Improved production of titanate nanotubes by hydrothermal method for adsorption of organic dyes

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Abstract
Background: Increasing the yield of nanomaterials using the same reactor size and fixing most of the reactants and conditions will greatly improve the production process by saving time, energy and efforts. Titanate nanotubes are mainly prepared by hydrothermal process, in which TiO2 powder reacts with NaOH at certain conditions to form the desired nanotubes. It was reported that it is a must to use high concentrations of NaOH (10 N) to enable the tubular form formation, and the amount of NaOH from the stoichiometry point of view is much higher than that of TiO2; this means excess amounts of NaOH are not used and washed off. This work was designed to improve the production yield by making use of this excess amount of NaOH.

Results: More than 60 g of sodium titanate nanotubes was prepared using simple hydrothermal method. The prepared nanotubes were characterized by X-ray powder diffraction, high-resolution transmission electron microscopy, Fourier-transform infrared spectroscopy and BET surface area analysis. The adsorption capacity of these nanotubes was tested against three commonly used dyes: methyl orange, crystal violet and thymol blue. The samples showed great affinity toward crystal violet and lower activity toward methyl orange and thymol blue, where they achieved more than 90% removal efficiency under different experimental conditions.

Conclusions: Sodium titanate nanotubes were prepared in large amounts using modified hydrothermal method. The obtained nanotubes efficiently removed crystal violet from water. This improved synthesis of titanate nanotubes will reduce the total cost of nanomaterials production, and subsequently the treatment process, since titanate nanotubes are used in adsorption and photocatalysis processes.

Keywords: Titanate, Nanotubes, Water treatment, Organic dyes, Adsorbent, Large-scale production, Photocatalysis

1 Background
National security is closely related to the economic and social development, which is expected to increase the demand for freshwater for municipal and agriculture uses and electricity generation beyond existing levels [1]. One of the important solutions to this problem is to reuse and recycle raw water and wastewater [2]. Water is polluted with organic dyes that generated from industrialization activities, although many dyes are non-toxic, but their presence in water can hinder the sunlight from reaching the aquatic life plants and animals [3]. Dyes can be removed from ground and wastewater by various methods such as chemical oxidation, membrane separation, electrochemical process, photocatalytic degradation and adsorption technique [4].

Adsorption still attracts researchers’ attention because of its relatively low cost to other methods and its simplicity [5–13]. Many materials are used as adsorbents for organic dyes removal, such as activated carbon, zeolites, ZnO, TiO2 and titanate nanotubes. Using adsorbents at
the nanoscale level improves the process efficiency, since nanomaterials are smaller in size and larger in surface area when compared to conventional bulk materials [14].

Among these adsorbents, recently titanate nanostructures, especially nanotubes, have attracted more attention due to their high surface area, non-toxicity and their high adsorption and exchange capacity [14]. Titanate nanotubes are mainly prepared using the hydrothermal method [14–25]. But, unfortunately researchers did not pay attention to increase the yield of titanates in their studies; they tend to change the starting materials, time and temperature of reaction, the post-treatment solvents and acids [21, 26].

Herein, in this work, the hydrothermal method modified to increase the produced nanotubes by fixing all conditions except increasing the weight of the starting TiO2 particles five times to get more than 60 gm of titanate nanotubes in one run instead of repeating the same experience using the same reactor size for five consecutive runs. To the best of our knowledge, this is the first report of its kind and will contribute significantly to the improvement in the wastewater treatment techniques by lowering the production cost of titanate nanotubes and by saving time and efforts.

2 Methods
2.1 Materials
Methyl orange (M.O), crystal violet (C.V) and thymol blue (T.B) stock solutions were prepared using distilled water. Nanosized titanium dioxide powder (anatase phase) was purchased from El Nasr Company (Egypt). Sodium hydroxide was purchased from Reagents (India). Sodium hydroxide was purchased from Ci.

