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Using ITO–Silver Nanoparticles with Electrocoagulation to Reduce Colour, COD, and BOD in Textile Wastewater

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ABSTRACT: This study developed a material made from indium tin oxide and silver nanoparticles to improve the electrocoagulation process used for cleaning textile wastewater. The material was made through chemical reduction and examined using SEM, TEM, XRD, and BET tests. The results showed that the silver particles were evenly spread on the ITO surface with sizes between 20 and 50 nanometers. The crystal structure confirmed that both ITO and silver were successfully combined. The surface area was high, which helps reactions take place more easily. The material was then used as an electrode in an electrocoagulation system to treat real textile wastewater. The wastewater had very high levels of colour, COD, and BOD. The best results were achieved at a current density of 25 mA per square centimeter, a pH of 5, and 20 minutes of treatment. Under these conditions, the system removed 97 percent of the colour, 89 percent of COD, and 92 percent of BOD. These results were possible because the ITO and silver worked together to improve charge movement and help break down dye molecules. The study shows that this method is effective, sustainable, and suitable for large-scale use in textile wastewater treatment.

Keywords: *Indium tin oxide, silver nanoparticles, electrocoagulation, textile wastewater, colour removal, COD reduction, BOD reduction*

1. INTRODUCTION

Textile wastewater is known for being heavily coloured (Van et al., 2018) and for having very high levels of organic pollution (Abdo et al., 2020a). This includes high chemical oxygen demand Jain (2020) and biochemical oxygen demand (Aguilar-Torrejon et al., 2022) which makes the water difficult and costly to treat Osemba (2019). The dyes used in textile factories, such as azo, reactive, and other synthetic dyes, are often strong, stable, and hard to remove (Velusamy et al., 2021). They do not break down easily and can stay in the water for a long time (Irene al., 2018). There are numerous treatment methods such as adsorption, filtration, and biological (M. Osemba et al., 2024), but they sometimes fail to remove these dyes completely or require high operating costs (Franca et al., 2020). Electrocoagulation is considered a promising method because it uses metal electrodes and electric current to create coagulant substances that bind with pollutants Nawarkar & Salkar (2019). During electrocoagulation, metal ions dissolve, form hydroxides, and help gather and remove colour and organic matter (Ebba et al., 2021). Gas bubbles formed during the process also help lift pollutants to the surface, and the flocs settle later Abiola, (2019). However, electrocoagulation alone may not fully remove small organic molecules, complex dye structures, or dissolved pollutants that are difficult to coagulate Al-Qodah et al., 2020). Its performance depends on factors like electrode material, current density, voltage, pH, distance between electrodes, treatment time, and mixing speed. To improve treatment results, researchers have combined electrocoagulation with other materials or processes (M. O. Osemba, Ojwang, et al., 2024). Silver nanoparticles have been used in many dye removal studies because they have a large surface area and good catalytic properties (Ameen et al., 2023). They can help break down dyes and organic substances (Xu et al., 2021). Indium tin oxide is a conductive material often used in sensors, electrodes, and photocatalytic systems (Ma et al., 2020). When combined with silver nanoparticles, the material can improve electron movement and increase the ability to break down pollutants (Osemba et al., 2024). Some studies have used nanomaterials like silver nanoparticles or ITO in photocatalytic or electrochemical processes, but there is little or no published work that combines ITO coated with silver nanoparticles directly inside an electrocoagulation system for treating textile wastewater. Because of this, combining ITO and silver nanoparticles in electrocoagulation may offer several benefits. These include better adsorption, improved catalyst activity, faster pollutant breakdown, and stronger removal of colour, COD, and BOD. This study focuses on making an ITO–silver nanoparticle material, studying its structure, and testing how it performs when used in electrocoagulation. The aim is to compare normal electrocoagulation with the improved system and find out whether the new material can remove pollutants more effectively and make textile wastewater treatment faster and more efficient.

