ENHANCEMENT OF PHOTOCATALYTIC ACTIVITY OF TITANIUM DIOXIDE-BASED PHOTOCATALYSTS

Doctoral (Ph.D.) theses

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1. Introduction and objectives

Among humanity's most pressing problems to be solved the supply of clean drinking water and wastewater treatment are of utmost importance. Due to the extensive usage of materials like pesticides, pharmaceuticals, organic dyes and other chemical products ordinary water treatment techniques cannot be applied in numerous cases, thus alternative methods are required. Advanced oxidation processes (AOP) are one of the most promising techniques to solve these problems, from which I focused on heterogeneous photocatalysis. It is based on the application of a semiconductor photocatalyst which can be activated by light to initiate the degradation of various organic pollutants. It is important to highlight that the efficiency of heterogeneous photocatalysis is inferior to ordinary water treatments methods in most cases, thus for its practical application it is imperative to enhance the photocatalytic activity of the semiconductors.

My aim was to synthesize titanium dioxide (TiO_2) based photocatalysts, enhance their photocatalytic activity applying various methods, examine their morpho-structural properties and to investigate their applicability for water treatment purposes. I set out to increase the photocatalytic activity *via* oxygen rich modification, morphological modification and noble metal deposition, and to compare their photocatalytic activity with home-made references and commercial titanium dioxides in some cases. Furthermore, my goal was to determine the cause of the increased efficiency and to reveal the causal relationship between the applied technique and enhanced photocatalytic activity based on these measurements to better understand those phenomena which are relevant in this regard.

2. Experimental methods and procedures

I synthesized titanium dioxide-based photocatalysts *via* sol-gel method and investigated the effects of various synthesis parameters (hydrogen peroxide concentration, pH, carbon sphere preparation/purification/elimination method, presence of Au/Pt noble metals) on their morpho-structural properties and photocatalytic activities.

A *Rigaku Miniflex II* diffractometer was used for the X-ray diffraction (XRD) measurements with the following parameters: $\lambda_{Cu\ K\alpha}$ = 0.15406 nm, 40 kV, and 30 mA, 20 – 40 (2θ°) region. Average primary crystal sizes were calculated using the Scherrer equation.

Morphology of the samples was analyzed by a *Hitachi S-4700 Type II* scanning electron microscope (SEM) and a *FEI TECNAI G² 20 X-Twin* type transmission electron microscope (TEM).

A *Jasco-V650* spectrophotometer with an integration sphere (*ILV-724*) was used for measuring the diffuse reflectance spectra of the samples (λ = 220 – 800 nm). The band gap energy values were calculated using the *Kubelka-Munk* theory.

Specific surface areas of the catalysts were determined by N_2 adsorption at 77 K, using a *BELCAT-A* device. The specific surface area was calculated *via* the BET method.

Infrared (IR) spectra were recorded by using a *Bruker Equinox 55* spectrometer. The spectra were recorded in the 400 – 4000 cm^{-1} region with a spectral resolution of 2 cm^{-1}.

Raman spectra were taken by a *Thermo Scientific DXR* Raman microscope using λ = 532 nm laser irradiation.

Thermogravimetric analysis (*Netzsch STA409 PC* connected to a *Pfeiffer QMS 200* mass spectrometer system) of the carbon sphere templates was performed in oxygen flow (40 $cm^3 \cdot min^{-1}$) with 5 °C·min^{-1} heating rate.

X-ray photoelectron spectroscopy (XPS) measurements were performed on a *Specs Phoibos 150 MCD* system employing a monochromatic Al-K_α source (1486.6 eV) at 14 kV and 20 mA, a hemispherical analyzer and a charge neutralization device.

Photocatalytic activity experiments were carried out in a double-walled glass vessel which was surrounded either by four energy saving compact fluorescence lamps (*Düwi 25920/R7S,* 24W) for the visible light measurements or 6 fluorescent tubes (*Vilber-Lourmat T-6L UV-A*, 6W) for the UV experiments. Changes in the phenol and oxalic acid concentration were measured by a *Hitachi* high-performance liquid chromatography (HPLC) system consisting *a Merck Hitachi L-7100* low-pressure pump and a *Merck-Hitachi L-4250* UV-Vis detector.