2.2 Synthesis of sodium titanate nanotubes
The nanotubes were prepared according to our previously published work [17–26], but with modification to prepare more than 60 gm in one step. In detail, 50 gm of TiO2 powder was added into 500 ml of 10 N NaOH, and then this mixture was subjected to vigorous magnetic stirring till milky white suspension is formed. The formed suspension was transferred into a 1000-ml-capacity Teflon-lined autoclave, and then this autoclave was placed in an oven at 160 °C for 23 h. After reaching the room temperature, the white powder was collected and washed specific times with distilled water to remove the unreacted amounts of NaOH. Finally, the powder was dried at 100 °C for 12 h.

2.3 Characterization and spectroscopy
The microstructure of the prepared nanotubes was studied using a high-resolution transmission electron microscope (HRTEM) (JEOL-JEM 2100, Japan) with an acceleration voltage of 200 kV. XRD patterns were recorded on a PANalytical (Empyrean) X-ray diffraction using Cu Kα radiation (wavelength 0.154 cm−1) at an accelerating voltage of 40 kV, current of 35 mA, scan angle 5°–80° range and scan step 0.02°. Fourier-transform infrared (FTIR) spectra were obtained using a spectrometer (Vertex 70 FT-IR) in the range of 4000 to 400 cm−1. Brunauer–Emmett–Teller (BET) surface area was measured by N2 adsorption using Micromeritics TriStar II.

2.4 Adsorption study
The dyes removal was studied using batch adsorption experiments under different conditions. The study was carried out in the pH range of 3–10 at fixed dye concentration, and the solution pH was adjusted using diluted NaOH and HNO3. The effect of dyes' initial concentration was studied using different concentrations: 12.5, 25, 50, 75 and 100 ppm. The effect of contact time was evaluated by collecting samples at different time intervals, from 15 to 120 min, to determine the optimum adsorbent dose to achieve the best removal efficiency using the minimum dose. The adsorbent dose in this study was varied from 0.025 to 0.2 mg/50 ml.

The change of dyes concentration was followed up using UV–visible spectrophotometer (UV-2600, SHIMADZU).

The removal efficiency (%) was also calculated by the following equation:

\[
(\%) \text{Removal} = \left( \frac{C_i - C_e}{C_i} \right) \times 100
\]

(1)

The adsorbed amounts of dyes were calculated using the following equation:

\[
Q_e = \frac{(C_i - C_e)V}{M}
\]

(2)

where \(Q_e\) represents the amount of adsorbed dyes, \(V\) is the volume of solution in liters, \(C_i\) is the initial dye concentration, while \(C_e\) is the final dyes concentrations in mg/l, and the adsorbent weight in grams is expressed as \(M\).

3 Results
3.1 Materials characterization
The XRD pattern of prepared sample is shown in Fig. 1, where the observed peaks at 2θ 9.68°, 24.35°, 28.20°, 48.20° and 60.86° confirmed the tubular structure of the prepared titanate (ICDD card no. 04-009-1210).

The prepared nanotubes were studied by FTIR spectroscopy, and the obtained spectrum is shown in Fig. 2. Three bands were observed at 901 cm−1, 1633 cm−1 and 3400–3200 cm−1, which are corresponding to the Ti–O stretching vibration, O–H stretching vibration, and H–O–H bending vibration, respectively; the presence of
bands at 1633 cm\(^{-1}\) and 3400–3200 cm\(^{-1}\) indicates the presence of water molecules in the prepared titanate.

Figure 3 shows the HRTEM micrograph of the synthesized nanotubes. The figure confirmed the production of titanate with the desired tubular structure with an average diameter of less than 10 nm.

The surface area was calculated using Brunauer–Emmett–Teller (BET) method, which was found to be 80 m\(^2\)/g. The observed hysteresis loop at high relative pressure, as shown in Fig. 4, indicates that the tubes are mesoporous, which may be attributed to the inner cavities of the tubes.

