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Eco-design for the sustainable scale-up of flexible transparent conductive electrodes at the early-stage development

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Silver nanowires (AgNWs) printed on regenerated cellulose (RC) substrate represent a promising class of flexible transparent conductive electrodes (TCEs), paving the way for a wide range of intelligent applications related to soft electronics. As this technology is still in its early stages, integrating sustainability into the design process is challenging, but it is essential for optimizing the transition from laboratory to large-scale production. This study presents a life cycle assessment (LCA)-based approach that combines experimental measurements, process modeling, and Green Chemistry Principles to evaluate the environmental performance of AgNWs-coated RC films, with eco-design strategies guiding scale-up. The results showed that lab-scale AgNWs-coated RC films have higher environmental burdens than conventional indium tin oxide (ITO)-coated polyethylene terephthalate (PET) films. However, eco-design strategies improving material and energy efficiency can substantially reduce these impacts. Specifically, greenhouse gas emissions of AgNWs-coated RC films can be reduced from 49 to 2.4 kg CO_2-eq per m^2, alongside reductions of 88–95% in other environmental impact categories. Among the various eco-design strategies, we identified waste acetone recovery during AgNWs and RC synthesis as the most critical factor, underscoring the importance of achieving a high acetone recovery rate to optimize the environmental performance of AgNWs-coated RC films in large-scale production. This study demonstrates the necessity of eco-design for emerging electronics, providing an approach for their sustainable scale-up.

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1. This study presents an eco-design approach integrating experimental measurements, process modeling, Green Chemistry Principles, and life cycle assessment for the sustainable scale-up of emerging electronics, illustrated through early-stage transparent conductive electrodes (TCEs).
2. We assess the new TCEs using silver nanowires (AgNWs) printed on regenerated cellulose substrates, providing complete life cycle inventory (LCI) data for the first time and comparing their environmental performance with traditional alternatives. Our analysis reveals that eco-design strategies for AgNWs-based TCEs improve material and energy efficiencies and reduce environmental impacts by 88–95% from laboratory to industrial-scale production.
3. Our analysis identifies future strategies for greener scaling up of TCEs. The LCI data and insights can inform future research on products utilizing AgNWs or cellulosic films. Our eco-design approach can be adapted to other emerging technologies for sustainable scaling up.

1. Introduction

Soft electronics are gaining increasing attention for their flexibility, stretchability, and biocompatibility, driving emerging market demands in applications such as flexible displays,[1] wearable sensors,[2] electronic skin,[3] touch panel,[4] and smart textile.[5] Flexible transparent conductive electrodes (TCEs) are critical components for soft electronics, providing essential conductivity, transparency, and flexibility.[6] Currently, most commercialized TCEs utilize indium tin oxide (ITO) coated on polyethylene terephthalate (PET) substrates through magnetron sputtering, a well-established technology.[7] However, ITO-coated PET films present several environmental and technical challenges. For instance, indium is classified as a critical metal in many countries, including the United States, which consumes approximately 20% of global production but has no domestic supply.[8] Moreover, the sputtering process is highly energy-intensive. The fossil-based,

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non-degradable PET substrate also raises concerns on resource use and end-of-life disposal.[9] Furthermore, the brittle nature of ITO limits its applicability in TCEs that require high flexibility and stretchability.[10] To address these challenges, researchers have been exploring alternative materials such as nanoparticles, nanowires, and cellulose,[11–13] and one promising option is silver nanowires (AgNWs) printed on a regenerated cellulose (RC) substrate.[14,15] The AgNWs-coated RC films incorporate highly conductive, readily available silver with a renewable bio-based, degradable cellulosic substrate, which can be produced using less energy-intensive printing processes such as screen printing and gravure printing.[16–18] Additionally, compared to ITO, nanowires offer superior flexibility and stretchability, enabling broader applications in soft electronics.[19–21]