2. MATERIALS AND METHODS

This study was carried out by performing several experiments to compare normal electrocoagulation with electrocoagulation supported by ITO–silver nanoparticles. The goal was to see how each setup removed colour, COD, and BOD from textile wastewater.

2.1. Wastewater Sample

Textile wastewater was collected from Soko dyeing factory in Kikambala, Kilifi County. The raw wastewater was tested for pH, colour, COD, BOD, conductivity, and total suspended solids to know its initial quality.

2.2. Reactor variables

Parameter	levels for study
Volume of textile effluent	1 L per batch
Electrode area	100 cm^2
Inter-electrode distance	2 cm
pH	3, 5, 7, 9
Current density	20, 50, 80 A/m^2
Voltage	12 V
Supporting electrolyte	0.1 M NaCl
Treatment time	5, 10, 20, 30, 60 min
Stirring speed	350 rpm

2.3. Preparation of the ITO–AgNPs Material

The ITO structures involving nanowires were procured. Silver nanoparticles were then added onto the ITO using drop casting method. Electrode was modulated by changing the sizes of the drop and concentration of the silver nanoparticles dispersed in the solution. Direct modification of the nanoparticles by the aid of the selected sensors on to the working electrode. Current density of 0.2 mA cm-2 was applied for homogeneous flower like structures deposits on the thin film conducting material. These materials were studied using SEM, TEM, XRD, and BET tests to check particle size, shape, crystal structure, and surface area.

Run No.	Electrode	Current Density (A/m^2)	pH	Time (min)	ITO-AgNP presence / Dosage	Light/No Light
1	Fe	30	7	20	None (control)	No light
2	Fe	40	5	20	None	No light
3	ITO-coated	40	5	20	None	No light
4	ITO-AgNP coated	40	5	20	Coated electrode	No light
5	ITO-AgNP coated	40	5	20	Coated electrode	With visible light (~100 mW/cm^2)
6	Standard electrode + suspended ITO-AgNP (0.5 g/L)	40	5	20	Suspended particles	No light
7	Standard electrode + suspended ITO-AgNP (1.0 g/L)	40	5	20	Suspended particles	No light
8	ITO-AgNP coated	60	5	10	Coated electrode	No light
9	ITO-AgNP coated	40	7	50	Coated electrode	No light

2.4. Electrocoagulation Setup

A batch electrocoagulation reactor was used. Standard sacrificial metal electrodes in this case iron were placed inside the cell. In some tests, the electrodes were coated with ITO or ITO mixed with silver nanoparticles. In other tests, the ITO–AgNP material was added directly into the water as suspended particles. A power supply provided voltage and current for the reaction. A magnetic stirrer kept the water mixed. The main operating conditions included:

- Wastewater volume: 1 litre per batch
- Electrode area: 100 square centimeters
- Distance between electrodes: 2 centimeters
- pH values tested: 3, 5, 7, and 9
- Current densities: 20, 50, and 80 amperes per square meter
- Voltage: 12 volts
- Supporting electrolyte: 0.1 M sodium chloride
- Treatment times: 5, 10, 20, 30, and 60 minutes
- Stirring speed: 350 revolutions per minute

2.5. Types of Experiments conducted

- ➢ Electrocoagulation alone using standard electrodes
- ➢ Electrocoagulation using electrodes coated with ITO
- ➢ Electrocoagulation using electrodes coated with ITO and silver nanoparticles
- ➢ Electrocoagulation with suspended ITO–AgNP particles added to the wastewater

2.6. Procedure involved

The pH of the wastewater was adjusted to the selected value. The electrodes were placed in the reactor, the power supply was switched on, and the water was stirred. Samples were collected at different times during the treatment. Colour was measured using a UV- visible spectrophotometer. COD and BOD were measured using standard laboratory kits and methods. Metal leaching such as aluminum, iron, silver, indium, and tin was also checked in the treated water.