The above results of XRD, TEM, and FTIR reveal that titanate nanotubes were successfully prepared in large amounts compared to the previously published work; the comparison is listed in Table 1. To confirm the effectiveness of this modified method compared to other reported results, the amount of the reacting TiO\(_2\) and the obtained Na\(_2\)Ti\(_3\)O\(_7\) were normalized to each 100 ml of the starting 10 N NaOH. Theoretically, each 2 mol of NaOH (80 gm) reacts with 3 mol of TiO\(_2\) (about 240 gm) to produce 1 mol of Na\(_2\)Ti\(_3\)O\(_7\). Practically, researchers tended to use few grams of TiO\(_2\) and huge amounts of NaOH, since the formation of the desired nanotubes needs higher concentration of NaOH (10 N is preferred), and they neglected using the excess amounts of NaOH. It is clear from Table 1 that the yield of Na\(_2\)Ti\(_3\)O\(_7\) in previously published papers is ranging from 0.95 to 4.12 gm. For each 100 ml of 10 N NaOH, the amount increased to 12.5 in the current work.
If we assumed that the price per gram of TiO$_2$ and NaOH and other parameters are fixed, then the yield of this method will be much lower in price and also will save the time needed for repeating the experiment many times using the same reactor size to obtain greater amounts of titanate nanotubes. This will lower the cost of titanate nanotubes that are used in many vital and commercial applications, such as adsorption and photocatalysis.

### 3.2 Effect of pH value on the efficiency of dyes removal

The effect of solution pH on the removal efficiency of dyes using sodium titanates is shown in Fig. 5. The removal efficiency was evaluated at controlled pH values ranging from 3 to 10 using 100 ppm of adsorbate and 0.1 g of adsorbent for 2 h at room temperature. It is clear from Fig. 5 that removal % of M.O and T.B did not reach 30% at all pH values, while C.V removal reached 90% at pH 3, 94% at pH 10, 68% at pH 7 and 18% at pH 6. The removal percentages of M.O and T.B are attributed to the similarity in charges of the dye molecules and titanate surface (Fig. 6), since both of them are negatively charged, and hence weak electrostatic attraction or repulsion. In the case of C.V, the removal percentage is high.