Although AgNWs-coated RC films are proposed to address the environmental concerns of ITO-coated PET films, the synthesis of AgNWs and RC is highly solvent-intensive.[22,23] For AgNWs, the polyol method is the most common synthesis approach, requiring ethylene glycol as the reducing agent, as well as ethanol and acetone for washing.[22] The synthesis of RC utilizes different solvents such as *N*,*N*-dimethylacetamide (DMAc)/lithium chloride (LiCl) and acetone.[23–25] Additionally, the polyol method for AgNWs synthesis is energy-intensive, requiring continuous heating at 151 °C for approximately two hours.[22] A quantitative, holistic environmental analysis, such as life cycle assessment (LCA), is necessary to determine whether AgNWs-coated RC films offer environmental advantages over ITO-coated PET films. While previous LCAs have evaluated various commercialized silver nanoparticle-based products, such as bandages, T-shirts, food containers, and towels,[26–28] there is a lack of studies assessing AgNWs-coated RC films. This may be because AgNWs-coated RC films are emerging materials that have primarily been studied at the laboratory scale. Only two LCAs on organic photovoltaics have included AgNWs, yet neither accounted for the solvent washing process or waste solvent treatments during AgNWs systhesis.[29,30] This may underestimate the environmental burdens of AgNWs.

Assessing the potential environmental impacts of early-stage technologies are challenging but essential for sustainability-informed design and optimization.[31–33] Previous studies have developed *ex-ante* and prospective LCA approaches for various emerging technologies, *e.g.*, biomass-based materials,[34,35] carbon capture and utilization,[36] renewable energy,[37] and e-waste treatment.[38] However, most of them have focused on environmental impact assessment rather than environmentally conscious design and optimization. A recent study has integrated LCA and techno-economic analysis (TEA) with Green Chemistry (GC) Principles to facilitate the environmentally-friendly design of nanomaterials.[39] However, this study has solely focused on biomass-based nanomaterials and single-material optimization. Complicated applications, such as TCEs in soft electronics, involve multiple materials, and thus require more comprehensive system-level assessment and optimization to achieve maximum environmental performance.

In this study, we address previous research gaps by integrating experimental measurements, process modeling, LCA, and GC principles to assess and eco-design the multi-material system of AgNWs-coated RC films from lab to industrial scale production. We compared the results with traditional ITO-coated PET films and identified design strategies that make AgNWs-coated RC films more environmentally favorable. Our research not only fills the gaps in environmental analyses of emerging TCEs, but also provides insights into the eco-design of multi-material systems and other applications of AgNWs or RC, such as wearable sensors and agricultural mulch.

2. Materials and methods

2.1 Materials

In this study, we utilized a water-based conductive ink containing AgNWs, as demonstrated in previous TCE research,[40] to fabricate AgNWs-coated RC films. The material and fabrication approach of the RC substrate followed a previous laboratory study,[16] which reported films with a transparency of 90%. Previous TCE research also showed that printing the selected conductive ink onto PET substrates resulted in a sheet resistance of 44 Ω sq^{-1}.[40] Since the RC substrate demonstrates similar properties to PET, we assumed that the TCEs fabricated with the selected conductive ink and RC substrate would exhibit a transparency exceeding 80% and a sheet resistance below 60 Ω sq^{-1}. The comparison baseline is a commercialized ITO-coated PET film from Sigma-Aldrich, which has a transparency of 80% and a sheet resistance of 60 Ω sq^{-1}.[41]

2.2 Goal and scope definition

In this LCA, the functional unit is 1 m^2 of TCE for flexible displays. As shown in Fig. 1, the cradle-to-gate system boundary includes the production of conductive materials and transparent substrates, along with the coating processes. The system boundary of AgNWs-coated RC films includes the raw material extraction and synthesis of AgNWs and the RC, conductive ink preparation from AgNWs, and ink coating onto the RC substrate using gravure printing. We selected ITO-coated PET films as the baseline; its system boundary encompasses the raw material extraction, ITO target production using ITO powder, the PET substrate production, and the sputtering process. Although the brittle nature of ITO results in lower mechanical stability and flexibility compared to AgNWs films,[42,43] potentially leading to a shorter lifetime in flexible displays, ITO exhibits superior chemical stability.[20] Therefore, this study assumes that the AgNWs-coated RC and ITO-coated PET films have the same lifetime. We explored two scenarios for AgNWs-coated RC films, using current laboratory synthesis methods and eco-design strategies based on GC principles. Our analysis primarily focuses on operations in the United States, but the methods can be applied to other regions.