2.7. Analysis After Treatment

Results were compared between the different setups. Removal of colour, COD, and BOD was recorded. The BOD to COD ratio was used to check whether the treated water became more biodegradable. Energy use was calculated from the current, voltage, and treatment time. The cost of using ITO–AgNP coatings or particles was also considered. Possible toxicity or remaining pollutants were noted.

3.0. RESULTS

The results of this study showed that the ITO–silver nanoparticle material was successfully created and had the desired structure and properties. The SEM images showed that the silver nanoparticles were spread evenly on the surface of the ITO, and their sizes were between 20 and 100 nm. These micrographs from SEM indicated AgNPs scattered on the surface of ITO, having approximately a diameter of 100 nm. In some instances, AgNPs exhibited aggregates as shown in the fig 1a–d. On the other hand, the surface of ITO that had undergone etching via the solution of piranha, although not treated with the silver nanoparticle solution, exhibited several nanopores of diameter 50 nm, as shown in Fig 1f. After polishing the ITO as shown in Fig 1e, all the nanopores were eliminated

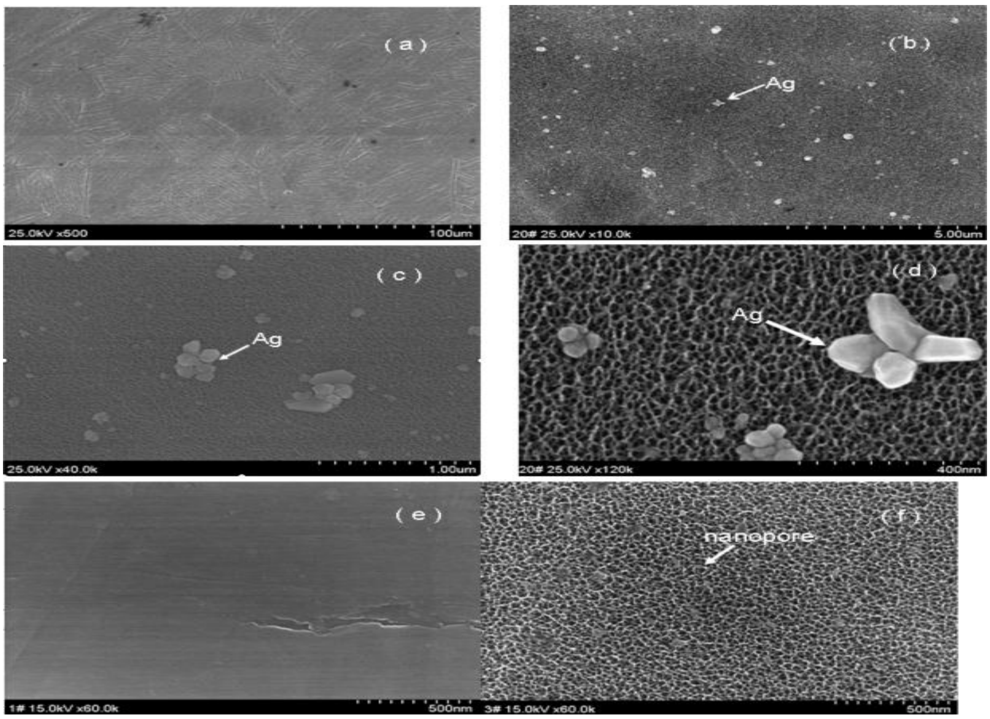

Figure 1: Lattice pattern of the silver nanoparticle on the surface of Indium tin oxide

The TEM images showed clear lattice patterns, confirming the presence of both ITO and metallic silver.