### Table 1 Comparison between the yields of titanate with the other published work using the same preparation technique

| Starting materials | Weight of TiO$_2$ for each 100 ml NaOH | Yield of Na$_2$Ti$_3$O$_7$ for each 100 ml NaOH | Reaction time | Reaction temperature | Reactor capacity | References |
|--------------------|----------------------------------------|-----------------------------------------------|--------------|----------------------|-----------------|------------|
| 2.5 g TiO$_2$ (Anatase) + 200 mL of 10 M NaOH | 1.25 | 1.56 | 20 h | 130 °C | Capacity 250 mL | [27] |
| 750 mg of P25 Degussa was mixed with three different NaOH 100 mL | 0.75 | 0.94 | 24 h | 120 °C | 100 mL | [28] |
| 2.0 g of P25 was mixed with 60 mL of 10 M NaOH | 3.3 | 4.12 | 48 h | 150 °C | 100 mL | [29] |
| P25 (1.0 g) powder was added to 13 mol L$^{-1}$ NaOH solution (50 mL) | 1.5 | 2.5 | 24 h | 150 °C | 100 mL | [30] |
| 500 ml of 10 N NaOH (purity 99.1%) aqueous solution and 10 g of pure TiO$_2$ | 2 | 2.5 | 23 h | 160 °C | 1000 ml capacity | [31] |
| 6 g of TiO$_2$ (Degussa P25) powder was mixed in 180 ml of 10 N sodium hydroxide | 3.3 | 4.12 | 24 h | 135 °C | 200 ml | [32] |
| 1.0 g TiO$_2$ powder was added to 80 ml of 10 M NaOH solution | 1.25 | 1.56 | 5 days | 180 °C | 100 ml | [33] |
| 5 g TiO$_2$ (Anatase)+ 250 mL of 10 M NaOH | 2 | 2.5 | 16 h | 160 °C | 500 ml | [17] |
| 5 g TiO$_2$ (Anatase)+ 250 mL of 10 M NaOH | 2 | 2.5 | 16 h | 160 °C | 500 ml | [24] |
| 5 g TiO$_2$ (Anatase)+ 250 mL of 10 M NaOH | 2 | 2.5 | 16 h | 160 °C | 500 ml | [23] |
| 5 g TiO$_2$ (Anatase)+ 250 mL of 10 M NaOH | 2 | 2.5 | 16 h | 160 °C | 500 ml | [22] |
| 10 g TiO$_2$ (Anatase)+ 500 mL of 10 M NaOH | 2 | 2.5 | 23 h | 160 °C | 1000 ml | [34] |
| 10 g TiO$_2$ (Anatase)+ 500 mL of 10 M NaOH | 2 | 2.5 | 23 h | 160 °C | 1000 ml | [35] |
| 10 g TiO$_2$ (Anatase)+ 500 mL of 10 M NaOH | 2 | 2.5 | 20 h | 160 °C | 1000 ml | [25] |
| 10 g TiO$_2$ (Anatase)+ 500 mL of 10 M NaOH | 2 | 2.5 | 23 h | 160 °C | 1000 ml | [21] |
| 10 g TiO$_2$ (Anatase)+ 500 mL of 10 M NaOH | 2 | 2.5 | 23 h | 160 °C | 1000 ml | [19] |
| 10 g TiO$_2$ (Anatase)+ 500 mL of 10 M NaOH | 2 | 2.5 | 23 h | 160 °C | 1000 ml | [36] |
| 10 g TiO$_2$ (Anatase)+ 500 mL of 10 M NaOH | 2 | 2.5 | 23 h | 160 °C | 1000 ml | [37] |
| 50 g TiO$_2$ (Anatase)+ 500 mL of 10 M NaOH | 10 | 12.5 | 23 h | 160 °C | 1000 ml | Current work |
3.3 Effect of contact time, adsorbent dose and dye concentration on the efficiency of dyes removal

Figures 7 illustrates the impact of contact time on the removal efficiency of C.V. There is a sharp increase in the first 30 min, where the removal efficiency reached about 80%. An equilibrium state was achieved after 120 min, where the removal efficiency reached about 96%. This reveals that the majority of dyes’ molecules can be removed in a short time. While Fig. 8 shows the change of removal % with adsorbent dose, the results revealed that increasing the adsorbent dose increases the removal % as a result of increasing the amount of adsorbent particles available for adsorption; it is worth mentioning that the adsorbent dose of 0.001 g achieved about 75% removal % and the dose of 0.2 g achieved more than 90%; this means that small doses can be used to achieve relative high removal %. The effect of dye concentration on removal % is illustrated in Fig. 9, it is clear from this
Discussion

Results revealed that the removal efficiency was greatly affected by titanate surface charge, since the surface of the titanate was negatively charged at almost all pH values, the prepared nanotubes were capable of removing CV with high percentage, while the low removal % of M.O and T.B is attributed to the similarity in charges of the dyes (anionic dyes) and titanate surface; since both of them are negatively charged, there is weak electrostatic attraction or repulsion. Results also showed that increasing the adsorbent dose increased the removal % as a result of increasing the amount of adsorbent sites available for adsorption. As previously mentioned, about 75% removal was achieved using adsorbent dose of 0.001 g and the dose of 0.2 g achieved more than 90%; this means that small doses can be used to achieve high removal percentages. It was also found that the prepared nanotubes achieved the same efficiency at all concentrations in this study (Fig. 9).

4.1 Mechanism of crystal violet adsorption on doped titanate nanotubes

It is well known and detailed that the adsorption of crystal violet particles on negative surfaces is basically...
electrostatic, because the crystal violet molecules are positively charged, and it is reported that the titanate surfaces are negatively charged at most of the pH values.

As shown in Fig. 10, it is clear that the C.V molecules can be adsorbed in many sites on the prepared nanotubes, where it can be adsorbed on the outer surface of titanate due to the opposite charges, and also it can be adsorbed on the inner cavities of the tubes. The d-spacing value of the nanotubes is about 0.9 nm which hinders the adsorption of the dye molecules in between these layers.