2.3 Life cycle inventory analysis

Experimental measurements and process modeling were used to collect comprehensive life cycle inventory (LCI) data. The quantities of conductive ink and RC substrate for AgNWs-

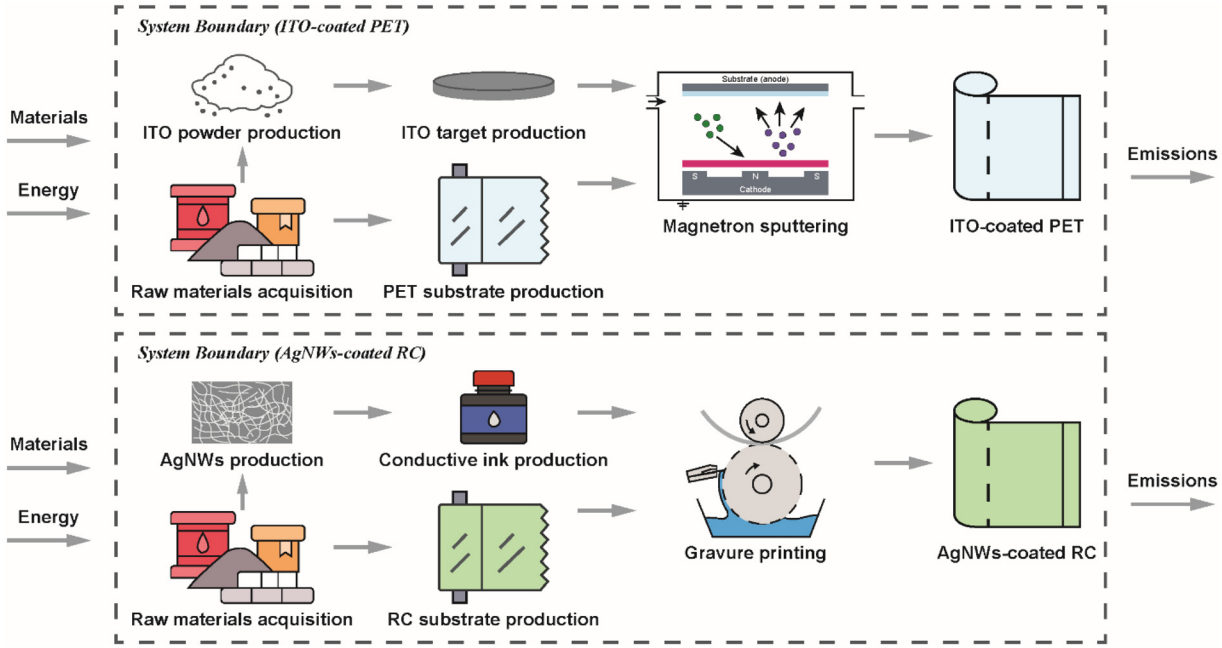

Fig. 1 System boundary of TCEs. ITO-coated PET films include ITO target (produced from ITO powder), PET substrate, and magnetron sputtering. AgNWs-coated RC films comprise AgNWs-based ink, RC substrate, and gravure printing.

coated RC films are based on experimental studies.[16,19] The conductive ink consists of 97.26% water, 0.2% AgNWs, and 2.54% other chemicals (2-amino-2-methyl-1-propanol, *n*-heptanol, Zonyl FSO-100, and diacetone alcohol).[40] Considering the trade-off between transparency and mechanical properties, we adopt a thickness of 60 μm for the RC substrate, which achieves both transparency (~90%) and tensile strength (~120 MPa), based on experimental measurements.[16] The energy demand for printing is based on previous research regarding AgNWs-based organic photovoltaic.[29,44] SI Tables S3 and S4 document LCI data for AgNWs-coated RC films and conductive ink, respectively.

