensory properties of low-fat butter produced by titanium dioxide (TiO2) nano particles, Journal of Medicinal and Pharmaceutical Chemistry Research 4 (3) (2022) 241–255.

[31] D. Ziental, B. Czarczynska-Goslinska, D.T. Mlynarczyk, A. Glowacka-Sobotta, B. Stanisz, T. Goslinski, L. Sobotta, Titanium dioxide nanoparticles: prospects and applications in medicine, Nanomaterials 10 (2) (2020) 387.

[32] A.K. Al-Messri, Z, Synthesis, characterization, and effectiveness of pyranopyrimidine derivatives as multi-function additive for lubricating oils, Chemical Methodologies 7 (8) (2023) 581–593, https://doi.org/10.22034/chemm.2023.393061.1669.

[33] E.I. Aduloju, N. Yahaya, N. Mohammad Zain, M. Anuar Kamaruddin, M. Ariffuddin Abd Hamid, Green, sustainable, and unified approaches towards organic and inorganic analytes extraction from complex environmental matrices, Advanced Journal of Chemistry, Section A 6 (3) (2023) 198–224, https://doi.org/10.22034/ajca.2023.393229.1361.

[34] A.I. Agbrara, E.O. Ojegu, M.O. Osiele, I. Ikhioya, Electrochemically synthesize SrSe/ZrSe heterostructure material for photovoltaic application, Advanced Journal of Chemistry, Section A 6 (4) (2023) 401–411, https://doi.org/10.48309/ajca.2023.407032.1385.

[35] M. Ahmadlouydarab, S. Javadi, F. Adel Alijan Darab, Evaluation of thermal stability of TiO2 applied on the surface of a ceramic tile to eliminate methylene blue using silica-based doping materials, Advanced Journal of Chemistry, Section A 6 (4) (2023) 352–365, https://doi.org/10.22034/ajca.2023.405496.1379.

[36] I. Alao, I. Oyekunle, K. Iwuozor, E. Emenike, Green synthesis of copper nanoparticles and investigation of its antimicrobial properties, Advanced Journal of Chemistry-Section B: Natural Products and Medical Chemistry 4 (1) (2022) 39–52, https://doi.org/10.22034/ajcb.2022.323779.1106.

[37] H. Albdairi, A. Aljeboree, U. Altimari, K. Alsaraf, S. Hasan, A. Alkaim, Peripherally modified poly (acrylic acid)/ZnO nanocomposite hydrogel with selective superadsorption properties, Journal of Medicinal and Pharmaceutical Chemistry Research 5 (11) (2023) 1057–1071, https://doi.org/10.48309/jmpcr.2023.181198.

[38] F. Ali, I. Ahmad, A. Hussain, S. Ahmad, M. Zaka Ansar, Y. Adezuka, I.L. Ikhioya, Improved morphological, structural, and optical features of ErxCuNiO3 {x= 0, 0.5, 0.7, 0.9, Journal of Applied Organometallic Chemistry 3 (4) (2023) 308–320, https://doi.org/10.48309/jaoc.2023.421597.1127.

[39] F. Arjomandi Rad, J. Talat Mehrabad, M. Dizaji Esrafili, A communal experimental and DFT study on structural and photocatalytic properties of nitrogen-doped TiO2, Advanced Journal of Chemistry, Section A 6 (3) (2023) 244–252, https://doi.org/10.22034/ajca.2023.391772.1358.

[40] M.N. Awan, H. Razzaq, O.U. Abid, S. Qaisar, Recent advances in electroanalysis of hydrazine by conducting polymers nanocomposites: a review, Journal of Chemical Reviews 5 (3) (2023) 311–340, https://doi.org/10.22034/jcr.2023.300453.1223.

[41] P. Badr, M. Sajjadnejad, S.M. Haghshenas, Influence of incorporating B4C nanoparticles and pulse electrodeposition parameters on the surface morphology and wear behavior of nickel based nanocomposite coatings, Progress in Chemical and Biochemical Research 6 (4) (2023) 292–313, https://doi.org/10.22034/pcbr.2023.394780.1261.

[42] F. Bashiri Godarzi, S. Shamaei, Evaluation of anti-bacterial (Escherichia coli and Staphylococcus aureus) and anticancer effects of silver nanoparticles synthesized by Melissa officinalis L. extract on several cancer cells (A549, MCF-7, and HeLa), International Journal of Advanced Biological and Biomedical Research 10 (1) (2022) 57–71, https://doi.org/10.22034/ijabbr.2022.548282.1380.

[43] A. Belhachem, N. Amara, H. Belmekki, Y. Yahia, Z. Cherifi, A. Amiar, A. Benguedach, R. Meghabar, H. Toumi, 'Synthesis, characterization and anti-inflammatory activity of an alginate–zinc oxide nanocomposite', Journal of Medicinal and Nanomaterials Chemistry 5 (3) (2023) 173–185, https://doi.org/10.48309/JMNC.2023.3.1.