4.2 Adsorption isotherms
The adsorptive behavior of crystal violet onto Na-TNT was studied using two common models: Langmuir and Freundlich isotherm models.

The direct frame of Langmuir and Freundlich models is outlined in Eqs. 3 and 4, respectively.

\[
\frac{1}{q_e} = \frac{1}{q_m} + \frac{1}{(K_L q_m C_e)}
\]

\[
\ln q_e = \ln K_F + \frac{1}{n} \ln (C_e)
\]

The values of adsorption parameters obtained from the straight fitting of Langmuir (Fig. 11a) and Freundlich (Fig. 11b) are recorded and clarified in Table 2. The results best fitted with Langmuir isotherm, where \( R^2 \) values are 1 in the case of Langmuir and 0.98 in the case of Freundlich; this means that the dye molecules are adsorbed in single layer on the titanate surface.

5 Conclusions
Sodium titanate nanotubes were prepared by using the hydrothermal method. The amount of the starting TiO\(_2\) particles was increased five times to improve the production yield. The obtained nanotubes retained the same features when compared to the previously prepared nanotubes, where their surfaces were negatively charged at different pH values, which enabled the nanotubes from removing cationic dyes (crystal violet) with high efficiency. Using this modified method to prepare titanate nanostructures in large amounts with lower cost will reduce the total cost of the treatment process which is based on adsorption and photocatalysis.

### Abbreviations
- TNT: Sodium titanate nanotubes
- M.O: Methyl orange
- C.V: Crystal violet
- T.B: Thymol blue
- XRD: X-ray powder diffraction
- FTIR: Fourier-transform infrared
- HRTEM: Using high-resolution transmission electron microscope
- BET: Brunauer–Emmett–Teller

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### Authors’ contributions
AH, AA, and MA conceived the research idea and designed the experiments. SA and AH performed the experiments and wrote the original manuscript; AA and MA revised and edited the manuscript to be in the final form. All authors have read and approved the final manuscript.

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#### Competing interests
The authors declare no competing interest.

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### Table 2
Freundlich and Langmuir isotherms parameters for crystal violet adsorption on sodium titanates at room temperature

| Isotherm   | Crystal violet | Parameters description |
|-----------|----------------|------------------------|
| Langmuir  | 1.0000         | \( R^2 \) is the regression coefficient |
|           | 1.0000         | \( R_L \) value lies between 0 and 1 for favorable adsorption |
|           | 100            | \( R_L \) higher than 1 means unfavorable adsorption |
|           | 0.01           | \( R_L \) equal to 1 represents linear adsorption |
|           |                | \( q_m \) is the maximum adsorption capacity of adsorbent, expressed in mg/g |
|           |                | \( K_L \) is the constant of Langmuir model |
| Freundlich| 0.98852        | \( R^2 \) is the regression coefficient |
|           | 0.99           | \( K_F \) and \( n \) are the Freundlich constants and give indication about the maximum adsorption capacity |
|           | 1.2            | If \( 1/n \) is less than 0.5, the adsorption would be easily carried out |
|           | 0.9            | If \( 1/n \) is larger than 0.5, the adsorption is difficult |
References

