SILESIAN UNIVERSITY OF TECHNOLOGY

Faculty of Chemistry
Department of Organic Chemistry, Bioorganic Chemistry and Biotechnology

Tomasz Wasiak, MSc

Doctoral Dissertation

Summary

New generation of catalysts based on nanomaterials for advanced organic chemistry

Supervisor: Dr. Dawid Janas, prof. SUT

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The thesis is based on the following published articles:

[P1] T. Wasiak, D. Janas, Nanowires as a versatile catalytic platform for facilitating chemical transformations, J. Alloys Compd. 892 (2022) 162158. https://doi.org/10.1016/j.jallcom.2021.162158

IF = 6.371, Ministerial points = 100

[P2] T. Wasiak, P.-M. Hannula, M. Lundström, D. Janas, Transformation of industrial wastewater into copper-nickel nanowire composites: straightforward recycling of heavy metals to obtain products of high added value, Sci. Rep. 10 (2020) 19190. https://doi.org/10.1038/s41598-020-76374-x

IF = 4.6, Ministerial points = 140

[P3] T. Wasiak, D. Łukowiec, S. Wacławek, J. Kubacki, D. Janas, Ni nanowires decorated with Pd nanoparticles as an efficient nanocatalytic system for Suzuki Coupling of anisole derivatives, Nano-Structures & Nano-Objects, 36 (2023) 101052. https://doi.org/10.1016/j.nanoso.2023.101052

IF = - (not released yet), Ministerial points = 40

[P4] T. Wasiak, D. Just, A. Dzienia, D. Łukowiec, S. Wacławek, A. Mielańczyk, S. Kodan, A. Bansal, R. Chandra, D. Janas, PdNPs/NiNWs as a welding tool for the synthesis of polyfluorene derivatives by Suzuki polycondensation under microwave radiation, Sci. Rep. 14 (2024) 2336
https://doi.org/ 10.1038/s41598-024-52795-w
IF = 4.6, Ministerial points = 140

[P5] D. Łukowiec, **T. Wasiak**, D. Janas, E. Drzymała, J. Depciuch, T. Tarnawski, J. Kubacki, S. Wacławek, A. Radoń, Pd decorated Co–Ni nanowires as a highly efficient catalyst for direct ethanol fuel cells, Int. J. Hydrogen Energy, 47 (2021) 97. https://doi.org/10.1016/j.ijhydene.2021.11.177

IF = 7.2, Ministerial points = 140

Total IF = 22.771   Total Ministerial points = 560

1. Introduction

The thesis consists of the following parts: Introduction, Aims and scope of the work, Results and discussion, Conclusions and further perspective. The first section contains basic information about nanomaterials and the state of their development. As my work focuses on metallic nanoparticles, particularly nanowire-like nanostructures, their synthesis and applications are presented first. Next, in the Aims and scope of the work, I outline the key objectives and perspectives of the dissertation. The subsequent main part of this thesis includes the obtained results and their discussion based on scientific papers published in research journals. Each subsection references to specific topic of nanowire synthesis, formation of composite materials and gauging of their catalytic properties in various chemical and electrochemical reactions. The last section underlines conclusions obtained from the described works and presents future opportunities for the investigated topic.

1.1. Nanotechnology – great potential in small things

Nanotechnology deals with the synthesis, structure, size modification and application of nano-size objects in the range 1-100 nm in at least one dimension. Quantum effects present in those entities provide improved characteristics such as higher surface area and reactivity or better optical/electrical properties. The development of nanotechnology, which converts nanoscience theoretical values to applicable forms, gave bountiful opportunities to improve many aspects of various fields such as chemistry, biology, medicine or electronics [1]. Nanowires (NWs) are anisotropic one-dimensional (1D) nanostructures built from various materials such as metals [2] non-metals [3], and their compounds with other elements [4,5]. Due to the work of many scientific groups, nanowire research soon transformed into an interdisciplinary field, connecting chemists, physicists, and material scientists to discover new nanomaterials and their unique properties. This resulted in a bountiful variety of nanowires with different compositions. The main efforts of those works were addressed to synthesis methods and application of nanowires in various key aspects of modern science and technology. The work described herein focuses on the catalytic properties of nanowire-based nanomaterials and therefore in the following paragraphs, the synthesis of such composites and their application in catalysis will be discussed.

1.2. Nanowire synthesis

In [P1], I conducted a literature study of nanowire synthesis and their application in catalysis. The most characteristic feature of nanowires is their anisotropic morphology, which provides beneficial properties that come from enhanced quantum effects. Formation of such structures can be achieved by two distinctive approaches. Top-down methods include techniques allowing selective removal of atoms from bulk substrate (Fig. 1).