3. Summary of new scientific results

T1. Anchoring peroxo groups on the surface of TiO_2 enhances its photocatalytic activity

T1.1. I have successfully applied the method of oxygen rich modification to enhance the photocatalytic activity of rutile phase titanium dioxide. I applied strongly acidic conditions to synthesize pure rutile phase titanium dioxide. I anchored peroxo groups on the surface of titanium dioxide by the addition of hydrogen peroxide during the synthesis. I ascertained that $n_{Ti} : n_{H_2O_2} = 1 : 2$ ratio had to be applied for the formation of peroxo groups. The presence of peroxo groups was proved *via* XPS measurements. Peroxo groups enhanced the visible light absorption of TiO_2 reinforced by DRS measurements.

T1.2. I have proved *via* photocatalytic activity measurements that TiO_2 containing peroxo groups had superior photocatalytic performance for phenol degradation under visible light irradiation compared to reference titanium dioxides without peroxo groups. The reason for the enhanced photocatalytic activity was deduced to be due to the resultant effect of the enhanced visible light absorption and the electron attracting inductive effect conveyed by the presence of peroxo groups. I showed that the order of the samples' visible light absorption was completely consistent with their photocatalytic activities reinforced by DRS measurements.

T1.3. I have successfully sensitized amorphous and anatase phase titanium dioxides as well applying the method of oxygen rich modification. For this purpose, pH>2 had to be set during the synthesis, while the crystallinity and crystalline composition of TiO_2 could be controlled *via* the temperature of the heat treatment. I proved that increasing the pH dramatically enhanced the visible light absorption of the photocatalysts and increased the amount of anchored peroxo groups (applying constant hydrogen peroxide concentration) as well in the case of both amorphous and anatase phase titanium dioxides.

T1.4. I have ascertained that the photocatalytic activity of the amorphous and anatase phase titanium dioxides surpassed even the photocatalytic activity of the peroxo group-containing rutile phase titanium dioxide. This result was in good accordance with the increased light absorption and higher amount of peroxo groups in the case of the amorphous and anatase phase titanium dioxides. I proved that the rutile phase titanium dioxides with higher crystallinity retained their photocatalytic activity to a higher degree following the photocatalytic activity measurements compared to the amorphous and anatase phase samples with lower crystallinity. Furthermore, I showed with XPS measurements that the peroxo group-containing titanium dioxides need to possess a certain level of crystallinity to retain the photocatalytic activity enhancement conveyed by the presence of peroxo groups.

T2. Formation of hollow spherical morphology increases the photocatalytic activity of TiO_2

T2.1. I have ascertained that by the hydrothermal treatment of sucrose solution such carbon spheres can be prepared which can be used effectively as templates for the shape-controlled synthesis of titanium dioxide hollow spheres. I proved that the pH of the carbon sphere precursor solution and the duration of the hydrothermal treatment have a determinative effect on their characteristics, thus these parameters can be used to systematically change the size and yield of the templates.

T2.2. I have successfully applied carbon sphere templates to synthesize titanium dioxide/carbon sphere composites and titanium dioxide hollow spheres. I was the first to use the synthesis method described in T1.1. to form TiO_2 coating (*i.e.* instead of using commercial TiO_2) on the surface of carbon spheres. During the comparison of titanium dioxide/carbon sphere composites and titanium dioxide hollow spheres I have established that the presence of carbon spheres significantly decreased the crystallinity and photocatalytic activity of the samples compared to the peroxo group-containing starting material. I proved

that eliminating the carbon sphere templates *via* calcination always resulted in titanium dioxide hollow spheres with higher crystallinity and photocatalytic activity.