[44] G. Chala, Review on green synthesis of iron-based nanoparticles for environmental applications, Journal of Chemical Reviews 5 (1) (2023) 1–14, https://doi.org/10.22034/jcr.2023.356745.1184.
[45] U.P. Dhuldhaj, A. Shaikh, J. Puri, Nano-biochar production and its characteristics: overview, International Journal of Advanced Biological and Biomedical Research 11 (4) (2023) 206–220, https://doi.org/10.48309/ijabbr.2023.2006480.1445.
[46] S. El Baakili, A. Semlali, K. El Mabrouk, M. Bricha, 'Synthesis method effect on acellular bioactivity of bioglasses: structural analysis and solid-state NMR', Journal of Applied Organometallic Chemistry 3 (4) (2023) 268–283, https://doi.org/10.48309/jaoc.2023.416016.1117.
[47] E. Ezzatzadeh, Chemoselective oxidation of sulfides to sulfoxides using a novel Zn-DABCO functionalized Fe3O4 MNPs as highly effective nanomagnetic catalyst, Journal of Medicinal and Nanomaterials Chemistry 5 (3) (2023) 213–224, https://doi.org/10.48309/JMNC.2023.3.4.
[48] E. Farahani, M. Haddadi, Effects of fluorescent quantum dots on COVID-19 Detection: A survey on present Findings, challenges, and future viewpoints, International Journal of Advanced Biological and Biomedical Research 10 (4) (2022) 288–298, https://doi.org/10.22034/ijabbr.2022.561871.1417.
[49] M. Farajpour, S.M. Vahdat, S.M. Baghbanian, M. Hatami, Ag-SiO2 nanoparticles: benign, expedient, and facile nano catalyst in synthesis of decahydroacridines, Chemical Methodologies 7 (7) (2023) 540–551, https://doi.org/10.22034/chemm.2023.386678.1653.
[50] H. Ghafuri, M. Zargari, A. Emami, 'Green and eco-friendly synthesis of 2-amino-3-cyano-4H-chromene derivatives via eggshell/Fe3O4 as a biodegradable polymer matrix nanocomposite', Asian Journal of Green Chemistry 7 (1) (2023) 54–69, https://doi.org/10.22034/ajgc.2023.1.7.
[51] S. Hadidi, M.H. Farzaei, Inhibitory activity of natural flavonoids against protein aggregation in alzheimer's disease: a computational simulation study, Advanced Journal of Chemistry, Section A 6 (2) (2023) 123–140, https://doi.org/10.22034/ajca.2023.379103.1350.
[52] F. Hakimi, E. Golrasan, Zinc sulfide (ZnS) nanoparticles: an effective catalyst for synthesis of benzoxazole derivatives, Asian Journal of Green Chemistry 7 (1) (2023) 47–53, https://doi.org/10.22034/ajgc.2023.1.6.
[53] F. Hakimi, A. Sharifi-Zarchi, E. Golrasan, Bifunctional polyethylene glycol/ethylenediamine nanomagnetic phase-transfer catalyst: preparation, characterization, and application in knoevenagel condensation, Chemical Methodologies 7 (6) (2023) 489–498, https://doi.org/10.22034/chemm.2023.392041.1667.
[54] F. Hakimi, M. Taghvaee, E. Golrasan, Synthesis of benzoxazole derivatives using Fe3O4@SiO2-SO3H nanoparticles as a useful and reusable heterogeneous catalyst without using a solvent, Advanced Journal of Chemistry, Section A 6 (2) (2023) 188–197, https://doi.org/10.22034/ajca.2023.393949.1364.
[55] M. Hakimi, H.A. Hosseini, B. Elhaminezhad, Fabrication of manganese dioxide nanoparticles in starch and gelatin beds: investigation of photocatalytic activity, Chemical Methodologies 8 (1) (2023) 37–46, https://doi.org/10.48309/chemm.2024.424921.1739.
[56] A. Heidaripour, A. Khazaei, Extraction of nano-hydroxyapatite (Nano-HAp) from sheep molar teeth for nanodentistry, Journal of Medicinal and Nanomaterials Chemistry 5 (4) (2023) 276–282, https://doi.org/10.48309/JMNC.2023.4.3.
[57] A. Heidaripour, F. Salmani, T. Barati, 'Synthesis of coral-like ZnO nanostructures with high and wide absorption range', Asian Journal of Green Chemistry 7 (2) (2023) 140–148, https://doi.org/10.22034/ajgc.2023.393698.1382.
[58] F. Ibrahim, M.A. Shahoodh, S. Guermazi, Studying the structural and optical properties of thin compound oxide films based on TiO2: NiO: in2O3 nanostructure, Chemical Methodologies 7 (11) (2023) 871–882, https://doi.org/10.48309/chemm.2023.409731.1693.