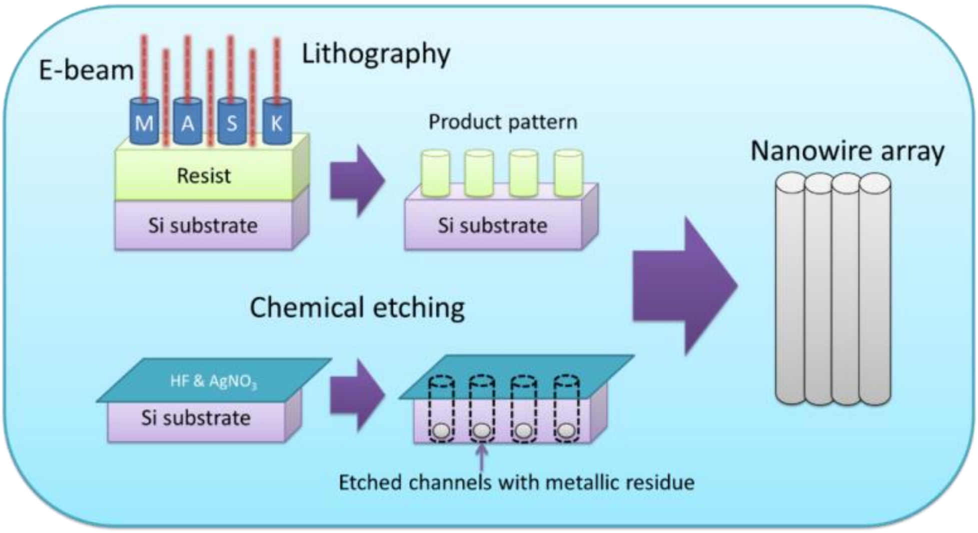

Fig. 1. Schematic illustration of methods of synthesis of nanostructure materials based on top-down approach.

A far more convenient alternative to top-down methods comes from bottom-up processes, where nanomaterials are built block-by-block from molecules. This approach utilizes chemical reactions, which provide the growth of nanoparticles (NPs) in a controlled manner (Fig. 2).

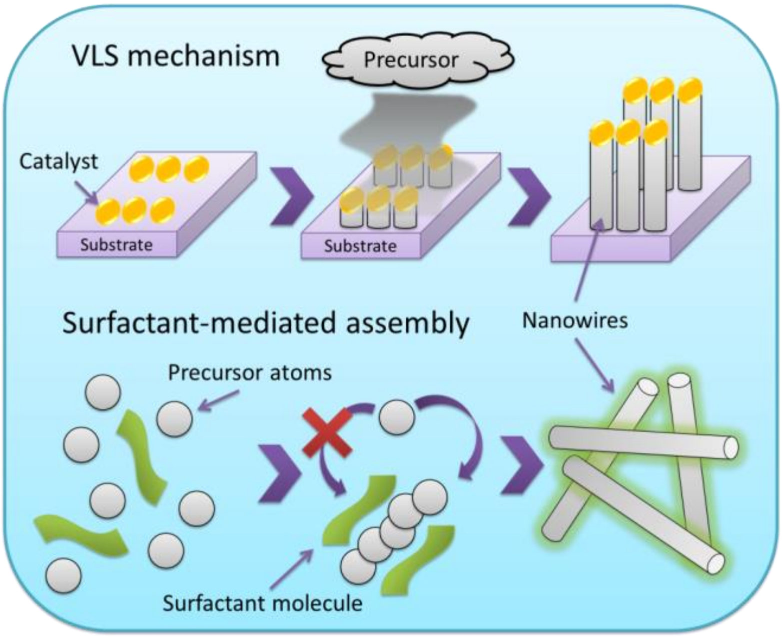

Fig. 2. Schematic illustration of methods of synthesis of nanostructure materials based on bottom-up approach.

1.3. Nanowires application in catalysis

Catalysis is a topic of high priority due to the widespread of catalyst-driven reactions across the entire chemical industry. The common property of a catalyst is lowering the activation energy; however, reaction mechanisms may vary due to catalyst composition, morphology, and working conditions. The most commonly used category in industry is homogeneous catalysis. It often exhibits higher activities, yields, and therefore better turnover numbers (TON) and frequencies (TOF), which are the most important industrial parameters. Despite such great advantages, they show some drawbacks, which have been targets of scientists for a long time. The catalyst is sometimes irrecoverable from the post-reaction mixture. This is a challenging issue, especially for drug synthesis, where highly toxic complex-based catalysts are used. Overall, homogeneous catalysis involves additional steps during the main process, like catalyst activation, providing inert atmosphere, or inconvenient catalyst separation, which can generate higher costs and hazards, which results in lower profits.

Such unfavorable quirks of homogeneous catalysis are absent when using heterogeneous counterparts. Even more emphasis in this regard is put on nanostructures, due to their unique properties and potential opportunities. A plentiful range of nanomaterials with various morphologies and compositions still wait to be discovered and tested as catalysts in numerous reactions. One such promising category is metal-based one-dimensional nanomaterials, such as nanowires, which proved to be an interesting emerging field for catalysis. Further discussion involves the state of nanowire application in coupling reactions, reduction, electrocatalysis, and photocatalysis (Fig. 3).

