

Original Research

PRODUCTION COST ASSESSMENT OF SnO₂-MWCNT@SS ELECTRODE FOR WASTEWATER TREATMENT

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Abstract

The rising concern over environmental pollution has catalyzed advances in wastewater treatment technologies, particularly advanced oxidation processes (AOPs). These processes are effective for degrading harmful organic pollutants such as bisphenol A (BPA) through electrochemical systems, leveraging the unique properties of nanostructured electrodes like SnO₂-MWCNT@SS (tin dioxide-multiwall carbon nanotube at stainless steel substrate). However, the economic feasibility of producing such innovative materials is as crucial as their performance. This paper presents the cost analysis of producing SnO₂-MWCNT@SS electrodes, evaluating its competitiveness against other commercial materials and the economic implications of transitioning to industrial-scale production.

Keywords: advanced oxidation, nanostructured anodes, SnO₂-MWCNT, cost production.

INTRODUCTION

Advanced oxidation processes (AOPs) have gained significant attention as effective technologies for treating wastewater contaminated with organic pollutants [1,2]. These processes degrade organic molecules through oxidation, primarily utilizing hydroxyl radicals generated in electrochemical systems [3]. The generation and activity of these radicals are inherently linked to the properties of the anode material employed in the treatment process [4]. Recent studies have indicated that the degradation efficiency of various pollutants, such as bisphenol A (BPA), can be optimized through the careful selection of anode materials, which can include noble and transition metals, metal oxides [5], and carbon-based nanoparticles like carbon nanotubes (CNTs) and graphene oxide [6].

In line with recent trends, our research group investigated one particularly promising composite, the tin dioxide-multiwall carbon nanotube (SnO₂-MWCNT), which was synthesized with the intention of combining the high conductivity and surface area of MWCNTs with the catalytic properties of SnO₂ [7]. When deposited on a stainless steel

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substrate, nanostructured anode, termed SnO₂-MWCNT@SS, has been designed and utilized in degrading BPA, demonstrating robust performance in both classic electro-oxidation and the electro-Fenton process [7,8]. Results highlighted its effectiveness for organic pollutant degradation, comparable to the currently favored boron-doped diamond (BDD) electrodes.

Understanding the economic viability of the SnO₂-MWCNT@SS anode requires a close examination of the associated production costs. In this study, the costs associated with the preparation of SnO₂-MWCNT@SS were estimated to assess the economic feasibility of its production and its competitiveness with other commercially available electrodes. The cost calculations reflect laboratory-scale production based on current market prices for energy and materials. The comprehensive breakdown of production costs allows for a clear understanding of the financial investments required at the laboratory scale, which sets a foundation for assessing industrial viability.

MATERIALS AND METHODS

Following the procedure detailed in our previous study [7], the production of SnO₂-MWCNT@SS involves three primary phases: (i) functionalization of MWCNTs, (ii) synthesis of SnO₂ nanoparticles, and (iii) preparation of the SnO₂-MWCNT nano-composite and its deposition onto an SS substrate. The preparation process yielded approximately 10 cm² of SnO₂-MWCNT@SS electrode per production cycle.

Each phase's costs reflect both the energy consumption and the reagents utilized, with total costs calculated according to Equation 1. The total production cost was estimated as the sum of the expenditures on energy and reagents required to produce 1 cm² of SnO₂-MWCNT@SS under laboratory conditions.

$$\text{Total costs} = C_{\text{fMWCNT}} + C_{\text{nano-SnO}_2} + C_{\text{SnO}_2\text{-MWCNT@SS}} \quad (1)$$

The production costs of each phase, denoted as C_{fMWCNT} , $C_{\text{nano-SnO}_2}$, and $C_{\text{SnO}_2\text{-MWCNT@SS}}$, respectively, were estimated using Equation (2) [9]:

$$\text{Production costs (C)} = \sum \text{Energy costs} + \sum \text{Reagents costs} \quad (2)$$

The sources providing the prices of energy and reagents used in SnO₂-MWCNT@SS preparation are listed in Table 1.