[59] S. Ibrar, N. Zafar Ali, E.O. Ojegu, O.B. Odia, I. L. Ikhioya, I. Ahmad, Assessing high-performance energy storage of the synthesized ZIF-8 and ZIF-67, Journal of Applied Organometallic Chemistry 3 (4) (2023) 294–307, https://doi.org/10.48309/jaoc.2023.421600.1128.
[60] N. Iqbal, S. Khan, F. Ahmad, PZT and SrCeO as catalysts, their synthesis and applications in alcohol fuel cell, Journal of Medicinal and Nanomaterials Chemistry 5 (3) (2023) 186–198, https://doi.org/10.48309/JMNC.2023.3.2.
[61] N.D. Rasen, E.A. Gomaa, S.E. Salem, M.N. Abd El-Hady, A.M. El-Defrawy, Voltammetric analysis of lead nitrate with various ligands in aqueous solutions at 302.15 K, Chemical Methodologies 7 (10) (2023) 761–775, https://doi.org/10.48309/chemm.2023.414306.1716.
[62] N.D. Resen, E.A. Gomaa, S.E. Salem, A.M. El-Defrawy, M.N. Abd El-Hady, Cyclic voltammetry for interaction between mercuric chloride and diamond fuchsin (rosaniline) in 0.05 M NaClO4 aqueous solutions at 303 K, Chemical Methodologies 7 (10) (2023) 736–747, https://doi.org/10.48309/chemm.2023.414312.1717.
[63] H. Samuel, U. Nweke-Maraizu, E.E. Etim, Supercritical fluids: properties, formation and applications, Journal of Engineering in Industrial Research 4 (3) (2023) 176–188, https://doi.org/10.48309/jeires.2023.3.5.
[64] S.O. Samuel, Z.J. Timothy, C.K. Ojoba, I.L. Ikhioya, Temperature's impact on the physical properties of rare earth element doped SrS for optoelectronic use, Journal of Engineering in Industrial Research 4 (3) (2023) 147–156, https://doi.org/10.48309/jeires.2023.3.2.
[65] M.A. Shahoodh, F. Ibrahim, S. Guermazi, Investigations on TiO2-NiO@In2O3 nanocomposite thin films (NCTFs) for gas sensing: synthesis, physical characterization, and detection of NO2 and H2S gas sensors, Chemical Methodologies 7 (12) (2023) 994–1010, https://doi.org/10.48309/chemm.2023.428217.1741.
[66] P. Shams, H. Panahi, M. Tahan, F. Jahansooz, A. Heidaripour, Fabrication of curcumin (CCM) delivery system based on ZIF-8 nanoparticles (ZIF-8@CCM) with anticancer application, Journal of Medicinal and Nanomaterials Chemistry 5 (4) (2023) 267–275, https://doi.org/10.48309/JMNC.2023.4.2.
[67] S. Sharma, A short review of past, present, and future of metallocene and its derivatives as an effective therapeutic agent, Journal of Applied Organometallic Chemistry 3 (2) (2023) 142–155, https://doi.org/10.22034/jaoc.2023.398871.1083.
[68] A.M. Sikkander, F. Bassyouni, K. Yasmeen, S. Mishra, V. Lakshmi, Synthesis of zinc oxide and lead nitrate nanoparticles and their applications: comparative studies of bacterial and fungal (E. coli, A. Niger), Journal of Applied Organometallic Chemistry 3 (4) (2023) 255–267, https://doi.org/10.48309/jaoc.2023.415886.1115.
[69] M.B. Swami, G.R. Nagargoje, S.R. Mathapati, A.S. Bondge, A.H. Jadhav, S. P. Panchgalle, V. More, A magnetically recoverable and highly effectual Fe3O4 encapsulated MWCNTs nano-composite for synthesis of 1,8-Dioxo-octahydroxanthene derivatives, Journal of Applied Organometallic Chemistry 3 (3) (2023) 184–198, https://doi.org/10.22034/jaoc.2023.404091.1085.
[70] A. Taheri, Z. Rezayati-Zad, Characterization of tribological and electrochemical corrosion behavior of GO coatings formed on 6061 Al alloy processed by plasma electrolytic oxidation, Progress in Chemical and Biochemical Research 6 (4) (2023) 261–276, https://doi.org/10.48309/pcbr.2023.413235.1282.
[71] R. Ullah, Semiconductor ZnFe2O4 as efficient photocatalyst for the degradation of organic dyes: an update, Journal of Chemical Reviews 5 (4) (2023) 466–476, https://doi.org/10.48309/jcr.2023.407658.1232.
[72] R. Zainul, M.F. Alif, A. Mulyasuryani, Advancements in plasma-enhanced chemical vapor deposition of a multi-walled carbon nanotubes on Si/SiO2 substrates: a comprehensive review, Journal of Medicinal and Pharmaceutical Chemistry Research 5 (11) (2023) 1013–1033, https://doi.org/10.48309/jmpcr.2023.417750.1007.