The LCI of ITO-coated PET films are based on supplier information.[41] Specifically, the ITO layer has a thickness of 100 nm, resulting in a total sputtering volume of 1×10^{-7} m^3. The PET substrate production includes the processes for producing PET granulates and extrusion. The LCI data lists of ITO-coated PET films and the PET substrate are provided in SI Tables S1 and S2, respectively. The ecoinvent database (version 3.9, cutoff model)[45] is used in this study for background process data (*e.g.*, LCI of upstream production of plastics, solvents, and energy).

Since AgNWs-coated RC films are produced at the laboratory scale without environmental optimization, we explored potential scaling-up strategies incorporating eco-design considerations compared with current synthesis methods, specifically for the AgNWs and the RC substrate. Compared to ITO-coated PET films, AgNWs-coated RC films incorporate bio-based, degradable substrates, aligning with the GC Principle 7 (use of renewable feedstock) and Principle 10 (design for degradation).[46] However, given the solvent- and energy-intensive synthesis of AgNWs and RC at the laboratory scale, there is potential to apply additional principles, such as the GC Principle 1 (waste prevention), Principle 5 (safer solvents and auxiliaries), and Principle 6 (design for energy efficiency),[46] to further minimize their environmental burdens in large-scale production.

The polyol process is considered the most feasible method for large-scale AgNWs production.[19,22] As shown in Fig. 2a, this process involves heating and stirring silver nitrate, polyvinylpyrrolidone (as a capping agent), ethylene glycol (serving as both solvent and reductant), and copper(II) chloride (as a catalyst) at 151 °C for approximately two hours. After cooling to room temperature, the produced AgNWs are washed with acetone and ethanol through centrifugation. SI Table S5 presents the LCI for AgNWs synthesis using the polyol method derived from experimental measurements.[19] Previous studies[29,30] do not include solvent waste treatment and upstream production of catalysts and capping agents. In this study, we accounted for waste solvent treatment through incineration (a common practice) in the current polyol method,[47] and solvent recovery for the eco-design strategy. Moreover, we conducted process modeling to determine the inventory data for the upstream production of catalyst and capping agent (see SI Tables S7 and S8).

Since the polyol process is highly solvent-intensive, we followed the GC Principle 1 (waste prevention) by incorporating waste solvent recovery strategies. As shown in Fig. 2b, we considered two solvent separation steps using distillation after each washing stage, recovering acetone, ethanol, and ethylene glycol. This approach aims to reduce the net solvent use and minimize waste incineration in the current polyol method.