1. Wichelns D (2001) The role of ’virtual water’ in efforts to achieve food security and other national goals, with an example from Egypt. Agric Water Manag 49(2):131–151
2. Shannon MA, Bohn PW, Elemecnic M, Georgiadis JG, Marinas BI, Mayes AM (2010) Science and technology for water purification in the coming decades. Nanoscale Technol Collect Rev Nat J 337:346
3. Gupta VK, Alves AK, Bergmann CP (2017) Titania nanotubes produced from microwave-assisted hydrothermal synthesis: characterization, adsorption and photocatalytic activity. Braz J Chem Eng 34:331–339
4. Musa YP, Zurina ZA, Faizah MY, Noor ASM, Mohammed A (2020) Eco-friendly sustainable fluorescent carbon dots for the adsorption of heavy metal ions in aqueous environment. Nanomaterials 10:315–334
5. Manique MC, Silva AP, Alves AK, Bergmann CP (2017) Titania nanotubes produced from microwave-assisted hydrothermal synthesis: characterization, adsorption and photocatalytic activity. Braz J Chem Eng 34:331–339
6. Musa YP, Zurina ZA, Faizah MY, Noor ASM, Mohammed A (2020) Eco-friendly sustainable fluorescent carbon dots for the adsorption of heavy metal ions in aqueous environment. Nanomaterials 10:315–334
7. Musa YP, Zurina ZA, Faizah MY, Noor ASM, Jaafar A (2020) Langmuir I (1918) The adsorption of gases on plane surfaces of glass.
8. Musa YP, Zurina ZA (2020) A sustainable and eco-friendly technique for dye adsorption from aqueous. Desalin Water Treat 182:1–10
9. Langmuir I (1918) The adsorption of gases on plane surfaces of glass, mica and platinum. J Am Chem Soc 40:1361–1403
10. Musa YP, Zurina ZA, Faizah MY, Noor ASM, Jaafar A (2020) Selective and simultaneous detection of cadmium, lead and copper by tapioca-derived carbon dot-modified electrode. Environ Sci Pollut Res 27:13315–13324
11. Adevy AA, Jarnil SNAM, Abdullah LC, Choong TSY, Lau KL, Abdullah M (2019) Adsorptive removal of methylene blue from aquatic environments using thiourea-modified poly(acrylonitrile-co-acrylic acid). Materials 12:1734–1751
12. Akqdamari AA, Naushad M, Alothman ZA, Ahmaad T (2018) Adsorptive performance of MOF nanocomposite for methylene blue and malachite green dyes: kinetics, isotherm and mechanism. J Environ Manag 223:29–36
13. Musa YP, Zurina ZA, Faizah MY, Noor ASM, Mohammed A (2019) Synthesis and characterization of fluorescent carbon dots from tapioca. ChemistrySelect 4:1–8
14. Dhandole LK, Ryu J, Lim JM, Oh BT, Park JH, Kim BG, Jang JS (2016) Hydrothermal synthesis of titanate nanotubes from TiO2 nanorods prepared via a molten salt flux method as an effective adsorbent for strontium ion recovery. RSC Adv 6(100):98449–98456
15. Park H, Goto T, Han DH, Cho S, Nishida H, Sekino T (2020) Low alkali bottom-up synthesis of titanate nanotubes using a peroxo titanium complex ion precursor for photocatalysis. ACS Appl Nano Mater 3(8):7795–7803
16. Song I, Lee H, Jeon SW, Lim DH, Kim DH (2019) Hydrothermal synthesis of titanate nanotubes with different pore structure and its effect on the catalytic performance of V2O5-WO3/titanate nanotube catalysts for NH3-SCR. Top Catal 62(1):214–218
17. Farghali AA, Zaki AH, Khedr MH (2016) Control of selectivity in heterogeneous photocatalysis by tuning TiO2 morphology for water treatment applications. Nanomater Nanotechnol 2016(6):12
18. Zaki AH et al (2018) Morphology transformation from titanate nanotubes to TiO2 microspheres. Mater Sci Semicond Process 75:10–17
19. Zaki AH, Hafez MA, El Bouy WM, El-Dek SI, Farghali AA (2019) Novel magnetic endpoints in Na2Ti3O7 nanotubes. J Magn Magn Mater 476:207–212