T2.3. I have pointed out that the morphology, crystalline composition and photocatalytic activity of titanium dioxide hollow spheres were greatly affected by the applied synthesis conditions (precursor quantity, template purification and elimination method). Based on XPS measurements the outstanding photocatalytic activity of the most efficient sample could be attributed to the lowest carbon content on its surface and the higher ratio of the polar O–C=O functional groups, which facilitated the direct contact between the water (matrix of the photocatalytic process) and the surface of the photocatalyst.

T2.4. I have successfully synthesized regular titanium dioxide hollow spheres using commercial titanium(IV) butoxide precursor. It was established, that the purification solvent (acetone or ethanol) did not influence the characteristics of the titanium dioxide hollow spheres. Applying 500 °C calcination temperature resulted in anatase phase titanium dioxide hollow spheres with regular hollow spherical morphology, while applying 800 °C yielded rutile phase titanium dioxide hollow spheres with less regular morphology.

T2.5. I have demonstrated that hollow spherical titanium dioxide had higher photocatalytic activity compared to the solid spherical reference under UV light irradiation in the case of both phenol and oxalic acid model pollutants. Based on indirect proofs and our experiences I showed that the increased photocatalytic activity of the samples could be attributed to their enhanced light trapping properties: the photocatalytic activity increased with increasing proportions of titanium dioxide hollow sphere diameters close to the integer multiple of the excitation light source's wavelength, *i.e.* in which case the occurrence of constructive interference was more probable.

T3. Enhancing the effectiveness of titanium dioxide hollow spherical morphology *via* the deposition of Au and Pt noble metal nanoparticles

T3.1. I have proved that Au and Pt noble metal nanoparticles can be deposited even on the surface of hollow spherical titanium dioxides while retaining the morphology. I ascertained that the presence of noble metals typically resulted in the enhancement of photocatalytic activity, thus reinforcing that two photocatalytic-activity-enhancement methods can be used effectively together with each other to significantly increase the photocatalytic activity in the case of both UV and visible light irradiation.

4. Applicability of the scientific results

During my research I successfully synthesized titanium dioxide-based photocatalysts and increased their photocatalytic activity applying various methods. My results may provide a good basis for the enhancement of photocatalytic activity *via* modifying the surface, morphology and optical properties of titanium dioxides increasing their efficiency to the level that can make them suitable to be used together with conventional water purification methods. Nowadays the development of visible light active photocatalysts is of particular importance, thus my corresponding results can contribute to the development of photocatalysts able to utilize artificial light and solar light as well with greater efficiency, making them suitable not only for water treatment, but for outdoor and indoor applications, and for the development of self-cleaning and air cleaning surfaces as well. I hope that with my results I contributed to the development of new type of materials; furthermore, that I was able to provide valuable insights concerning the dependence of synthesis parameters and morpho-structural characteristics on the resulting photocatalytic activity of titanium dioxides, which could be useful for scientists working in the same research field as well.

5. Publications and conference participations

Hungarian Scientific Bibliography (MTMT) identifier: 10052868

Publications related to the scientific topic of the dissertation:

[1] **T. Gyulavári**, Z. Pap, G. Kovács, L. Baia, M. Todea, K. Hernádi, G. Veréb: *Peroxo group enhanced nanorutile as visible light active photocatalyst*
Catalysis Today, 284 (2017) 129-136.
IF = 4.667

[2] B. Réti, G.I. Kiss, **T. Gyulavári**, K. Baan, K. Magyari, K. Hernadi: *Carbon sphere templates for TiO_2 hollow structures: Preparation, characterization and photocatalytic activity*
Catalysis Today, 284 (2017) 160-168.
IF = 4.667

[3] **T. Gyulavári**, G. Veréb, Z. Pap, A. Dombi, K. Hernádi: *Associating low crystallinity with peroxo groups for enhanced visible light active photocatalysts*
Catalysis Today, 313 (2018) 231-238.
IF = 4.888