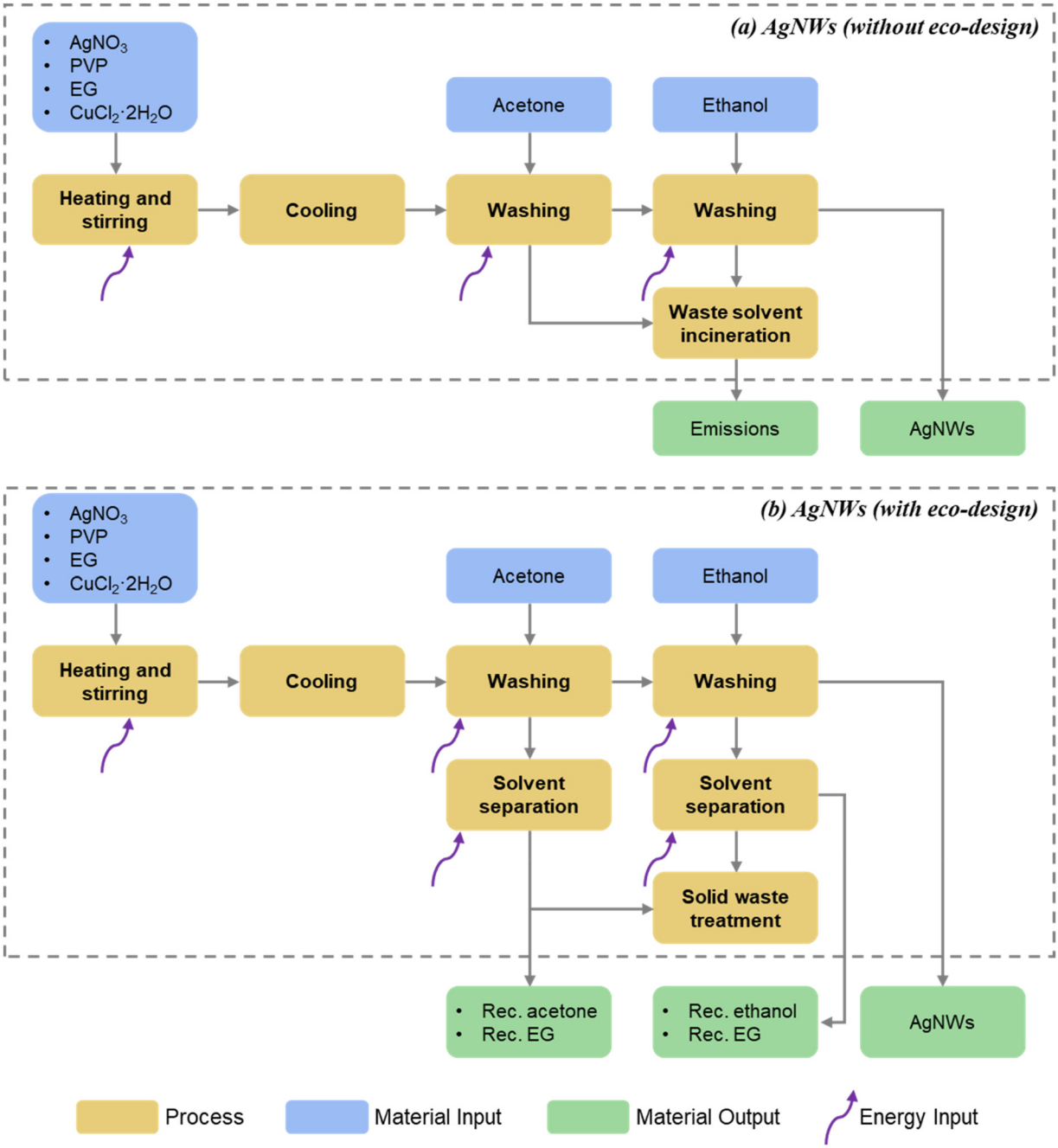

Fig. 2 Process flow chart of AgNWs production using (a) the current polyol method and (b) eco-design considerations based on various GC Principles. "Rec." denotes recycled.

Energy requirements for distillation were determined using Aspen Plus modeling,[48] with detailed assumptions provided in section S2.1. Moreover, energy data for heating and stirring during silver nitrate reduction were first collected for laboratory equipment with low energy efficiency. Following the GC Principle 6 (design for energy efficiency), this study includes a 500-liter industrial reactor with optimized heat retention for large-scale AgNWs production.[49] Section S2.2 documents the energy modeling for the industrial reactor. The resulting LCI for the eco-designed AgNWs synthesis is provided in SI Table S10.