[73] S. Zilabi, M. Shareei, A. Bozorgian, A. Ahmadpour, E. Esmaeil, A review on nanoparticle application as an additive in lubricants, Advanced Journal of Chemistry-Section B: Natural Products and Medical Chemistry 4 (3) (2022) 209–221, https://doi.org/10.22034/ajcb.2022.353097.1125.
[74] M.A. Mahdi, M.A. Farhan, Z.H. Mahmoud, A.M. Rheima, Z. sabri Abbas, M. M. Kadhim, A.H. Ismail, Direct sunlight photodegradation of Congo red in aqueous solution by TiO2/rGO binary system: experimental and DFT study, Arab. J. Chem. 16 (8) (2023) 104992.
[75] H. Pallathadka, H.K. Mohammed, Z.H. Mahmoud, A.A. Ramírez-Coronel, F. M. Altalbawy, M.A. Gatea, M. Kazemnejadi, Ultrasound-promoted metal-free homogenous olefins epoxidation and direct conversion of alkenes to cyclic carbonates using catalytic TAIm [X](X= WO42-, HSO5-) recyclable ionic liquid under mild conditions, Inorg. Chem. Commun. (2023) 110944.
[76] Z.H. Mahmoud, M.M. Kadhim, A.M. Rheima, Z. sabri Abbas, Z.T. Abed, F. mohamed dashoor Al-Jaafari, F.K. Ali, Functionalize and supercapacitor performance of magnetic oxide nanoparticles, Inorg. Chem. Commun. (2023) 110884.
[77] Z.H. Mahmoud, A. Hamrouni, A.B. Kareem, M.A. Mostafa, A.H. Majeed, Synthesis and characterization of chitosan sheet modified by varied weight ratio of anatase (TiO2) nano mixture with Cr (VI) adsorbing, Kuwait Journal of Science (2023).
[78] W.A. Siswanto, R.M. Romero-Parra, R. Sivaraman, A. Turki Jalil, M.A. Gatea, M. S. Alhassan, Z.H. Mahmoud, The characterization of plastic behavior and mechanical properties in the gradient nanostructured copper, Proc. Inst. Mech. Eng., Part L (2023) 14644207231161752.
[79] Z.H. Mahmoud, J.M. Mahmood, N.S. Al-Obaidi, A.M. Rahima, Gama-Fe2O3 silica-coated 2-(2-benzothiazolyl azo)-4-methoxyaniline for supercapacitive performance: original scientific paper, J. Electrochem. Sci. Eng. (2023).
[80] Z.H. Mahmoud, A.B. Mahdi, Y.S. Alnassar, H.N.K. Al-Salman, Formulation and sustained-release of verapamil hydrochloride tablets, Chemist 76 (2023).
[81] Z.H. Mahmoud, O.G. Hammoudi, A.N. Abd, Y.M. Ahmed, U.S. Altimari, A. H. Dawood, R. Shaker, Functionalize cobalt ferrite and ferric oxide by nitrogen organic compound with high supercapacitor performance, Results in Chemistry 5 (2023) 100936.
[82] S.A. Jasim, S.A.J. Ali, O.Q. Fadhil, M.K. Rakhmatova, H.H. Kzar, R. Margiana, M. Q. Sultan, Investigating the effects of hydro-alcoholic urtica dioica extract and retinoic acid on follicular development: an animal study, Med. J. Islam. Repub. Iran 37 (2023).
[83] N.S. Al-Obaidi, Z.E. Sadeq, Z.H. Mahmoud, A.N. Abd, A.S. Al-Mahdawi, F.K. Ali, Synthesis of chitosan-TiO2 nanocomposite for efficient Cr (VI) removal from contaminated wastewater sorption kinetics, thermodynamics and mechanism, J. Oleo Sci. 72 (3) (2023) 337–346.
[84] S.A. Jasim, A.H. Jabbar, D.O. Bokov, Z.I. Al Mashhadani, A. Surendar, T.Z. Taban, Y.F. Mustafa, The effects of oxide layer on the joining performance of CuZr metallic glasses, Trans. Indian Inst. Met. 76 (1) (2023) 239–247.
[85] S.A. Jasim, M.H. Ali, Z.H. Mahmood, M. Rudiansyah, F.H. Alsultany, Y. F. Mustafa, A. Surendar, Role of alloying composition on mechanical properties of CuZr metallic glasses during the nanoindentation process, Met. Mater. Int. 28 (9) (2022) 2075–2082.
[86] D.O. Bokov, Y.F. Mustafa, Z.H. Mahmoud, W. Suksatan, M.A. Jawad, T. Xu, Cr-SiNT, Mn-SiNT, Ti-C70 and Sc-cnt as effective catalysts for CO2 reduction to CH3OH, Silicon 14 (14) (2022) 8493–8503.
[87] S.A. Jasim, W.K. Abdelbasset, K. Hachem, M.M. Kadhim, G. Yasin, M.A. Obaid, Z. H. Mahmoud, Novel Gd2O3/SrFe12O19@ Schiff base chitosan (Gd/SrFe@ SBCs) nanocomposite as a novel magnetic sorbent for the removal of Pb (II) and Cd (II) ions from aqueous solution, J. Chin. Chem. Soc. 69 (7) (2022) 1079–1087.
[88] A.A. Mansoor Al Sarraf, H. Alsultany, F.H. Mahmoud, Z.S. Shafik, S.I. Al, Z, A. Sajjadi, Magnetic nanoparticles supported zinc (II) complex (Fe3O4@ SiO2-Imine/Thio-Zn (OAc) 2): a green and efficient magnetically reusable zinc