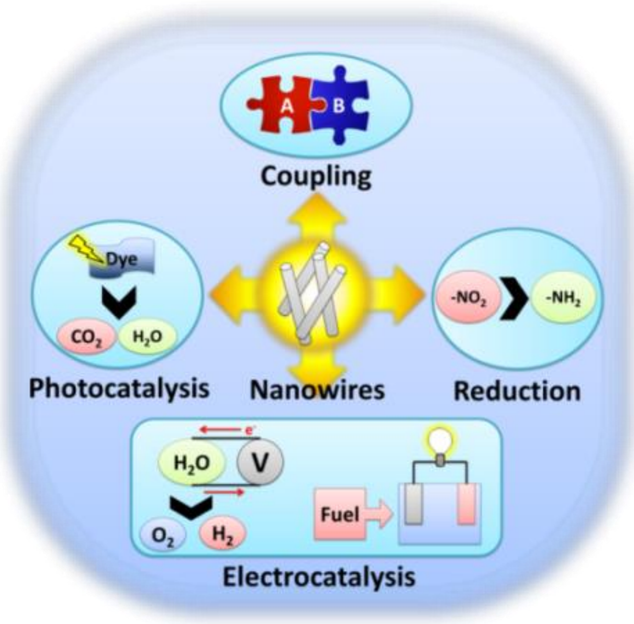

Fig. 3. Application of NWs as catalysts.

2. Aims and scope of the work

This thesis is focused on the synthesis of nanomaterials and their application as catalysts for organic chemistry reactions. Nanowires were chosen as primary nanoscale objects to study since they are not explored extensively enough in catalysis-related literature. Their composition was based on inexpensive and abundant elements such as copper, nickel, and cobalt. For improving performance of formed catalytic systems, a small amount of noble metal nanoparticles was implemented as highly active catalytic sites. The synthetic paths involved in this thesis comprised essential chemical transformations of great importance for chemical industry. The developed methods and techniques used were convenient and unsophisticated in practice which in the future could be easily scaled up. The following works described in this dissertation include:

- Synthesis of bimetallic nanowires from highly toxic industrial wastewater
- Decoration of metallic nanowires with nanoparticles to obtain composite nanocatalysts for coupling reaction to obtain small organic molecules and conjugated polymers
- Design and application of trimetallic nanocomposite as electrocatalyst for ethanol electrooxidation

Obtained nanomaterials were characterized by various techniques, which provided essential information and insight into possible assembly mechanism and their catalytic properties. The discussed results were published in reputed scientific journals, which underline the significance of the accomplished goals.

3. Results and Discussion

3.1. Recycling of heavy metals by transforming industrial wastewater into Cu-Ni nanowire composites

During my internship at Aalto University in Finland, along with scientists from the Department of Chemical and Metallurgical Engineering, I studied the synthesis of non-noble metal nanowires from industrial wastewater [P2]. Such complex mixtures are a critical issue due to high toxicity and growing volumes, however, they are also a perfect source of metal ions, which can be extracted and converted into useful materials. A schematic illustration of Cu-NiNWs synthesis process is covered in Figure 4 and nanowire growth mechanism is explained in Figure 5.

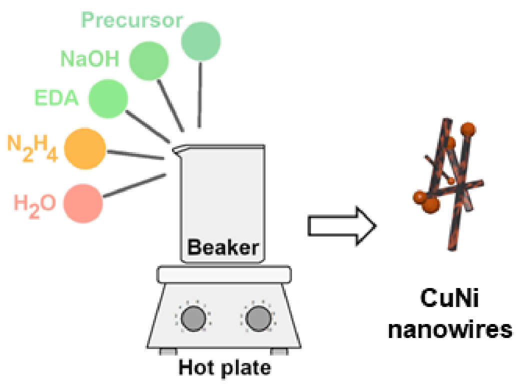

Fig. 4. Scheme of the synthesis procedure**.** Reproduced with permission from [6]. Copyright (2020) Springer Nature.

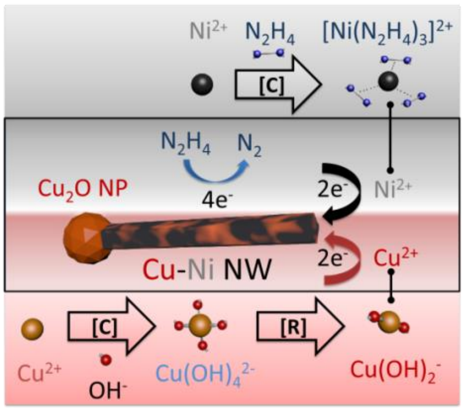

Fig. 5. Growth of a CuNi NW. [C] complexation, [R] reduction. Reproduced with permission from [6]. Copyright (2020) Springer Nature.

After tuning reaction parameters, I obtained a set of nanostructures, which allowed discovery of key parameters for proper NW growth (Fig. 6). Firstly, precursor solution concentration is crucial as an excess of metal ions leads to unwanted radial growth of spherical nanoparticles. Secondly, the length of NWs strictly depends on the reduction rate. Thirdly, the capping agent is the main factor in the anisotropic growth of NWs and must be dosed appropriately, so the full encapsulation of NWs may be omitted. Lastly, prolonged time is needed for higher conversion of starting material into advanced nanostructures. To summarize, I was able to achieve promising results by utilizing simple wet chemical reduction under controlled conditions to transform industrial wastes into nanostructures.