The synthesis of RC substrate requires suitable solvents to dissolve cellulose, enabling it to be reformed into solid, transparent films,[14] which is why it is referred to as "regenerated cellulose". Previous research has proposed several solvent systems, such as *N*-methylmorpholine-*N*-oxide,[50] DMAc/LiCl,[51] ionic liquids,[52] and alkali/urea.[53] In this study, we focus on DMAc/LiCl—a well-established, non-derivatizing co-solvent system widely used for cellulose processing with homogenous reaction conditions.[54] As shown in Fig. 3a, the synthesis begins with the activation and dissolution of microcrystalline

Fig. 3 Process flow chart of RC substrate production using (a) the current synthesis method and (b) eco-design considerations based on various GC Principles. "Rec." denotes recycled.

cellulose (MCC) using DMAc/LiCl, followed by centrifugation, casting, coagulation with acetone, washing with water, and drying.[16] SI Table S11 presents the LCI of the current synthesis method, showing substantial consumption of DMAc (12 kg), acetone (97 kg), and water (34 metric tons) per kilogram of RC substrate produced. To enhance material efficiency, a filtration process is included after MCC activation for recovering 98% of the DMAc, as shown in Fig. 3b. After coagulation, 1% of acetone, DMAc, and LiCl are assumed to remain with the RC for the subsequent washing process. The waste solvents are treated through distillation, recovering 99.5% of the acetone and 98% of the DMAc based on Aspen Plus modeling. The remaining LiCl is reused in the dissolution process. Additionally, the cellulose concentration in the target RC substrate is increased from 6.5 to 15 wt%, aiming to further reduce the initial demand of DMAc and LiCl during mixing and dissolution, as demonstrated in previous research.[55] For the washing process, we assumed that large scale operations would improve water use efficiency, reducing water consumption by 50% compared to the laboratory scale. Furthermore, an ion exchange process is incorporated after washing to recover 90% of the water. In addition to material use improvements, we also applied the GC Principle 6 by utilizing an industrial reactor for heating and stirring and replacing the energy-intensive centrifugation step with a degassing process. SI Table S13 provides the LCI for the RC substrate synthesis incorporating

eco-design. Given the uncertainties in process performances of proposed eco-design strategies, a sensitivity analysis is conducted to understand the impacts of performance variations and identify the most influential factors. The eco-design parameters and their ranges are documented in SI Table S15.

2.4 Life cycle impact assessment

In this study, nine environmental impact indicators were evaluated, including global warming potential (GWP) for greenhouse gas (GHG) emissions, acidification, photochemical smog formation, ozone depletion, eutrophication, ecotoxicity, cumulative energy demand, as well as human health particulate, cancer, and noncancer. The GWP was calculated using the methodology of the Intergovernmental Panel on Climate Change 2021.[56] The cumulative energy demand considers direct and indirect non-renewable energy use.[57] The remaining indicators were assessed using the TRACI 2.1 method.[58] openLCA v2.4.1[59] was used to conduct the LCIA calculations.

3. Results and discussion

Fig. 4 shows the cradle to gate environmental impacts of 1 m^2 of AgNWs-coated RC films without (Ag/RC) and with eco-design (Ag/RC-Eco), compared to the baseline ITO-coated PET films. Without eco-design, the environmental impacts of AgNWs-coated RC films are substantially higher than those of ITO-coated PET films, ranging from 4.6 times in ecotoxicity to 16 times in GHG emissions (Ag/RC *versus* the baseline). The only exception is ozone depletion, where the result of AgNWs-coated RC films is lower than that of the ITO-coated PET films, even without eco-design. The largest contributor to the impacts of AgNWs-coated RC films is the synthesis of the RC substrate, followed by manufacturing (gravure printing), with conductive materials (AgNWs ink) showing the lowest impacts. For the ITO-coated PET films, the manufacturing (sputtering process) is the main contributor to most of the environmental impacts, except in ecotoxicity, human health noncancer, and ozone depletion, which are dominated by conductive materials (ITO target) or PET substrate. The cumulative energy demand results follow a similar trend to the GHG emissions and are presented in SI Fig. S1.