Table 1 Consumer prices of energy and reagents used in the cost analysis (Consumer price list)

No	Consumer	Price
1	Electricity	0.1867 €/ kWh
2	MWCNT	17.32 €/ g
3	Nitric acid, 3 M	141.60 €/ L
4	Deionized water	18.60 €/ L
5	Hydrogen peroxide, 30 %	31.50 €/ L
6	Tin (II) chloride dehydrate	0.286 €/ g
7	Ammonia solution, 25 %	26.60 €/ L

Table 2 continued

8	Silver nitrate, 1 M	124.00 €/ L
9	Glacial acetic acid, 100 %	36.52 €/ L
10	Ethylene glycol	54.20 €/ L
11	Air	3.429 €/ m ³
12	Dimethylformamide	50.40 €/ L
13	Distilled water	1.00 €/ L
14	Acetone	39.00 €/ L
15	SS substrate	0.036 €/cm ²

RESULTS AND DISCUSSION

Cost of MWCNT functionalization

To initiate the production of SnO₂-MWCNT composite, MWCNTs must be effectively functionalized to enhance their interaction with metal oxides. Under laboratory conditions, approximately 20 g of functionalized MWCNT (fMWCNT) was prepared per production cycle. The cost for producing 1 mg of fMWCNT was estimated to be approximately 0.4 € (Table 2). The costs include the purchase of reagents such as nitric acid, hydrogen peroxide, and deionized water, along with energy consumption for mixing and drying processes, which collectively demonstrate that reagent costs dominate this phase. This high material cost underscores the importance of effective source management to optimize overall expenditure.

Table 3 Cost breakdown for producing 1 mg of functionalized MWCNT

STEP	Consumer	Consumption per cycle	Cost, €/ mg	No *
Mixing	MWCNT	25 mg	0.02165	2
Mixing	Nitric acid, 3 M	25 ml	0.177	3
Mixing	Stirrer (1.05 kW)	1.5 h at 70 °C	0.014702625	1
Washing 1	Deionized water	50 ml	0.0465	4
Dissolving	Hydrogen peroxide, 30 %	40 ml	0.063	5
Sonification	Ultrasonic bath (0.161 kW)	15 min at 25 °C	0.000375734	1
Washing 2	Deionized water	50 ml	0.0465	4
Drying	Oven (1.6 kW)	2 h at 75 °C	0.029872	1
TOTAL			0.399600359	

* No in Consumer price list (Table 1)

Cost of SnO₂ nanoparticles synthesis

The synthesis of SnO₂ nanoparticles was the second production phase, with an estimated cost of 3.96 € per gram of product (Table 3). The synthesis efficiency was approximately 80%, suggesting areas for cost reduction through improved methodologies or economies of scale. Therefore, similar to MWCNT functionalization, surpassing the financial limitations of raw materials and energy remains essential for a cost-efficient production model.

Table 4 Cost breakdown for producing 1 g of SnO₂ nanoparticles

STEP	Consumer	Consumption per cycle	Cost, €/ g	No*
Dissolving	Tin (II) chloride dehydrate	2.26 g	0.3575	6
Dissolving	Deionized water	20 ml	0.205752212	4
Dissolving	Ammonia solution, 25 %	2 ml	0.029424779	7
Washing	Ammonia solution, 25 %	2 ml	0.029424779	7
Washing	Silver nitrate, 1 M	1 ml	0.068584071	8
Mixing	Glacial acetic acid, 100%	2 ml	0.04039823	9
Mixing	Ethylene glycol	0.839 ml	0.025151438	10
Mixing	Stirrer (1.05 kW)	1 h at 70 °C	0.108426438	1
Drying	Oven (1.6 kW)	12 h at 120 °C	1.982654867	1
Annealing	Furnace (3.5 kW)	1 h (ramping)	0.36142146	1
Annealing	Furnace (3.5 kW)	2 h at 600 °C	0.72284292	1
Annealing	Air	3 h	0.010241482	11
Cooling	Air	3 h	0.010241482	11
TOTAL			3.958891814	

* No in Consumer price list (Table 1)

Cost of SnO₂-MWCNT@SS electrode preparation

The final preparation stage integrates the functionalized MWCNT and synthesized SnO₂ nanoparticles onto a stainless steel substrate. The total cost of producing 1 cm² of SnO₂-MWCNT@SS electrode is remarkably low, estimated at just 0.1579 €. The breakdown of costs for producing 1 cm² of SnO₂-MWCNT@SS electrode is presented in Table 4. The major costs are associated with reagents processing (Mixing step) and electrode preparation (other steps).

Table 5 Cost breakdown for producing 1 cm² of the SnO₂-MWCNT@SS electrode

STEP	Consumer	Consumption per cycle	Cost, €/ cm ²	No*
Mixing	nano-SnO ₂	3.5 mg	0.001386	2
Mixing	fMWCNT	1 mg	0.04	3
Mixing	Dimethylformamide	1 ml	0.00504	12
Mixing	Ultrasonic bath (0.161 kW)	5 h	0.01502935	1
Washing	Distilled water	10 ml	0.001	13
Washing	Acetone	10 ml	0.039	14
Washing	Deionized water	10 ml	0.0186	4
Coating	SS substrate	10 cm ²	0.036	15
Drying	IC lamp (0.3 kW)	20 min	0.001867	1
TOTAL			0.15792235	

* No in Consumer price list (Table 1)

The cost distribution is illustrated in Figure 1(a), while the contributions of energy and reagents to the total cost are shown in Figure 1(b). A comparison of the estimated cost with the price of similar commercial materials is presented in Figure 1(c).