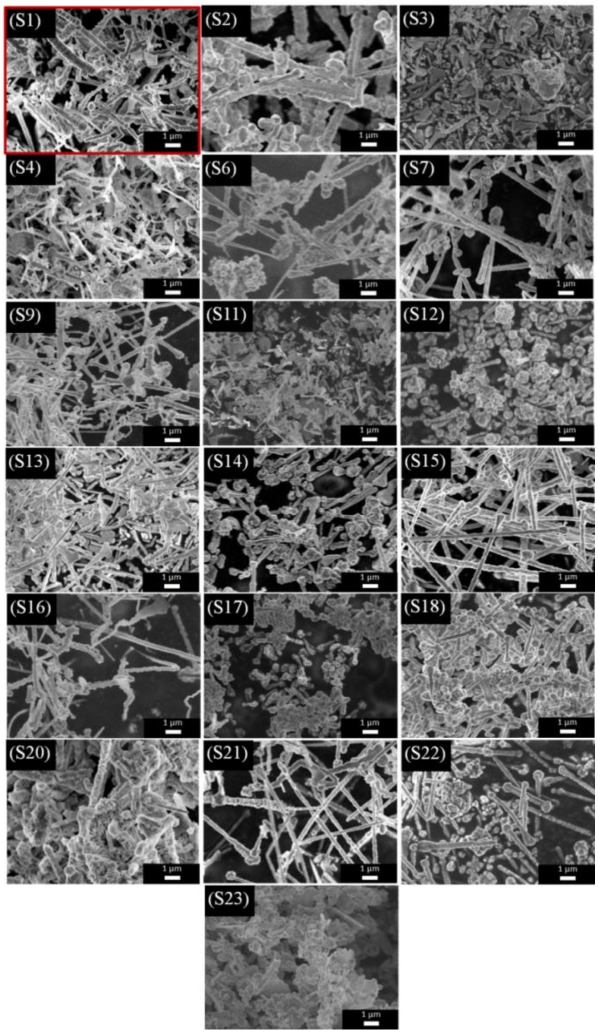

Fig. 6. SEM micrographs of the obtained selected nanostructures. SEM micrograph of the first sample produced using reference conditions is highlighted (denoted as S1 in the text). Reproduced with permission from [6]. Copyright (2020) Springer Nature.

3.2. PdNPs/NiNWs as catalytic platform for Suzuki coupling of anisole derivatives

Rapid development of catalytic platforms for coupling reactions is crucial due to their involvement in synthetic routes of fine chemicals, especially pharmaceuticals. Suzuki-Miyaura reaction is essential, as the organoboron and organohalide substrate range contains numerous easy-to-handle species. I created Pd decorated Ni NWs, which showed promising results in the catalysis of Suzuki cross-coupling process [P3]. Metallic nanowires, which acted as magnetic support material, were prepared by simple wet chemical reduction of precursor solution with hydrazine. Self-assembly of Ni atoms was enhanced by applying an external magnetic field, which improved anisotropic growth by aligning metal atoms along the field. Palladium nanoparticles were deposited on NW surfaces by sonochemical technique. Substrate scope is presented in Table 1.

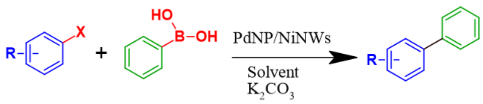

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Table 1. Suzuki coupling of various halo-derivatives with phenylboronic acid in the presence of microwaves (Reaction 1). Reproduced and modified with permission from [7]. Copyright (2023) Elsevier.

R	X	K_2CO_3 [mmol]	Temp. [°C]	Time [min]	Isolated Yield [%]	TOF [min^{-1}]
4-OMe	Br	2	70	15	48%	49.88
4-OMe	Br	1	70	15	77%	80.02
4-OMe	Br	1	90	15	95%	98.73
4-OMe	Br	1	110	15	87%	90.41
3-OMe	Br	2	70	15	96%	99.76
3-OMe	Br	1	70	15	76%	78.98
3-OMe	Br	2	90	15	100%	103.92
3-OMe	Br	2	110	15	85%	88.33
4-Me	Br	2	70	15	27%	28.06
4-Me	Br	1	70	15	18%	18.71
4-Me	Br	2	90	15	40%	41.57
4-Me	Br	2	110	15	70%	72.75
4-MeO	Br	2	70	15	0%	0.00
4-OH	Br	2	70	15	0%	0.00
4-NO_2	Br	2	70	15	0%	0.00
4-OMe	I	2	70	15	97%	100.80
4-OMe	I	1	70	15	36%	37.41
4-OMe	I	2	90	15	79%	82.10
4-OMe	I	2	110	15	85%	88.33
4-COOMe	I	2	70	15	0%	0.00

Reaction conditions: 0.75 mmol of phenylboronic acid, 0.5 mmol of aryl halide, 2 mL EtOH, 2 mL H_2O, 10 mg of nanocatalyst (0.34% Pd/NiNWs).

At first, reactions in conventional manners were carried out in DMF/water medium, however, applying a different organic solvent (ethanol), enhanced the yield of the synthesis of 4-methoxybiphenyl. This resulted also in less toxic and easier post-treatment workup due to lower boiling point of ethanol. Positive outcomes were limited by low TOF values of 1 min^{-1}, which needed to be improved. A microwave reactor was used for further study to reduce time from 24 hours to only 15 minutes, which improved TOF significantly. The parameter study resulted in enhanced yields for anisole and toluene derivatives above 80% and 70% respectively (Table 1). Other moieties such as nitro-, hydroxyl- esters, and carbonyl- were also tested, however, without any success. Therefore, it can be concluded that prepared PdNPs/NiNWs composite catalyst exhibits high selectivity towards anisoles and toluenes. I concluded that microwave irradiation plays a vital role in the catalytic cycle of studied composite nanomaterial. A more direct approach to heating the molecules was beneficial due to the removal of the temperature gradient inside the reaction mixture. This resulted in faster reaction times, as kinetics were enhanced significantly. The reaction mechanism followed a classical palladium-driven Suzuki coupling catalytic cycle (Fig. 7).