Our results show the essential role of eco-design in minimizing the potential environmental burdens of emerging technologies. Eco-design significantly decreases the impacts of AgNWs-coated RC films, making them lower (*e.g.*, a 23% decrease in GHG emissions) than those of ITO-coated PET films (Ag/RC-Eco *versus* the baseline). This improvement is mainly attributed to at least a 96% reduction in the environmental burdens of RC substrates, achieving similar impacts to those of PET substrates. Moreover, due to lower energy demand, gravure printing for AgNWs shows lower impacts than sputtering for the baseline. Another contributor is the better environmental performance of AgNWs ink than ITO target, regardless of eco-design. This is mainly due to the superior conductivity of silver, resulting in a lower amount (~0.2 g of AgNWs in 11.7 g of ink) needed compared to ITO (~4.8 g) for a similar sheet resistance of TCEs.[40] These advancements result in superior environmental performance of the eco-designed AgNWs-coated RC films compared to the baseline in almost all impact indicators, except eutrophication that is mainly contributed by fertilizer usages in biomass production for RC substrate.

Fig. 5 and 6 further break down the contribution of eco-design to reducing the environmental burdens of AgNWs and RC substrate production, respectively. Specifically, we differentiate the eco-design improvements in energy and material efficiency for producing 1 kg of AgNWs (Fig. 5) and RC substrate (Fig. 6). For AgNWs production, material efficiency improvement through solvent recovery leads to the largest reductions in most impact indicators, except human health particulate, where energy efficiency improvement *via* using industrial reactors with optimized heat loss makes a larger contribution. This highlights the important role of proper spent solvent management in improving the environmental performance of AgNWs synthesis. Compared to solvent incineration, efficient recovery of spent solvents can reduce the impacts of AgNWs production by up to 78.8%. The smallest improvement due to eco-design is observed in ecotoxicity, which decreases by only 6.1%. This is because ecotoxicity is primarily driven by the upstream silver mining process, and thus not affected significantly by optimizing material and energy efficiencies in TCEs production.

Although eco-design substantially reduces most impact indicators in AgNWs synthesis, it results in only a marginal improvement in the overall impact of TCEs production. This is due to the lower contribution of AgNWs-based ink to the overall LCA results, compared to the RC substrate and printing process in TCEs, as shown in Fig. 4. The AgNWs loading in this study is based on achieving a sheet resistance below 60 $\Omega\ sq^{-1}$ for flexible displays.[40] However, for other applications such as wearable sensors, inks with high conductivity (for example, a sheet resistance of less than 1 $\Omega\ sq^{-1}$) may be required, necessitating a AgNWs loading more than 30 times that in the current study.[19] This would make AgNWs a potential hotspot for the overall environmental performance, and our eco-design strategies could inform strategies to reduce their impacts.

Regarding the eco-design of RC substrate production, Fig. 6 shows that improving material efficiency by using a high cellulose fraction and recovering spent solvents and water reduces all impact indicators by 96–98%. This reduction is significantly larger than that achieved by energy efficiency improvement (by replacing centrifugation with degassing and using industrial reactors with optimized heat loss). Compared to AgNWs production and the printing process, the eco-design of RC substrate has a greater influence on improving the overall environmental performance of TCEs, as depicted in Fig. 4. This underscores that an effective strategy for material use and waste management is not only essential for an eco-friendly RC substrate but also crucial for the sustainability of cellulosic TCEs.

To understand the impacts of uncertainties in key eco-design factors, we conducted a sensitivity analysis considering the conversion yield of silver to AgNWs, recovery rates of