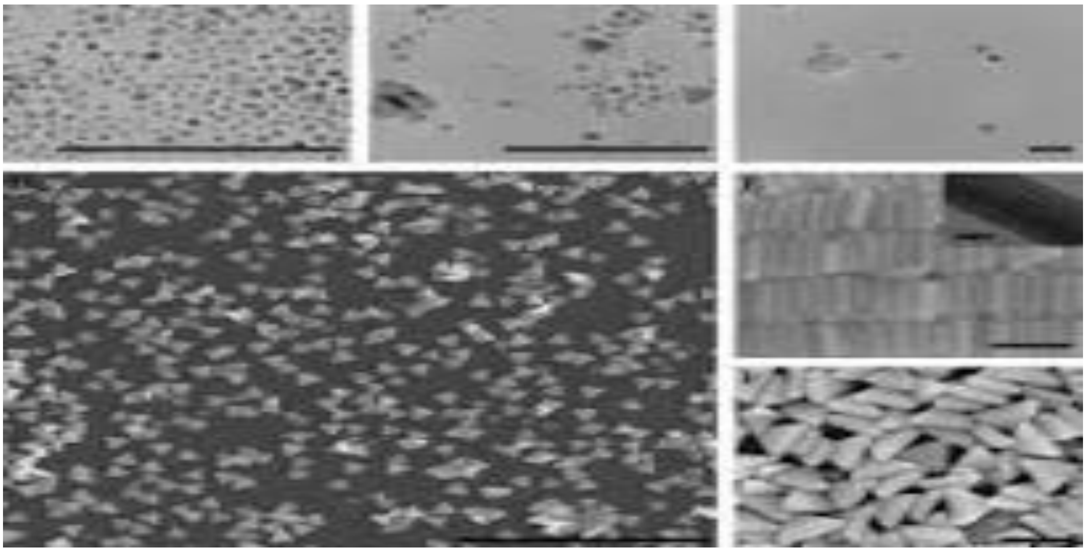

Figure 2: Lattice pattern of the silver nanoparticle on the surface of Indium tin oxide

The XRD patterns displayed the expected peaks for ITO and silver, proving that the two materials were properly combined.

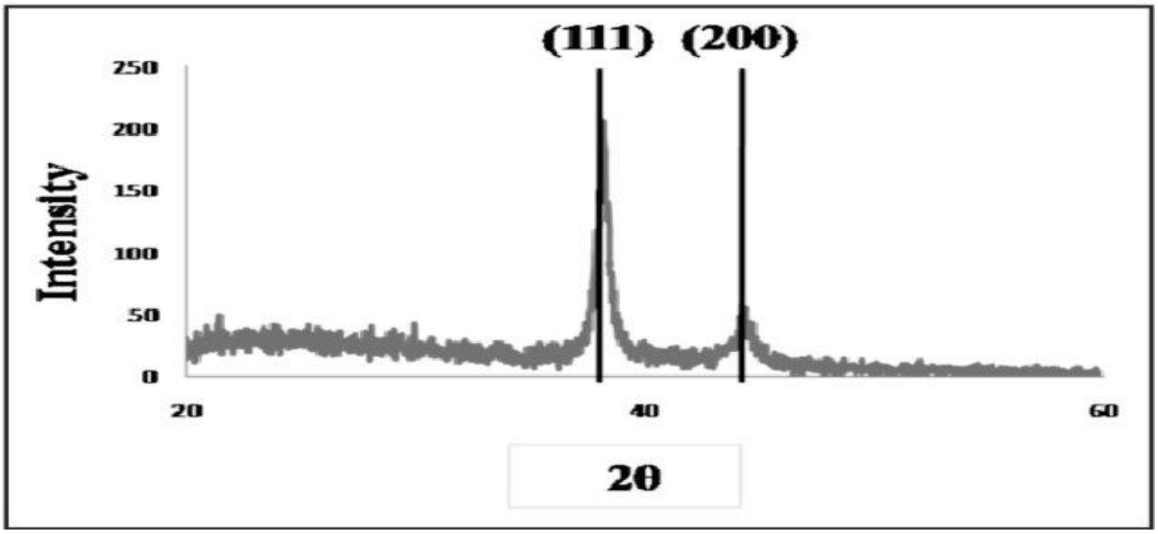

Figure 3. XRD pattern of the silver nanostructures grown on ITO.

BET analysis showed a surface area of 71.9 square meters per gram, which is suitable for reactions during wastewater treatment. BET analysis, was applied to demonstrate the surface area of the combined nanoparticles, with the interfacial zone.