The calculated production costs of SnO₂-MWCNT@SS electrode with all required commodities reveal a significant potential for market competitiveness. Figure 1(a) indicates that reagents treatment for nanomaterial preparation accounts for over 60 % of total costs. The stainless steel substrate emerges as an essential cost driver, representing over 35 % (37.32 %) of the electrode preparation costs. Interestingly, energy utilization accounts for only 14.25 %

of the total production cost (Figure 1 (b)), confirming that the process is energy efficient and primarily dependent on raw materials. This finding also emphasizes the importance of selecting low-cost yet high-performance materials to enhance overall production efficiency.

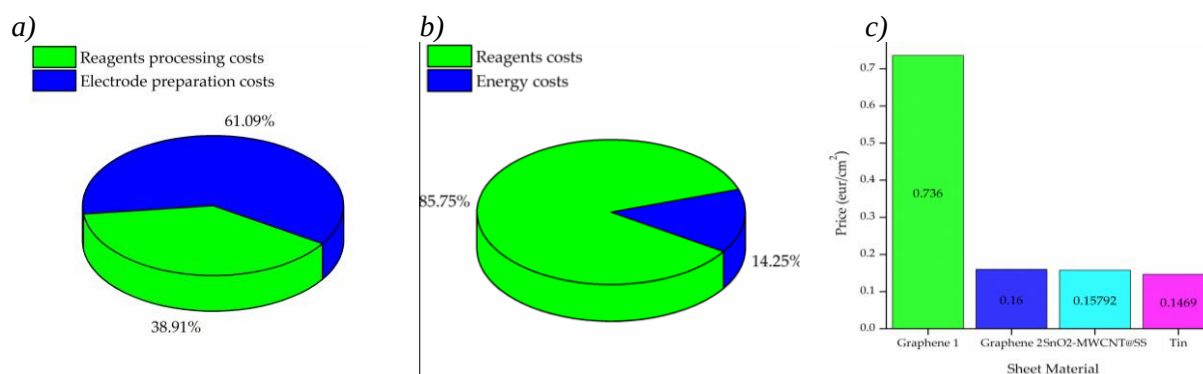


Figure 1 Breakdown of total production costs for the SnO₂-MWCNT@SS electrode: a) comparison of reagent processing costs vs. electrode preparation costs; b) contribution of energy vs. reagent costs; c) cost comparison with similar commercial products

As shown in Figure 1(c), when benchmarked against the price of similar carbon-based materials such as graphene sheets, SnO₂-MWCNT@SS exhibits costs that are approximately 1.30 – 78.54 % lower. The cost is also comparable to commercial tin sheets, with only a 7.50% price increase. Notably, SnO₂-MWCNT@SS is 94.28 % (or 17.5 times) cheaper than commercially available graphite plate electrodes for flow electrolysis cells. This comparative analysis not only validates the economic benefits of SnO₂-MWCNT@SS production but also signals a potential shift in industry practices, favoring the adoption of cost-effective nanostructured anodes over traditional materials.

CONCLUSION

When analyzing the input costs and following the methodology for lab-scale production, initial estimates suggest that the production and use of SnO₂-MWCNT@SS is economically feasible, especially when compared with BDD electrodes, which involve significantly higher production costs due to complex synthesis techniques and material expenses. The assessed production costs demonstrate strong potential for competing with existing commercial alternatives while maintaining advanced performance capabilities and enhancing the efficiency of organic pollutant degradation processes. Furthermore, the anticipated cost reductions achievable via larger-scale production with technical-grade reagents would increase the attractiveness of these electrodes, making them a viable solution for addressing environmental concerns. Finally, the production of SnO₂-MWCNT nano-composite and its use as a coating can also be economically beneficial in extending the lifetime of existing SS electrodes, solidifying the role of SnO₂-MWCNT@SS in sustainable wastewater treatment solutions.

In conclusion, the SnO₂-MWCNT@SS anode represents a significant development in the field of advanced oxidation processes for wastewater treatment. Its low production costs combined with demonstrated high efficacy in degrading BPA suggest that it possesses robust

potential in competing with existing electrode materials. As the field of electrochemical technologies continues to evolve, the economic viability and effectiveness of SnO₂-MWCNT@SS will likely make it a crucial in achieving effective wastewater treatment solutions in the near future.

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