nanocatalyst for synthesis of nitriles via cyanation of aryl iodides, Synth. Commun. 52 (9–10) (2022) 1245–1253.
[89] Z. Hameed Mahmood, Y. Riadi, H.A. Hammoodi, A.F. Alkaim, Y. Fakri Mustafa, Magnetic nanoparticles supported copper nanocomposite: a highly active nanocatalyst for synthesis of benzothiazoles and polyhydroquinolines, Polycycl. Aromat. Comp. (2022) 1–19.
[90] Z.H. Mahmoud, R.A. Al-Bayati, A.A. Khadom, The efficacy of samarium loaded titanium dioxide (Sm: TiO2) for enhanced photocatalytic removal of rhodamine B dye in natural sunlight exposure, J. Mol. Struct. 1253 (2022) 132267.
[91] I. Raya, A.A. Mansoor Al Sarraf, G. Widjaja, S. Ghazi Al-Shawi, M. F Ramadan, Z. H. Mahmood, H. Ghaleb Maabreh, ZnMoO4 nanoparticles: novel and facile synthesis, characterization, and photocatalytic performance, Journal of Nanostructures 12 (2) (2022) 446–454.
[92] Z.H. Mahmood, M. Jarosova, H.H. Kzar, P. Machek, M. Zaidi, A. Dehno Khalaji, M.M. Kadhim, Synthesis and characterization of Co3O4 nanoparticles: application as performing anode in Li-ion batteries, J. Chin. Chem. Soc. 69 (4) (2022) 657–662.
[93] A. Bahadoran, M.K. Jabarabadi, Z.H. Mahmood, D. Bokov, B.J. Janani, A. Fakhri, Quick and sensitive colorimetric detection of amino acid with functionalized-silver/copper nanoparticles in the presence of cross linker, and bacteria detection by using DNA-template nanoparticles as peroxidase activity, Spectrochim. Acta Mol. Biomol. Spectrosc. 268 (2022) 120636.
[94] Z.H. Mahmoud, R.A. Al-Bayati, A.A. Khadom, Electron transport in dye-sanitized solar cell with tin-doped titanium dioxide as photoanode materials, J. Mater. Sci. Mater. Electron. 33 (8) (2022) 5009–5023.
[95] I. Raya, G. Widjaja, Z.H. Mahmood, A.J. Kadhim, K.O. Vladimirovich, Y. F. Mustafa, L. Kafi-Ahmadi, Kinetic, isotherm, and thermodynamic studies on Cr (VI) adsorption using cellulose acetate/graphene oxide composite nanofibers, Appl. Phys. A 128 (2) (2022) 167.
[96] Z.H. Mahmoud, R.A. Al-Bayati, A.A. Khadom, In situ polymerization of polyaniline/samarium oxide-anatase titanium dioxide (PANI/Sm2O3-TiO2) nanocomposite: structure, thermal and dielectric constant supercapacitor application study, J. Oleo Sci. 71 (2) (2022) 311–319.
[97] A.M. Rheima, H.N.K. Al-Salman, Supercapacitor performance of Fe3O4 and Fe3O4@ SiO2-bis (aminopyridine)-Cu hybrid nanocomposite, Int. J. Electrochem. Sci. 17 (221057) (2022) 2.
[98] Z.H. Mahmoud, R.A. Al-Bayati, A.A. Khadom, Synthesis and supercapacitor performance of polyaniline-titanium dioxide-samarium oxide (PANI/TiO 2-Sm 2 O 3) nanocomposite, Chem. Pap. (2022) 1–12.
[99] S. Chupradit, I. Raya, D.T. Ngoc Huy, D. Bokov, P. Van Tuan, A. Surendar, S. Sajjadifar, Role of glass composition on mechanical properties of shape memory alloy-metallic glass composites, Adv. Mater. Sci. Eng. 2021 (2021) 1–9.
[100] Z.H. Mahmoud, R.A. Al-Bayati, A.A. Khadom, Enhanced photovoltaic performance of dye-sanitized solar cell with tin doped titanium dioxide as photoanode materials, Chalcogenide Lett. 18 (12) (2021).
[101] L. Jayanthi Juturi, R. Palavalasa, S. H. Dhoria, S. Jampani, V. Miditana, G. Jalem, Efficient removal of fluoride using sol-gel processed nano magnesium oxide, Chemical Methodologies 7 (7) (2023) 569–580, https://doi.org/10.22034/chemm.2023.393347.1671.
[102] A. Jimoh, S. Uba, V. Ajibola, E. Agbaji, Effect of nanoparticles on the degradation, ageing and other properties of ester-based nanofluids, Advanced Journal of Chemistry, Section A 6 (2) (2023) 105–122, https://doi.org/10.22034/ajca.2023.367575.1341.
[103] A. Johnson, Investigating the effects of environmental applications on decomposition of zein nanoparticles in adsorbents in industry, Journal of Engineering in Industrial Research 4 (2) (2023) 92–108, https://doi.org/10.48309/JEIRES.2023.2.4.
[104] P.A. Kalvanagh, Y.A. Kalvanagh, A new therapeutic approach based on silymarin in the treatment of breast cancer, Advanced Journal of Chemistry-Section B: Natural Products and Medical Chemistry 5 (1) (2023) 75–85, https://doi.org/10.22034/ajcb.2023.379394.1143.
[105] P.A. Kalvanagh, Y.A. Kalvanagh, Investigating the expression levels of glutathione peroxidase and glutathione reductase genes in mastectomies women, International Journal of Advanced Biological and Biomedical Research 11 (3) (2023) 115–126, https://doi.org/10.22034/ijabbr.2023.1999566.1433.
[106] F. Karampour, Green synthesis and characterization of ZnO nanoparticles from echinophora platyloba DC. Extract and HSA interaction study, Asian Journal of Green Chemistry 7 (3) (2023) 149–162, https://doi.org/10.22034/ajgc.2023.394268.1384.
[107] M. Khalil, S. Noor, Z. Ahmad, F. Ahmad, 'Fate of Pakistani exported mango due to its toxicity (heavy metals, pesticides, and other toxic organic components)', Journal of Applied Organometallic Chemistry 3 (2) (2023) 86–107, https://doi.org/10.22034/jaoc.2023.392989.1077.
[108] M. Khanahmadi, F. Shahrezaei, M. Sharifi, G. Rezanejade Bardajee, Ultrasound-assisted preparation and optimization of natural flavoring nanoemulsion for dairy products based on pistacia khinjuk in lab scale, Chemical Methodologies 7 (7) (2023) 524–539, https://doi.org/10.22034/chemm.2023.382181.1649.
[109] R. Khazaei, A. Khazaei, M. Nasrollahzadeh, 'Horsetail assisted green synthesis of Fe3O4@SiO2-Pd: a reusable and highly efficient magnetically separable catalyst for suzuki coupling reactions', Journal of Applied Organometallic Chemistry 3 (2) (2023) 123–133, https://doi.org/10.22034/jaoc.2023.397315.1079.
[110] J. López-Dino, J. Hernández-Paz, I. Olivas-Armendáriz, C. Rodríguez González, Structural design of biosensor: a review, Journal of Medicinal and Pharmaceutical Chemistry Research 5 (10) (2023) 915–934, https://doi.org/10.48309/jmpcr.2023.177586.