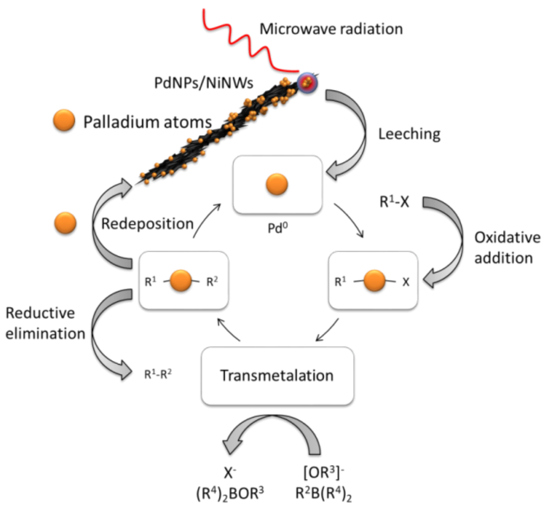


Fig. 7. Proposed mechanism for the PdNPs/NiNWs-catalyzed Suzuki cross-coupling reaction. Reproduced with permission from [7]. Copyright (2023) Elsevier.

This study showed how important nanomaterials are during the development of modern catalysts for advanced chemical transformations. Their notable catalytic activities, promoted by well-developed surface area and quantum effects can be further enhanced by synergistic effects, by alloying and composing them together into highly efficient catalytic platforms.

3.3. Nanocatalytic approach for polyfluorene derivative synthesis by applying microwave radiation to PdNPs/NiNWs catalyst

This work [P4] is an expansion of the previously presented concept of the Suzuki coupling reaction, whose promising results encouraged further research on larger chemical species. π-conjugated polymers are substances with a bountiful variety of chemical structures. They possess an interesting ability to extract specific chiralities of carbon nanotubes in solution by depositing only on the preferred species. Consequently, conjugated polymer extraction (CPE) emerged as a promising solution compared to other single-walled carbon nanotube (SWCNT) purification methods. However, conjugated polymer synthesis struggles with optimization and mass control. Inhomogeneous polymers, which differ from batch to batch hinder SWCNTs separation [8]. Therefore, crucial efforts have to be made to improve their synthesis protocols. I applied PdNPs/NiNWs as a nanotechnological approach in Suzuki polycondensation to alleviate this problem (Fig. 8). The catalyst was prepared similarly to the one in previously presented article.

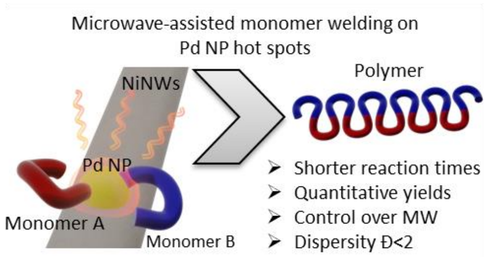
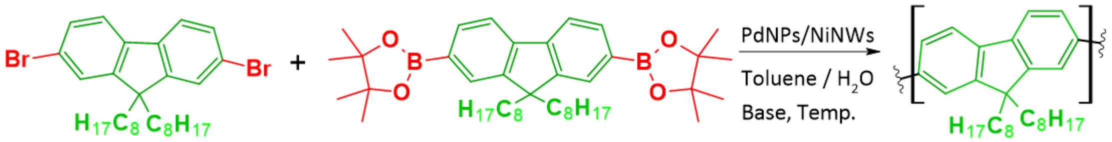


Fig. 8. Illustrative expression of key aspects of [P4]. Reproduced with permission from [9]. Copyright (2024) Springer Nature.

For investigation of catalytic properties, a fluorene-based polymer was chosen as the targeted product, precisely poly (9,9-dioctylfluorenyl-2,7-diyl) (PFO) (Reaction 2). Additionally, microwave heating was applied to reduce reaction time. However, during this research, a more detailed investigation of energy supply was conducted, by applying two different modes. A Standard Mode (SM) reached the designated temperature by varying microwave power. After that temperature oscillated around the target value with a 1°C buffer. The second mode called Solid Phase Synthesis (SPS) relied on constant power. The target temperature range was achieved under a stable supply of microwaves. A list of conducted experiments may be found below (Table 3).



(2)

Table 3. Microwave-assisted PFO synthesis via Suzuki polycondensation at Standard and SPS modes. Reproduced and modified with permission from [9]. Copyright (2024) Springer Nature.