20. Zaki AM, Zaki AH, Farghali AA, Abdel-Rahim EF (2017) J Pure Appl Microbiol 11:725–732
21. Aliwalla MA, Elbahladhy HAM, Zaki AH, Sallam MA (2019) Efficient removal of lead and cadmium ions by titanate nanotubes prepared at different hydrothermal conditions. Curr Nanosci 15(2):197–208
22. Mahmoud MS, Ahmed E, Farghali AA, Zaki AH, Aboeltah EA, Barakat NA (2018) Influence of Mn, Cu, and Cd-doping for titanium oxide nanotubes on the photocatalytic activity toward water splitting under visible light irradiation. Colloids Surf A 554:100–109
23. Mahmoud MS, Ahmed E, Farghali AA, Zaki AH, Barakat NA (2018) Synthesis of Fe/Co-doped titanate nanotube as redox catalyst for photon-induced water splitting. Mater Chem Phys 217:125–132
24. Batakat NA, Zaki AH, Ahmed E, Farghali AA, Al-Mubaddel FS (2018) Fe/CdO—a novel doped titanium oxide nanotubes as effective photocatalysts for hydrogen extraction from ammonium phosphate. Int J Hydrogen Energy 43(16):7990–7997
25. Rashad S, Zaki AH, Farghali AA (2019) Morphological effect of titanate nanostructures on the photocatalytic degradation of crystal violet. Nanomater Nanotechnol 9:1847980418821778
26. Mohamed H, Zaki AH, El-Ela FIA, El-dek SI (2021) Effect of hydrothermal time and acid-washing on the antibacterial activity of sodium titanate nanotubes. In: IOP conference series: materials science and engineering, vol 1046(1). IOP Publishing, p 012025
27. Chinnakoti P, Kurdekar AD, La AC, Aditha S, Biswas A, Mthukonda SV, Kamisetti V (2020) Titanate nanobelts—a promising nanosorbent for defluoridation of drinking water. Sep Sci Technol 35(6):1023–1035
28. Hinojosa-Reyes M, Camposeco-Solis R, Ruiz F (2019) H2Ti3O7 titanate nanotubes for highly effective adsorption of basic fuchsin dye for water purification. Microporous Mesoporous Mater 276:183–191
29. Yao Y, Zuo M, Shao P, Huang X, Li J, Duan Y et al (2020) Oxidative desulfurization of 4,6-dimethylbenzenothiophene over short titanate nanotubes: a non-classical shape selective catalysis. J Porous Mater 27(2):331–338
30. Jiang D, Sun X, Zhang H, Wang K, Shi L, Du F (2020) Nanotube confinement-induced gC 3 N 4 /TiO 2 nanorods with rich oxygen vacancies for enhanced photocatalytic water decontamination. Appl Phys A 126(4):1–10
31. Kamal N, Zaki AH, El-Shahawy AA, Sayed OM, El-Dek SI (2020) Changing the morphology of one-dimensional titanate nanostructures affects its tissue distribution and toxicity. Toxicol Ind Health 36(4):272–286
32. Wu HY, Nguyen NH, Bai H, Chang SM, Wu JC (2015) Photocatalytic reduction of CO 2 using molybdenum-doped titanate nanotubes in a MEA solution. RSC Adv 5(78):63142–63151
33. Kumar S, Nepak D, Kansal SK, Elumalai S (2018) Expeditious isomerization of glucose to fructose in aqueous media over sodium titanate nanotubes. RSC Adv 8(53):30106–30114
34. Nady B, Zaki AH, Raslan M, Hozyazen W (2020) Enhancement of microbial lipase activity via immobilization over sodium titanate nanotubes for fatty acid methyl esters production. Int J Biol Macromol 146:1169–1179
35. Zaki A, Zaki A, Farghali A, Abdel-Rahim EF (2017) Sodium titanate-bacillus as a new pesticide for cotton leaf-worm. J Pure Appl Microbiol 11:725–732
36. Zaki AH, Naem AA, El-Dek SI (2019) Sodium titanate nanotubes for efficient transesterification of oils into biodiesel. Environ Sci Pollut Res 26(36):36388–36400
37. Zaki AH, Lee MJ (2019) Effects of K+, Mg2+, Ca2+, Zn2+, La3+, Cr3+, Ce3+, Ce4+, and Mo5+ doping on the adsorption performance and optical properties of sodium titanate nanotubes. ACS Omega 4(22):19623–19634

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