[4] **T. Gyulavári**, G. Veréb, Z. Pap, B. Réti, K. Baan, M. Todea, K. Magyari, I.M. Szilágyi, K. Hernadi: *Utilization of Carbon Nanospheres in Photocatalyst Production: From Composites to Highly Active Hollow Structures*
Materials, 12 (2019) 2537.
IF = 2.972

[5] **T. Gyulavári**, K. Kovács, Z. Kovács, E. Bárdos, G. Kovács, K. Baan, K. Magyari, G. Veréb, Zs. Pap, K. Hernadi: *Preparation and characterization of noble metal modified titanium dioxide hollow spheres – new insights concerning the light trapping efficiency*
Submitted, Acta Materialia
(IF = 7.293)

ΣIF = 17.194

ΣCitations = 39 (Independent: 33)

Other publications:

[6] G. Veréb, **T. Gyulavári**, Z. Pap, L. Baia, K. Mogyorósi, A. Dombi, K. Hernádi: *Visible light driven photocatalytic elimination of organic- and microbial pollution by rutile-phase*

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[7] A. Szabo, E. Kecsenovity, Z. Papa, **T. Gyulavari**, K. Nemeth, E. Horvath, K. Hernadi: *Influence of synthesis parameters on CCVD growth of vertically aligned carbon nanotubes over aluminum substrate*
Scientific Reports, 7 (2017) 9557.
IF = 4.122

[8] E. Bárdos, G. Kovács, **T. Gyulavári**, K. Németh, E. Kecsenovity, P. Berki, L. Baia, Z. Pap, K. Hernádi: *Novel synthesis approaches for WO_3-TiO_2/MWCNT composite photocatalysts- problematic issues of photoactivity enhancement factors*
Catalysis Today, 300 (2018) 28-38.
IF = 4.888

[9] G. Simon, **T. Gyulavári**, K. Hernádi, M. Molnár, Z. Pap, G. Veréb, K. Schrantz, M. Náfrádi, T. Alapi: *Photocatalytic ozonation of monuron over suspended and immobilized TiO_2 – study of transformation, mineralization and economic feasibility*
Journal of Photochemistry and Photobiology A: Chemistry, 356 (2018) 512-520.
IF = 3.261

[10] G. Veréb, V. Kálmán, **T. Gyulavári**, S. Kertész, S. Beszédes, G. Kovács, K. Hernádi, Z. Pap, C. Hodúr, Z. László: *Advantages of TiO_2/carbon nanotube modified photocatalytic membranes in the purification of oil-in-water emulsions*
Water Science and Technology-Water Supply, 19 (2019) 1167-1174.
IF = 0.922

[11] A. Szabó, P. Andricevic, Z. Pápa, **T. Gyulavári**, K. Németh, E. Horváth, L. Forró, K. Hernadi: *Growth of CNT Forests on Titanium Based Layers, Detailed Study of Catalysts*
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[12] A. Szabó, L.P. Bakos, D. Karajz, **T. Gyulavári**, Z.R. Tóth, Z. Pap, I.M. Szilágyi, T. Igricz, B. Parditka, Z. Erdélyi, K. Hernadi: *Decoration of Vertically Aligned Carbon Nanotubes with Semiconductor Nanoparticles Using Atomic Layer Deposition*
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IF = 2.972

[13] K. Magyari, Z.R. Tóth, Z. Pap, E. Licarete, D.C. Vodnar, M. Todea, **T. Gyulavári**, K. Hernadi, L. Baia: *Insights into the effect of gold nanospheres, nanotriangles and spherical nanocages on the structural, morphological and biological properties of bioactive glasses*

Journal of Non-Crystalline Solids, 522 (2019) 119552.
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[14] L. Nánai, A. Szabó, **T. Gyulavári**, J. Budai, K. Hernadi: *Manual spray coating: A cheap and effective method to build catalyst layers for carbon nanotube forest growth*
Thin Solid Films, (2019) 137491.
IF = 1.888

ΣIF = 27.724

ΣCitations = 37 (Independent: 25)

ΣΣIF = 44.918

ΣΣCitations = 76 (Independent: 58)

National and international conference participations:

(1) **Gyulavári Tamás**: Vízkezelés különböző részecskeméretű rutil fázisú titán-dioxid fotokatalizátorokkal
SZTE-TTIK Környezettudományi Diákköri Konferencia
Szeged, Hungary (2014) – oral presentation (1st place)

(2) **Gyulavári Tamás**: Vízkezelés különböző részecskeméretű rutil fázisú titán-dioxid fotokatalizátorokkal
XIV. Országos Felsőoktatási Környezettudományi Diákkonferencia
Pécs, Hungary (2014) – oral presentation (1st place)

(3) **Tamás Gyulavári**, Gábor Veréb, Zsolt Pap, László Manczinger, Károly Mogyorósi, András Dombi, Klára Hernádi: Visible light driven photocatalytic elimination of organic and microbial pollutions by rutile phase titanium-dioxides
4th European Young Engineers Conference
Warsaw, Poland (2015) – poster presentation

(4) **Tamás Gyulavári**, Gábor Veréb, Zsolt Pap, Klára Hernádi, András Dombi: Látható fénnyel történő vízkezelés rutil fázisú titán-dioxid fotokatalizátorokkal
Proceedings of the 21st International Symposium on Analytical and Environmental Problems
Szeged, Hungary (2015) – poster presentation

(5) **Gyulavári Tamás**, Kása Zsolt, Veréb Gábor, Saszet Kata, Pap Zsolt, Dombi András, Baia Lucian, Hernádi Klára: Vízkezelés látható fényre aktív titán-dioxid és bizmut-volframát fotokatalizátorokkal
Ötödik Környezetkémiai Szimpózium

Tihany, Hungary (2016) – oral presentation

(6) **Tamás Gyulavári**, Gábor Veréb, Zsolt Pap, András Dombi, Klára Hernádi: *Hidrogén-peroxid alkalmazása látható fénnyel gerjeszthető anatáz fázisú titán-dioxidok előállítására*
Proceedings of the 22nd International Symposium on Analytical and Environmental Problems
Szeged, Hungary (2016) – poster presentation

(7) **Gyulavári Tamás**, Veréb Gábor, Pap Zsolt, Dombi András, Hernádi Klára: *Preparation of visible light active, non-doped, anatase titanium dioxide*
22nd International Conference on Chemistry
Timisoara, Romania (2016) – oral presentation

(8) **Gyulavári Tamás**, Veréb Gábor, Pap Zsolt, Kovács Gábor, Baia Lucian, Todea Milica, Dombi András, Hernádi Klára: *Facile sol-gel synthesis for the preparation of highly visible light active anatase titanium dioxides*
5th European Conference on Environmental Applications of Advanced Oxidation Processes
Prague, Czech Republic (2017) – poster presentation

(9) **Tamás Gyulavári**, Gábor Veréb, Zsolt Pap, Klára Hernádi: *Üreges szerkezetű titán-dioxidok előállítása széngömb templát segítségével*
Proceedings of the 23rd International Symposium on Analytical and Environmental Problems
Szeged, Hungary (2017) – poster presentation

(10) **Gyulavári Tamás**, Veréb Gábor, Pap Zsolt, Hernádi Klára: *Preparation of titanium dioxide hollow structures using carbon sphere templates*
23rd International Conference on Chemistry
Deva, Romania (2017) – oral presentation

(11) **Tamás Gyulavári**, Gábor Veréb, Zsolt Pap, Klára Hernádi: *Preparation of rutile titanium dioxide hollow structures with high visible light activity*
III. International Symposium on Nanoparticles/Nanomaterials and Applications
Lisbon, Portugal (2018) – poster presentation

(12) **Gyulavári Tamás**, Veréb Gábor, Pap Zsolt, Hernádi Klára: *Preparation of carbon sphere-based titanium dioxide hollow structures with high photocatalytic activity*
24th International Conference on Chemistry
Sovata, Romania (2018) – oral presentation