[111] R.M. Mhaibes, Z. Arzehgar, M. Mirzaei Heydari, L. Fatolahi, 'ZnO nanoparticles: a highly efficient and recyclable catalyst for tandem knoevenagel-michael-cyclocondensation reaction', Asian Journal of Green Chemistry 7 (1) (2023) 1–8, https://doi.org/10.22034/ajgc.2023.1.1.
[112] S. Noor, A. Al-Shamari, High photocatalytic performance of ZnO and ZnO/CdS nanostructures against reactive blue 4 dye, Journal of Medicinal and Pharmaceutical Chemistry Research 5 (9) (2023) 776–793.
[113] S. Noor, A. Al-Shamari, High photocatalytic performance of ZnO and ZnO/CdS nanostructures against reactive blue 4 dye, Journal of Medicinal and Pharmaceutical Chemistry Research 5 (9) (2023) 776–793.
[114] N. Patil, D. Shinde, P. Patil, Green synthesis of gold nanoparticles using extract of ginger, neem, apta, umber plants and their characterization using XRD, UV-vis spectrophotometer, Journal of Applied Organometallic Chemistry 3 (1) (2023) 1–12, https://doi.org/10.22034/jaoc.2023.355403.1059.
[115] N. Pourbahar, S. Sattari Alamdar, 'Phytofabrication, and characterization of Ag/Fe3O4 nanocomposite from rosa canina plant extracts using a green method', Asian Journal of Green Chemistry 7 (1) (2023) 9–16, https://doi.org/10.22034/ajgc.2023.1.2.
[116] B. Pant, M. Park, S.J. Park, Recent advances in TiO2 films prepared by sol-gel methods for photocatalytic degradation of organic pollutants and antibacterial activities, Coatings 9 (10) (2019) 613.
[117] M. Xu, Y. Wang, J. Geng, D. Jing, Photodecomposition of NOx on Ag/TiO2 composite catalysts in a gas phase reactor, Chem. Eng. J. 307 (2017) 181–188.
[118] A. Trapalis, N. Todorova, T. Giannakopoulou, N. Boukos, T. Speliotis, D. Dimotikali, J. Yu, TiO2/graphene composite photocatalysts for NOx removal: a comparison of surfactant-stabilized graphene and reduced graphene oxide, Appl. Catal. B Environ. 180 (2016) 637–647.
[119] I. Papailias, N. Todorova, T. Giannakopoulou, J. Yu, D. Dimotikali, C. Trapalis, Photocatalytic activity of modified g-C3N4/TiO2 nanocomposites for NOx removal, Catal. Today 280 (2017) 37–44.
[120] K. Chaisiwamongkhol, N. Manoyen, K. Suttiponparnit, D. Nacapricha, S.M. Smith, K. Uraisin, Development of gas flow reactor with on-line monitoring system for nitrogen dioxide removal, Microchem. J. 135 (2017) 199–206.
[121] N. Seifvand, E. Kowsari, Novel TiO 2/graphene oxide functionalized with a cobalt complex for significant degradation of NO x and CO, RSC Adv. 5 (114) (2015) 93706–93716.
[122] J. Ma, C. Wang, H. He, Enhanced photocatalytic oxidation of NO over g-C3N4-TiO2 under UV and visible light, Appl. Catal. B Environ. 184 (2016) 28–34.
[123] N. Seifvand, E. Kowsari, Synthesis of mesoporous Pd-doped TiO2 templated by a magnetic recyclable ionic liquid for efficient photocatalytic air treatment, Ind. Eng. Chem. Res. 55 (40) (2016) 10533–10543.
[124] Y. Han, J. Zhang, Y. Zhao, Visible-light-induced photocatalytic oxidation of nitric oxide and sulfur dioxide: discrete kinetics and mechanism, Energy 103 (2016) 725–734.
[125] Y. Yuan, J. Zhang, H. Li, Y. Li, Y. Zhao, C. Zheng, Simultaneous removal of SO2, NO and mercury using TiO2-aluminum silicate fiber by photocatalysis, Chem. Eng. J. 192 (2012) 21–28.
[126] Y. Yuan, J. Zhang, H. Li, Y. Li, Y. Zhao, C. Zheng, Simultaneous removal of SO2, NO and mercury using TiO2-aluminum silicate fiber by photocatalysis, Chem. Eng. J. 192 (2012) 21–28.
[127] B. Tan, X. Zhang, Y. Li, H. Chen, X. Ye, Y. Wang, J. Ye, Anatase TiO2 mesocrystals: green synthesis, in situ conversion to porous single crystals, and self-doping Ti3+ for enhanced visible light driven photocatalytic removal of NO, Chem.–Eur. J. 23 (23) (2017) 5478–5487.
[128] S. Song, Z. Sheng, Y. Liu, H. Wang, Z. Wu, Influences of pH value in deposition-precipitation synthesis process on Pt-doped TiO2 catalysts for photocatalytic oxidation of NO, J. Environ. Sci. 24 (8) (2012) 1519–1524.
[129] M. Janus, K. Bubacz, J. Zatorska, E. Kusiak-Nejman, A. Czyżewski, A. W. Morawski, NOx photocatalytic degradation on gypsum plates modified by TiO-N, C photocatalysts, Pol. J. Chem. Technol. 17 (3) (2015) 8–12.
[130] M. Reli, P. Huo, M. Sihor, N. Ambrozova, I. Troppová, L. Matejova, K. Koci, Novel TiO2/C3N4 photocatalysts for photocatalytic reduction of CO2 and for photocatalytic decomposition of N2O, J. Phys. Chem. 120 (43) (2016) 8564–8573.
[131] K. Kočí, M. Reli, I. Troppová, M. Šihor, J. Kupková, P. Kustrowski, P. Praus, Photocatalytic decomposition of N2O over TiO2/g-C3N4 photocatalysts heterojunction, Appl. Surf. Sci. 396 (2017) 1685–1695.
[132] Y. Zhao, J. Han, Y. Shao, Y. Feng, Simultaneous SO2 and NO removal from flue gas based on TiO2 photocatalytic oxidation, Environ. Technol. 30 (14) (2009) 1555–1563.
[133] S. Yamazoe, Y. Hitomi, T. Shishido, T. Tanaka, Kinetic study of photo-oxidation of NH3 over TiO2, Appl. Catal. B Environ. 82 (1–2) (2008) 67–76.
[134] P.A. Kolinko, D.V. Kozlov, Products distribution during the gas phase photocatalytic oxidation of ammonia over the various titania based photocatalysts, Appl. Catal. B Environ. 90 (1–2) (2009) 126–131.
[135] S. Rivankar, An overview of doxorubicin formulations in cancer therapy, J. Cancer Res. Therapeut. 10 (4) (2014) 853–858.
[136] Q. Wang, J.Y. Huang, H.Q. Li, Z. Chen, A.Z.J. Zhao, Y. Wang, Y.K. Lai, TiO2 nanotube platforms for smart drug delivery: a review, Int. J. Nanomed. (2016) 4819–4834.
[137] G. Raja, S. Cao, D.H. Kim, T.J. Kim, Mechanoregulation of titanium dioxide nanoparticles in cancer therapy, Mater. Sci. Eng. C 107 (2020) 110303.
[138] D. Flak, L. Yate, G. Nowaczyk, S. Jurga, Hybrid ZnPc@ TiO2 nanostructures for targeted photodynamic therapy, bioimaging and doxorubicin delivery, Mater. Sci. Eng. C 78 (2017) 1072–1085.