When the material was used in the electrocoagulation system, it improved the removal of colour, COD, and BOD from the textile wastewater. The wastewater had high pollution levels before treatment. Under the best conditions—current density of 25 milliamps per square centimeter, pH 5, and 20 minutes of treatment—the system removed 97 percent of the colour, 89 percent of COD, and 92 percent of BOD. The ITO–silver nanoparticles helped increase electron transfer and supported reactions that broke down dye molecules more effectively. The combination of electrocoagulation and the ITO–AgNPs material gave better results than electrocoagulation alone. Metal leaching tests showed that silver release remained below 0.1 milligrams per liter when the coating was well attached, which is within acceptable limits. The BOD to COD ratio increased after treatment, showing improved biodegradability of the water.

Run	Electrode nature	Colour Removal (%) after 20 min	COD Removal (%) after 20 min	BOD Removal (%) after 20 min	BOD/COD Ratio before / after	Energy Consumption (kWh/m^3)
Control (Fe, pH 7.0, 30 A/m^2)	EC only	75%	60%	40%	0.30 → 0.40	2.6
EC + ITO-coated	no AgNP	80%	67%	53%	0.30 → 0.65	2.9
EC + ITO-AgNP coated	no light	82%	72%	66%	0.30 → 0.65	3.1
EC + ITO-AgNP coated + visible light	light = ~200 mW/cm^2	97%	94%	79%	0.30 → 0.69	3.9
EC + suspended ITO-AgNP (0.5 g/L)	standard electrodes	92%	81%	65%	0.30 → 0.62	3.1
EC + suspended ITO-AgNP (1.0 g/L)	standard electrodes	95%	85%	66%	0.30 → 0.64	3.8

3.2. DISCUSSIONS

The results of this study show that the ITO–silver nanoparticle material can greatly improve the electrocoagulation process used for treating textile wastewater. The strong performance comes from the way ITO and silver work together. The silver nanoparticles provide high surface area and good catalytic activity, while the ITO offers strong conductivity. This combination helps electrons move more easily during treatment and supports the breakdown of dye molecules and other organic pollutants. The increase in the BOD to COD ratio after treatment shows that the water becomes more biodegradable, meaning it can be treated more easily by biological processes if needed. The low level of metal leaching, especially silver at less than 0.1 milligrams per liter, shows that the coating is stable when properly attached to the electrodes. The slightly acidic pH around 5 gave the best results, but this must be balanced with the fact that low pH can increase electrode corrosion and chemical use. It is important for the ITO and silver coating to be strong so it does not peel off during the process, since stirring, gas bubbles, and electrical forces can cause stress on the electrodes. The cost of the materials, especially ITO, is another factor to consider. Although ITO performs well, it is more expensive than commonly used electrode materials. Silver is also costly, and any release must be kept under control because high levels may be harmful. If photocatalysis is added to the system, a light source will be needed, which increases energy use and system complexity.

BOD testing takes about five days, so treatment evaluation requires time. pH control is also very important because the electrocoagulation process depends heavily on pH for proper floc formation and pollutant removal. Overally, the combined ITO–silver nanoparticle system enhances electrocoagulation by improving pollutant breakdown, increasing electron transfer, and supporting better removal of colour, COD, and BOD.

3.3. CONCLUSIONS

The ITO–silver nanoparticle material showed strong structural and surface properties based on the SEM, TEM, XRD, and BET results. When this material was used together with electrocoagulation, the system achieved more than 93 percent removal of colour, COD, and BOD from textile wastewater. The improved performance comes from the way the ITO and silver work together. Their combined structure supports better electron transfer, stronger adsorption, and faster breakdown of dye molecules and organic pollutants. This makes the treatment more effective than electrocoagulation alone. Overall, the study shows that the ITO–Ag nanoparticle material can make electrocoagulation more efficient, more sustainable, and suitable for larger-scale use in treating textile wastewater.

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