No.	Mode	Power [W]	Base/Conc.	T [°C]	Yield [%]	TOF [h^{-1}]	M_n [kg/mol]	M_w [kg/mol]	Đ
1	SM	0-200	Na_2CO_3/1M	80	0	-	-	-	-
2	SM	0-200	Na_2CO_3/1M	110	62	1793	1.88	3.06	1.63
3	SM	0-200	Na_2CO_3/1M	130	57	1648	8.08	11.31	1.40
4	SM	0-200	K_2CO_3/1M	80	34	983	3.14	3.99	1.27
5	SM	0-200	K_2CO_3/1M	110	69	1995	5.25	8.45	1.61
6	SM	0-200	K_2CO_3/1M	130	75	2168	4.56	6.61	1.45
7	SPS	80	Na_2CO_3/1M	75-80	0	-	-	-	-
8	SPS	80	Na_2CO_3/1M	105-110	82	2371	8.32	16.31	1.96
9	SPS	80	Na_2CO_3/1M	125-130	41	1185	4.95	6.68	1.35
10	SPS	80	K_2CO_3/1M	75-80	51	1475	3.45	4.59	1.33
11	SPS	80	K_2CO_3/1M	105-110	69	1995	6.61	11.90	1.80
12	SPS	80	K_2CO_3/1M	125-130	60	1735	6.19	8.66	1.40
13	SPS	100	Na_2CO_3/1M	105-110	88	2544	14.32	25.99	1.82
14	SPS	120	Na_2CO_3/1M	105-110	78	2255	8.37	12.67	1.51

Reaction conditions: 0.12 mmol of diarylbromide, 0.12 mmol of diarylboronate ester, 2 mL of base solution, 2 mL of toluene, 1 drop of Alliquat 336, and 10 mg of PdNPs/NiNWs catalyst. The reaction was carried out for 1 hour. The degree of polymerization was estimated by dividing M_n by monomer mass (0.388 kg/mol).

In both microwave modes, reaction times were shortened from 3 days of conventional heating down to 1 hour. In most conducted experiments, polymer yields exceeded 60%. By tuning certain conditions such as temperature, heating mode, or base, a strong connection to molecular weight and yield was observed. This study showed how the development of a new catalytic system can improve conjugated polymer synthesis. Quantitative yields proved the high activity of the presented catalyst. A wide range of molecular weights suggests possible tuning and optimization opportunities, which can lead to even more controlled polycondensation. It is worth mentioning that this was the first attempt at using such a catalytic system in this kind of reaction. In addition to catalysis studies, obtained polymers were exploited in CPE protocols, in which an enriched (7,5) SWCNT chirality fraction was successfully extracted from polychiral raw material by wrapping them with the said polymer.

3.4. Pd/Co-NiNWs as catalytic solution for direct ethanol fuel cells

The last work [P5] of this monothematic cycle is connected to electrocatalysis. Green and sustainable sources of electric power are a common focus of numerous studies, due to the never-ending electricity demand driven by the continuous development and growth of the human population. Direct extraction of electrical energy from stored sources can be achieved in fuel cells. Recently, this topic has become a crucial issue due to ecological regulations regarding fossil fuel exploitation. Alcohol electrooxidation is considered an alternative source of electricity for small devices and in the automobile industry. I participated in study of cobalt-nickel nanowires decorated with palladium nanoparticles, which revealed promising properties towards ethanol electrooxidation. During synthesis, nanostructures with various metal compositions were obtained. STEM images (Fig. 9) showed that a higher concentration of Co nanowires created a bead-like anisotropic structure, whereas the increase of Ni content created spikes along the surface. Those features had a key influence on nanowire surfaces and therefore, controlled palladium nanoparticle deposition.