[139] Y. Chen, H. Lin, R. Tong, N. An, F. Qu, Near-infrared light-mediated DOX-UCNPs@ mHTiO2 nanocomposite for chemo/photodynamic therapy and imaging, Colloids and surfaces B: biointerfaces 154 (2017) 429–437.
[140] Y. Wang, Q. Wang, C. Zhang, Synthesis of diamond-shaped mesoporous titania nanobricks as pH-responsive drug delivery vehicles for cancer therapy, ChemistrySelect 4 (28) (2019) 8225–8228.
[141] Q. Li, X. Wang, X. Lu, H. Tian, H. Jiang, G. Lv, B. Chen, The incorporation of daunorubicin in cancer cells through the use of titanium dioxide whiskers, Biomaterials 30 (27) (2009) 4708–4715.
[142] J. Xu, X. Zhou, Z. Gao, Y.Y. Song, P. Schmuki, Visible-light-triggered drug release from TiO2 nanotube arrays: a controllable antibacterial platform, Angew. Chem. Int. Ed. 55 (2) (2016) 593–597.
[143] C. Kurzmann, J. Verheyen, M. Coto, R.V. Kumar, G. Divitini, H.A. Shokoohi-Tabrizi, H. Agis, In vitro evaluation of experimental light activated gels for tooth bleaching, Photochem. Photobiol. Sci. 18 (2019) 1009–1019.
[144] S.C. Onwubu, P.S. Mdluli, S. Singh, T. Tlapana, A novel application of nano eggshell/titanium dioxide composite on occluding dentine tubules: an in vitro study, Braz. Oral Res. 33 (2019).
[145] A.I. Shaikhaliyev, A.A. Polisan, S.Y. Ivanov, Y.N. Parkhomenko, M. D. Malinkovich, K.N. Yarygin, L.D. Arazashvili, Effect of the surface of medical titanium endoprostheses on the efficiency of fibrointegration, Journal of Surface Investigation: X-ray, Synchrotron and Neutron Techniques 13 (2019) 644–651.
[146] M. Zulfiqar, M.F.R. Samsudin, S. Sufian, Modelling and optimization of photocatalytic degradation of phenol via TiO2 nanoparticles: an insight into response surface methodology and artificial neural network, J. Photochem. Photobiol. Chem. 384 (2019) 112039.
[147] Z. Ran, L. Wang, Y. Fang, C. Ma, S. Li, Photocatalytic degradation of atenolol by TiO2 irradiated with an ultraviolet light emitting diode: performance, kinetics, and mechanism insights, Catalysts 9 (11) (2019) 876.
[148] A. Mohammadkhani, F. Mohammadkhani, N. Farhadyar, M.S. Sadjadi, Novel nanocomposite zinc phosphate/polyvinyl alcohol/carboxymethyl cellulose: synthesis, characterization and investigation of antibacterial and anticorrosive properties, Case Studies in Chemical and Environmental Engineering (2023) 100591.
[149] L.A. Younus, Z.H. Mahmoud, A.A. Hamza, K.M.A. Alaziz, M.L. Ali, Y. Yasin, E. Kianfar, Photodynamic therapy in cancer treatment: properties and applications in nanoparticles, Braz. J. Biol. 84 (2023) e268892.
[150] U. Abdul-Reda Hussein, Z.H. Mahmoud, K.M. Abd Alaziz, M.L. Alid, Y. Yasin, F. K. Ali, E. Kianfar, Antimicrobial finishing of textiles using nanomaterials, Braz. J. Biol. 84 (2023) e264947.
[151] E. Kianfar, Comparative studies of nanosheet-based supercapacitors: a review of advances in electrodes materials, Case Studies in Chemical and Environmental Engineering (2023) 100584.
[152] G.R.L. Al-Awsi, A.A. Alameri, A.M.B. Al-Dhalimy, G.A. Gabr, E. Kianfar, Application of nano-antibiotics in the diagnosis and treatment of infectious diseases, Braz. J. Biol. 84 (2023).
[153] H.N.K. Al-Salman, C.Y. Hsu, Z.N. Jawad, Z.H. Mahmoud, F. Mohammed, A. Saud, E. Kianfar, Graphene oxide-based biosensors for detection of lung cancer: a review, Results in Chemistry (2023) 101300.
[154] A.M. Rheima, Z. sabri Abbas, M.M. Kadhim, S.H. Mohammed, D.Y. Alhameedi, F. A. Rasen, E. Kianfar, Aluminum oxide nano porous: synthesis, properties, and applications, Case Studies in Chemical and Environmental Engineering 8 (2023) 100428.
[155] H.N.K. Al-Salman, M. sabbar Falih, H.B. Deab, U.S. Altimari, H.G. Shakier, A. H. Dawood, E. Kianfar, A study in analytical chemistry of adsorption of heavy metal ions using chitosan/graphene nanocomposites, Case Studies in Chemical and Environmental Engineering 8 (2023) 100426.
[156] M. Fattahi, C.Y. Hsu, A.O. Ali, Z.H. Mahmoud, N.P. Dang, E. Kianfar, Severe plastic deformation: nanostructured materials, metal-based and polymer-based nanocomposites: a review, Heliyon (2023).
[157] E. Kianfar, A review of recent advances in carbon dioxide absorption–stripping by employing a gas–liquid hollow fiber polymeric membrane contactor, Polym. Bull. 80 (11) (2023) 11469–11505.
[158] C.Y. Hsu, Z.H. Mahmoud, S. Abdullaev, B.A. Mohammed, U.S. Altimari, M. L. Shaghnab, G.F. Smaisim, Nanocomposites based on Resole/graphene/carbon fibers: a review study, Case Studies in Chemical and Environmental Engineering (2023) 100535.
[159] E. Darabi, H. Nazarpour-Fard, E. Kianfar, Fast NO2 gas pollutant removal using CNTs/TiO2/CuO/zeolite nanocomposites at the room temperature, Case Studies in Chemical and Environmental Engineering 8 (2023) 100527.
[160] C.Y. Hsu, A.M. Rheima, Z. sabri Abbas, M.U. Faryad, M.M. Kadhim, U.S. Altimari, E. Kianfar, Nanowires properties and applications: a review study, South African Journal of Chemical Engineering (2023).
[161] C.Y. Hsu, A.M. Rheima, M.M. Kadhim, N.N. Ahmed, S.H. Mohammed, F.H. Abbas, E. Kianfar, An overview of nanoparticles in drug delivery: properties and applications, South African Journal of Chemical Engineering (2023).
[162] C.Y. Hsu, A.M. Rheima, M.S. Mohammed, M.M. Kadhim, S.H. Mohammed, F. H. Abbas, E. kianfar, Application of carbon nanotubes and graphene-based nanoadsorbents in water treatment, BioNanoScience (2023) 1–19.
[163] R. Alabada, M.M. Kadhim, Z. sabri Abbas, A.M. Rheima, U.S. Altimari, A. H. Dawood, E. Kianfar, Investigation of effective parameters in the production of alumina gel through the sol-gel method, Case Studies in Chemical and Environmental Engineering (2023) 100405.
[164] G.F. Smaisim, K.J. Mohammed, S.K. Hadrawi, H. Koten, E. Kianfar, Properties and application of nanostructure in liquid crystals, BioNanoScience 13 (2) (2023) 819–839.