(13) **Tamás Gyulavári**, Kata Kovács, Boglárka Hampel, Gábor Veréb, Zsolt Pap, Klára, Hernádi: *Preparation and characterization of noble metal modified titanium dioxide hollow structures*
II. Sustainable Raw Materials International Project Week And Scientific Conference
Szeged, Hungary (2019) – oral presentation

(14) **Tamás Gyulavári**, Gábor Veréb, Balázs Réti, Kornélia Baán, Milica Todea, Klára Magyari, Zsolt Pap, Imre Miklós Szilágyi, Klára Hernádi: *The quality of carbon spheres as a crucial parameter in the pre-determination of the photocatalytic activity of titania hollow structures*
6th European Conference on Environmetal Applications of Advanced Oxidation Processes
Portorož-Portorose, Slovenia (2019) – poster presentation

(15) **Tamás Gyulavári**, Kata Kovács, Boglárka Hampel, Gábor Veréb, Zsolt Pap, Klára Hernádi: *Preparation and characterization of noble metal modified titanium dioxide hollow structures*
6th European Conference on Environmetal Applications of Advanced Oxidation Processes
Portorož-Portorose, Slovenia (2019) – poster presentation

(16) **Gyulavári Tamás**, Kovács Kata, Veréb Gábor, Pap Zsolt, Hernádi Klára: *Preparation and characterization of noble metal modified titanium dioxide hollow spheres*
25th International Conference on Chemistry
Cluj-Napoca, Romania (2019) – oral presentation

National and international conference participations as co-author:

(17) Veréb Gábor, Manczinger László, **Gyulavári Tamás**, Mogyorósi Károly, Dombi András, Hernádi Klára: *Photocatalytic water treatment by various rutile phase TiO_2 photocatalysts under visible light irradiation*
Fourth International Conference on Semiconductor Photochemistry
Prague, Czech Republic (2013) – poster presentation

(18) Gábor Veréb, **Tamás Gyulavári**, Zsolt Pap, Lucian Baia, Teodora Radu, Károly Mogyorosi, András Dombi, Klára Hernádi: *Visible light activated rutile-phase titanium dioxides in photocatalytic water treatment processes*
20th International Conference on Chemistry
Cluj-Napoca, Romania (2014) – poster presentation

(19) Gácsi Attila, Kutus Bence, Cseh Attila, Bélteki Rita, **Gyulavári Tamás**, Bárdos Enikő, Pálinkó István, Sipos Pál: Formation of Ca-Al containing layered double hydroxides and its solubility product determination in highly caustic solutions
NanoOstrava 2015 – Nanomaterials and Nanotechnology Meeting
Ostrava, Czech Republic (2015) – poster presentation

(20) Attila Gácsi, Bence Kutus, Rita Bélteki, **Tamás Gyulavári**, Attila Cseh, István Pálinkó, Pál Sipos: *Determining of the solubility product of CaAl-layered double hydroxide*
18th International Symposium on Intercalation Compounds
Strasbourg, France (2015) – poster presentation

(21) Bárdos, Enikő, Kovács Gábor, Orbán Eszter, **Gyulavári Tamás**, Németh Krisztián, Kecsenovity Egon, Berki Péter, Baia Lucian, Pap Zsolt, Hernádi Klára: *Szerves modellszennyezők lebontása TiO_2-WO_3 alapú nanokompozitok segítségével*
Ötödik Környezetkémiai Szimpózium
Tihany, Hungary (2016) – oral presentation

(22) Bárdos Enikő, Kovács Gábor, **Gyulavári Tamás**, Németh Krisztián, Kecsenovity Egon, Berki Péter, Baia Lucian, Pap Zsolt, Hernádi Klára: *WO_3-TiO_2/MWCNT nanokompozitok előállítása és fotokatalitikus vizsgálata*
Proceedings of the 22nd International Symposium on Analytical and Environmental Problems
Szeged, Hungary (2016) – poster presentation