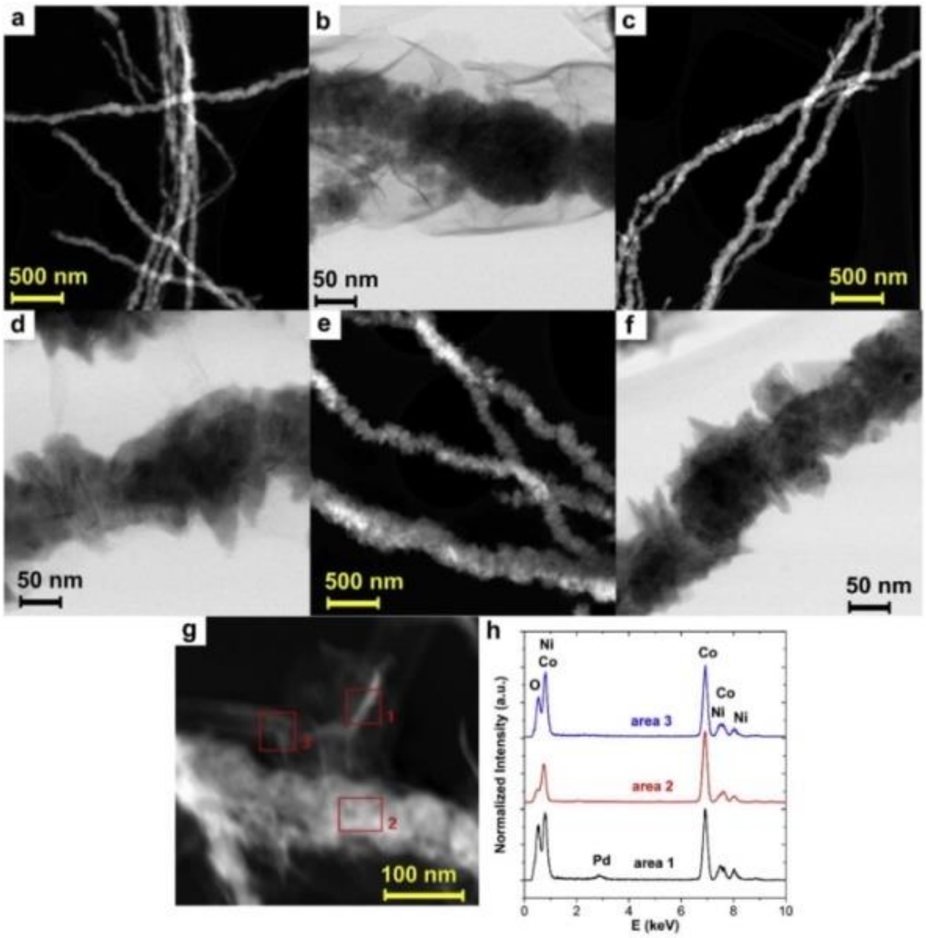


Fig. 9. STEM (a-g) images of CoNi NWs; h – EDX spectra of selected sample. Reproduced with permission from [10]. Copyright (2022) Elsevier.

To investigate catalytic activity towards application in fuel cells, ethanol electrooxidation was focused as a research subject, due to low toxicity and inexpensive sources of such fuel. The addition of ethanol into the electrolyte solution was followed by Ar bubbling in order to remove dissolved oxygen. The lowest catalytic activity was recorded for Co_5-Ni_5 and Co_9-Ni_1 samples. Passivated by plate-like oxides, the nanowire core was separated from PdO_2 deposited on the edges of those structures, which hindered the synergistic effect of the catalytic platform. On the other hand, Co_3-Ni_7 samples gave the highest mass activities due to the appropriate contribution of Ni(Co) cubic and highly disordered $Co_{0.75}Ni_{0.25}$ phases (5252 mA/mg_{Pd} for 0.5 mM Pd precursor and 8003 mA/mg_{Pd} for 0.75 mM) (Fig. 10).

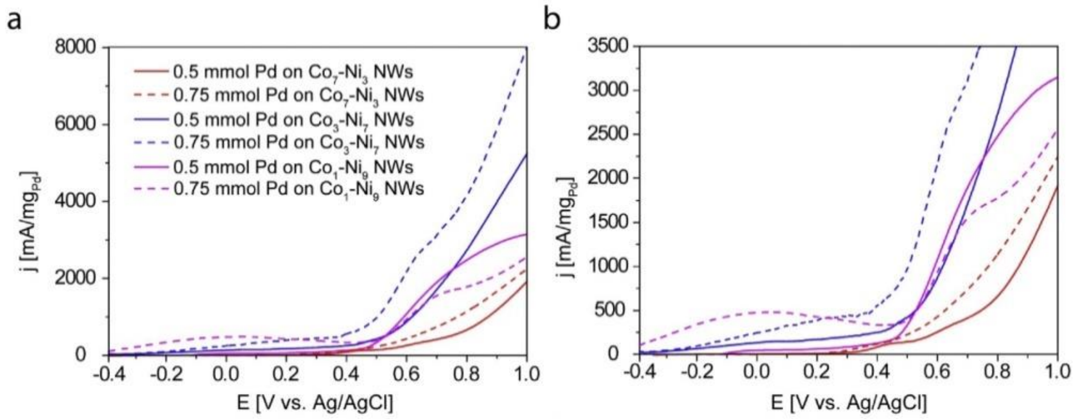


Fig. 10. (a) Comparison of the cyclic voltammograms of electrocatalysts in the form of cobalt-nickel nanowires with different Co:Ni ratios decorated by Pd in argon-saturated 1.0 M NaOH + 0.5 M CH_3CH_2OH solution at a scan rate of 20 mV/s; (b) plot showing an enlargement of the data between 0 and 3500 mA/mg_{Pd}. Reproduced and modified with permission from [10]. Copyright (2022) Elsevier.

The presented work showed a strong correlation between the morphology of support nanostructure and the crystallization of noble metal. The phase composition of Co-Ni nanowires controlled the way of decoration with palladium by preferring oxidized or metallic forms of nanoparticles. As a result, the catalytic properties of the final nanocomposite could be optimized to meet requirements for highly active and durable catalytic systems for specified applications. Obtained findings unravel a part of mechanisms, which drive the deposition of palladium species on metal-based anisotropic nanomaterials and reveal new opportunities for studies in the future.

4. Conclusions and further perspective

This dissertation was focused on a nanotechnological approach for catalysis-related chemical transformations. As a main target, the application of nanowires as catalysts was explored. The introduction section highlighted the most common routes for the synthesis of such anisotropic nanostructures and their participation in catalytical studies of various chemical reactions. Literature showed how nanowires impact the modern development of catalysis, in which their contribution exhibits promising results in many fields such as organic chemistry, electrocatalysis, and photocatalysis. However, there are still countless compositions of nanowires, which are waiting for proper characterization and may find an intriguing and prosperous application in this area and beyond.