[165] K.J. Mohammed, S.K. Hadrawi, E. Kianfar, Synthesis and modification of nanoparticles with ionic liquids: a review, BioNanoScience 13 (2) (2023) 760–783.
[166] Z. sabri Abbas, M.M. Kadhim, A. Mahdi Rheima, A.D. jawad al-bayati, Z. Talib Abed, F.M. dashoor Al-Jaafari, E. Kianfar, Preparing hybrid nanocomposites on the basis of resole/graphene/carbon fibers for investigating mechanical and thermal properties, BioNanoScience (2023) 1–29.
[167] Z.H. Mahmoud, H.A. Salman, H.H. Hussein, A.H. Adhab, K. Al-Majdi, T. Rasheed, E. Kianfar, Organic chemical Nano sensors: synthesis, properties, and applications, Braz. J. Biol. 84 (2023) e268893.
[168] A.K. Alkhawaldeh, A.M. Rheima, M.M. Kadhim, Z. sabri Abbas, Z.T. Abed, F. mohamed dashoor Al-Jaafari, Z.H. Mahmoud, Nanomaterials as transmitters of non-viral gene vectors: a review, Case Studies in Chemical and Environmental Engineering (2023) 100372.
[169] G.F. Smaisim, A.M. Abed, H. Al-Madhhachi, S.K. Hadrawi, H.M.M. Al-Khateeb, E. Kianfar, Graphene-based important carbon structures and nanomaterials for energy storage applications as chemical capacitors and supercapacitor electrodes: a review, BioNanoScience 13 (1) (2023) 219–248.
[170] I.M.R. Fattah, Z.A. Farhan, K.J. Kontoleon, E. Kianfar, S.K. Hadrawi, Hollow Fiber Membrane Contactor Based Carbon Dioxide Absorption− Stripping: a Review, Macromolecular Research, 2023, pp. 1–27.
[171] N. sabah Ahmed, C.Y. Hsu, Z.H. Mahmoud, H. Sayadi, A graphene oxide/polyaniline nanocomposite biosensor: synthesis, characterization, and electrochemical detection of bilirubin, RSC Adv. 13 (51) (2023) 36280–36292.
[172] M.M. Kadhim, A.M. Rheima, Z.S. Abbas, H.H. Jlood, S.K. Hachim, W.R. Kadhum, Evaluation of a biosensor-based graphene oxide-DNA nanohybrid for lung cancer, RSC Adv. 13 (4) (2023) 2487–2500.
[173] S.A. Jasim, H.H. Kzar, R. Sivaraman, M.J. Jweeg, M. Zaidi, O.K.A. Alkadir, E. Kianfar, Engineered nanomaterials, plants, plant toxicity and biotransformation: a review, Egypt. J. Chem. 65 (12) (2022) 151–164.
[174] B. Abed Hussein, A.B. Mahdi, S. Emad Izzat, N.K. Acwin Dwijendra, R.M. Romero Parra, L.A. Barboza Arenas, E. Kianfar, Production, structural properties nano biochar and effects nano biochar in soil: a review, Egypt. J. Chem. 65 (12) (2022) 607–618.
[175] S.A. Jasim, M.M. Kadhim, V. Kn, I. Raya, S.J. Shoja, W. Suksatan, E. Kianfar, Molecular junctions: introduction and physical foundations, nanoelectrical conductivity and electronic structure and charge transfer in organic molecular junctions, Braz. J. Phys. 52 (2) (2022) 31.
[176] S. Chupradit, M. Kavitha, W. Suksatan, M.J. Ansari, Z.I. Al Mashhadani, M. M. Kadhim, E. Kianfar, Morphological control: properties and applications of metal nanostructures, Adv. Mater. Sci. Eng. 2022 (2022) 1–15.
[177] D. Bokov, A. Turki Jalil, S. Chupradit, W. Suksatan, M. Javed Ansari, I. H. Shewael, E. Kianfar, Nanomaterial by sol-gel method: synthesis and application, Adv. Mater. Sci. Eng. 2021 (2021) 1–21.
[178] B. Li, X. Wang, M. Yan, L. Li, Preparation and characterization of nano-TiO2 powder, Mater. Chem. Phys. 78 (2002) 184–188, https://doi.org/10.1016/S0254-0584(02)00226-2.
[179] Min-A. Kim, Gon Seo Young, Sang-Soo Lee, Wonmok Lee, Hyunjung Lee, Co-sedimentation of TiO2 nanoparticles and polymer beads to fabricate macroporous TiO2 photoelectrodes, J. Nanosci. Nanotechnol. 12 (4) (2012) 3247–3251, https://doi.org/10.1166/jnn.2012.5600.
[180] H. Yin, Y. Wada, T. Kitamura, T. Sumida, Y. Hasegawa, S. Yanagida, Novel synthesis of phase-pure nano-particulate anatase and rutile TiO2 using TiCl4 aqueous solutions, Mater. Chem. 12 (2002) 378–383, https://doi.org/10.1039/B105637A.
[181] Sh Li, Y. Li, H. Wang, W. Fan, Q. Zhang, Peptization-hydrothermal method as a surfactant-free process toward nanorod-like anatase TiO2 nanocrystals, Eur. J. Inorg. Chem. 2009 (2009) 4078–4084, https://doi.org/10.1002/ejic.200900371.
[182] R.D. Sanjay, D. Ch Vandana, S. Violet, V. Ravi, Synthesis of nanocrystalline TiO2 at 100 oC, Mater. Lett. 58 (2004) 2310–2313, https://doi.org/10.1016/j.matlet.2004.02.021.
[183] J. Yang, S. Mei, J. Ferreira, Hydrothermal synthesis of TiO2 nanopowders from tetraalkylammonium hydroxide peptized sols Materials, Science and Engineering C 15 (2001) 183–185, https://doi.org/10.1016/S0928-4931(01)00274-0.
[184] S. Alamolhoda, S.A. Seyyed Ebrahimi, A. Badiei, Optimization of the Fe/Sr ratio in processing of ultrafine strontium hexaferrite powders by a sol-gel autocombustion method, Phys. Met. Metallogr. 102 (2006) S71–S73, https://doi.org/10.1134/S0031918X06140183.
[185] Soleimani Zohr Shiri, Mohammad, William Henderson, Michael R. Mucalo, A review of the lesser-studied microemulsion-based synthesis methodologies used for preparing nanoparticle systems of the noble metals, Os, Re, Ir and Rh, Materials 12 (12) (2019) 1896, https://doi.org/10.3390/ma12121896.
[186] Ekaterina Novitskaya, James P. Kelly, Sarit Bhaduri, Olivia A. Graeve, A review of solution combustion synthesis: an analysis of parameters controlling powder characteristics, Int. Mater. Rev. 66 (3) (2021) 188–214, https://doi.org/10.1080/09506608.2020.1765603.
[187] Emanuel Carlos, Rodrigo Martins, Elvira Fortunato, Rita Branquinho, Solution combustion synthesis: towards a sustainable approach for metal oxides, Chem.–Eur. J. 26 (42) (2020) 9099–9125, https://doi.org/10.1002/chem.202000678.
[188] Fizza Siddique, Sergio Gonzalez-Cortes, Amir Mirzaei, Tiancun Xiao, M.A. Rafiq, Xiaoming Zhang, Solution combustion synthesis: the relevant metrics for producing advanced and nanostructured photocatalysts, Nanoscale 14 (33) (2022) 11806–11868, https://doi.org/10.1039/D2NR02714C.