(23) Gergő Simon, **Tamás Gyulavári**, Klára Hernádi, Zsolt Pap, Gábor Veréb, Krisztina Schrantz, Tünde Alapi: *Photocatalytic ozonation of monuron over suspended and immobilized TiO_2*
Proceedings of the 22nd International Symposium on Analytical and Environmental Problems
Szeged, Hungary (2016) – oral presentation

(24) Bárdos Enikő, Kovács Gábor, **Gyulavári Tamás**, Németh Krisztián, Kecsenovity Egon, Berki Péter, Baia Lucian, Pap Zsolt, Hernádi Klára: *Preparation, Characterization and Photocatalytic Activity of WO_3-TiO_2/MWCNT Nanocomposites*
22nd International Conference on Chemistry
Timisoara, Romania (2016) – oral presentation

(25) Pap Zsolt, Fodor Szilvia, **Gyulavári Tamás**, Kovács Gábor, Tóth Zsejke, Kása Zsolt, Bárdos Enikő, Rózsa Georgina, Simon Gergő, Kozmér Zsuzsanna et al.: *New nanocomposites and nanostructures in water cleaning*
22nd International Conference on Chemistry
Timisoara, Romania (2016) – oral presentation

(26) Szabó Anna, Kovács Anita, **Gyulavári Tamás**, Kovács Gábor, Pap Zsolt, Hernádi Klára: *Synthesis and characterization of vertically aligned carbon nanotubes and CNT-WO3-based composites*
5th European Conference on Environmental Applications of Advanced Oxidation Processes
Prague, Czech Republic (2017) – poster presentation

(27) Gábor Veréb, **Tamás Gyulavári**, Orsolya Virág, Krisztina Vajda, Zsolt Pap, Tünde Alapi, Zsuzsanna László, András Dombi, Klára Hernádi: *UV és látható fénnyel gerjeszthető fotokatalizátorok a napfényt hasznosító heterogén fotokatalízisben*
Proceedings of the 23rd International Symposium on Analytical and Environmental Problems
Szeged, Hungary (2017) – poster presentation

(28) Kovács Gábor, Szabó Anna, Kovács Anita, **Gyulavári Tamás**, Pap Zsolt, Hernádi Klára: *Synthesis and Characterization of Vertically Aligned Carbon Nanotubes and CNT-WO_3-based Composites*
23rd International Conference on Chemistry
Deva, Romania (2017) – oral presentation

(29) Klára Hernádi, Anna Szabó, Zsuzsanna Pápa, **Tamás Gyulavári**, Krisztián Németh, Judit Budai: *CCVD growth of vertically aligned carbon nanotubes over various substrates*
III. International Symposium on Nanoparticles/Nanomaterials and Applications
Lisbon, Portugal (2018) – oral presentation

(30) Viktória Kálmán, Gábor Veréb, **Tamás Gyulavári**, Szabolcs Kertész, Sándor Beszédes, Klára Hernádi, Cecilia Hodúr, Zsuzsanna László: *Advantages of TiO_2/carbon Nanotube Modified Photocatalytic Membranes in the Purification of Oil in Water Emulsions*
10th Eastern European IWA Young Water Professionals Conference
Zagreb, Croatia (2018) – poster presentation

(31) Klára Hernádi, Anna Szabó, Zsuzsanna Pápa, **Tamás Gyulavári**, Krisztián Németh, Zsolt Tóth, Judit Budai: *Challenges in The Growth of Vertically Aligned Carbon Nanotubes: Substrate, Catalyst Layer, CVD Conditions and Much More*
Nanoworld Conference: Useful Science and Technology for a Just World
San Francisco, USA (2018) – oral presentation

(32) Kálmán Viktória, Kertész Szabolcs, Beszédes Sándor, Pap Zsolt, **Gyulavári Tamás**, Hodúr Cecilia, László Zsuzsanna, Veréb Gábor: *Membrane Filtration of Oil-in-water Emulsions with TiO_2/carbon Nanotube Modified Photocatalytic Membranes*
24th International Conference on Chemistry
Sovata, Romania (2018) – poster presentation