At this stage, the main targets for nanowires are electronic devices, while other fields of exploitation such as catalysis remain to be explored to a more satisfactory extent. Presented outcomes of long-term research confirmed the significance of nanowires in catalysis and their properties, proving that subsequent research in this area is strongly advised. Further study of the topics discussed in this dissertation should focus on expanding the scope of metallic nanowires and nanoparticles as well as their bimetallic counterparts. Additional interest should be devoted to non-noble metals such as Ni, Cu, or Fe, whose abundance and low price are major benefits for the convenient production of nanomaterials. Synergistic effects of numerous composites may reveal enhanced catalytic properties in presented fields of catalysis. Moreover, other application opportunities should be exploited to attract more attention of scientific and industrial communities. For instance, processes in the gaseous phase or plasma-enhanced synthesis should also be considered, as they could gain from the catalytic properties of such nanomaterials. The study of nanowires in catalysis is an enormous blank spot in science, which should be addressed with high priority, as those nanomaterials have the potential to revolutionize this research field.

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6. Wasiak, T., Hannula, P.-M., Lundström, M. & Janas, D. Transformation of industrial wastewater into copper-nickel nanowire composites: straightforward recycling of heavy metals to obtain products of high added value. *Sci. Rep.* **10**, Article 19190 (2020).

7. Wasiak, T., Łukowiec, D., Wacławek, S., Kubacki, J. & Janas, D. Ni nanowires decorated with Pd nanoparticles as an efficient nanocatalytic system for Suzuki coupling of anisole derivatives. *Nano-Structures & Nano-Objects* **36**, 101052 (2023).

8. Ouyang, J. *et al.* Impact of Conjugated Polymer Characteristics on the Enrichment of Single-Chirality Single-Walled Carbon Nanotubes. *ACS Appl. Polym. Mater.* **4**, 6239–6254 (2022).

9. Wasiak, T. *et al.* PdNPs/NiNWs as a welding tool for the synthesis of polyfluorene derivatives by Suzuki polycondensation under microwave radiation. *Sci. Rep.* **14**, 2336 (2024).

10. Łukowiec, D. *et al.* Pd decorated Co–Ni nanowires as a highly efficient catalyst for direct ethanol fuel cells. *Int. J. Hydrogen Energy* **47**, 41279–41293 (2022).

Academic achievements

1. Publications

1.1. T. Siudyga, M. Kapkowski, D. Janas, T. Wasiak, R. Sitko, M. Zubko, J. Szade, K. Balin, J. Klimontko, D. Lach, J. Popiel, A. Smoliński, J. Polanski, Nano-Ru Supported on Ni Nanowires for Low-Temperature Carbon Dioxide Methanation, Cat. 10 (2020) 513. https://doi.org/10.3390/catal10050513

1.2. [P2] T. Wasiak, P.-M. Hannula, M. Lundström, D. Janas, Transformation of industrial wastewater into copper-nickel nanowire composites: straightforward recycling of heavy metals to obtain products of high added value, Sci. Rep. 10 (2020) Article 19190. https://doi.org/10.1038/s41598-020-76374-x

1.3. [P5] D. Łukowiec, T. Wasiak, D. Janas, E. Drzymała, J. Depciuch, T. Tarnawski, J. Kubacki, S. Wacławek, A. Radoń, Pd decorated Co–Ni nanowires as a highly efficient catalyst for direct ethanol fuel cells, Int. J. Hydrogen Energy (2021). https://doi.org/10.1016/j.ijhydene.2021.11.177

1.4. [P1] T. Wasiak, D. Janas, Nanowires as a versatile catalytic platform for facilitating chemical transformations, J. Alloys Compd. 892 (2022) 162158. https://doi.org/10.1016/j.jallcom.2021.162158

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2. **Research projects**

04.2018 – 12.2021

Co-Investigator in the project "Nanohybr1Ds: Hybrids composed of carbon nanotubes and metallic nanowires for harvesting energy from waste heat" (LIDER/0001/L8/16/NCBR/2017), LIDER 9, Principal Investigator: Dawid Janas Ph.D. DSc, source of funding: National Center of Research and Development, amount of funding: 1 199 995 zł.

3. **Pending patents**

T. Wasiak, D. Janas, *Method of producing hybrid materials and carbon nanomaterials*, application no: P.435987 (submission date: 16.11.2020)

4. **Internships**

4.1. 05.08 – 30.08.2019: Aalto University in Espoo (Finland)

4.2. 11.03 – 08.04.2023: Indian Institute of Technology in Roorkee (India)

5. **Conferences**

5.1. InterNanoPoland, Katowice, Poland, 14-15.04.2021, Poster: *Copper-nickel nanocomposites originating from industrial wastes as a modern approach in recycling*, T. Wasiak, P-M. Hannula, M. Lundström, D. Janas

5.2. International Conference on the Science and Application of Nanotubes and Low-Dimensional Materials NT21, Houston, USA, 6-11.06.2021, Poster: *Complex industrial waste solutions as an alternative source of metal ions for copper-nickel nanocomposites,* T. Wasiak, P-M. Hannula, M. Lundström, D. Janas

5.3. IEEE NAP, Bratislava, Slovakia, 10-15.09.2023, Poster: *Nickel nanowires decorated with palladium nanoparticles as powerful catalysts facilitating synthesis of polyfluorene derivatives by Suzuki polycondensation*, T. Wasiak, D. Just, A. Dzienia, D. Łukowiec, S. Wacławek, A. Mielańczyk, D. Janas