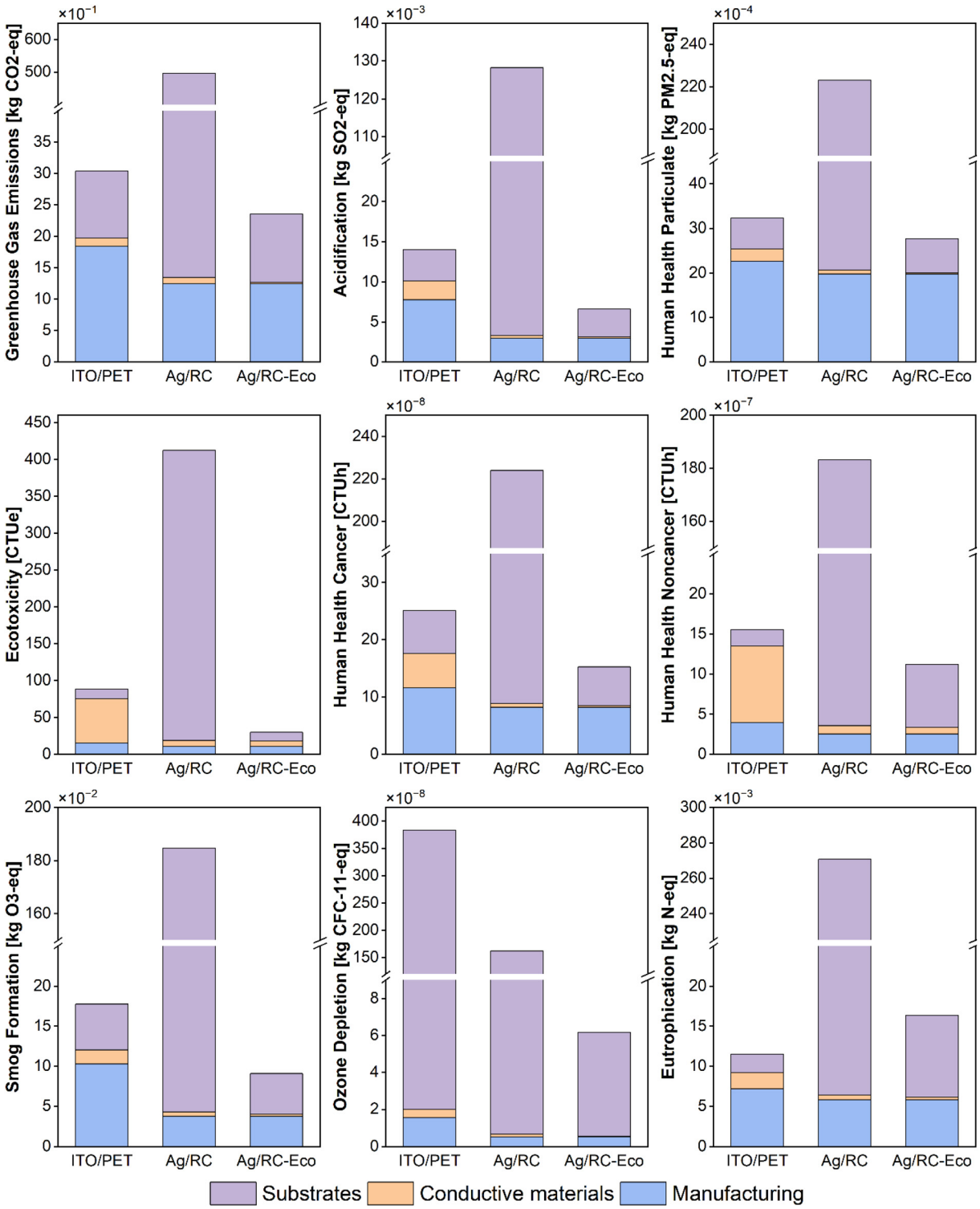

Fig. 4 Environmental impacts of TCEs across the three scenarios. The baseline is the ITO-coated PET films, which utilizes ITO as the conductive material, PET as the substrate, and sputtering as the manufacturing method. "Ag/RC" and "Ag/RC-Eco" represent AgNWs-coated RC films with and without eco-design, respectively, using AgNWs as the conductive material, RC as the substrate, and gravure printing as the manufacturing method. The results of cumulative energy demand are presented in SI Fig. S1.

ethanol and ethylene glycol in AgNWs synthesis, water use and recycling in RC synthesis, and acetone recovery in both syntheses. Fig. 7 shows the results for GHG emissions, eutrophication, and ozone depletion. Other impact categories present similar trends, and their results are provided in SI Fig. S2 and S3. The impacts of recovery rates of other solvents differ by

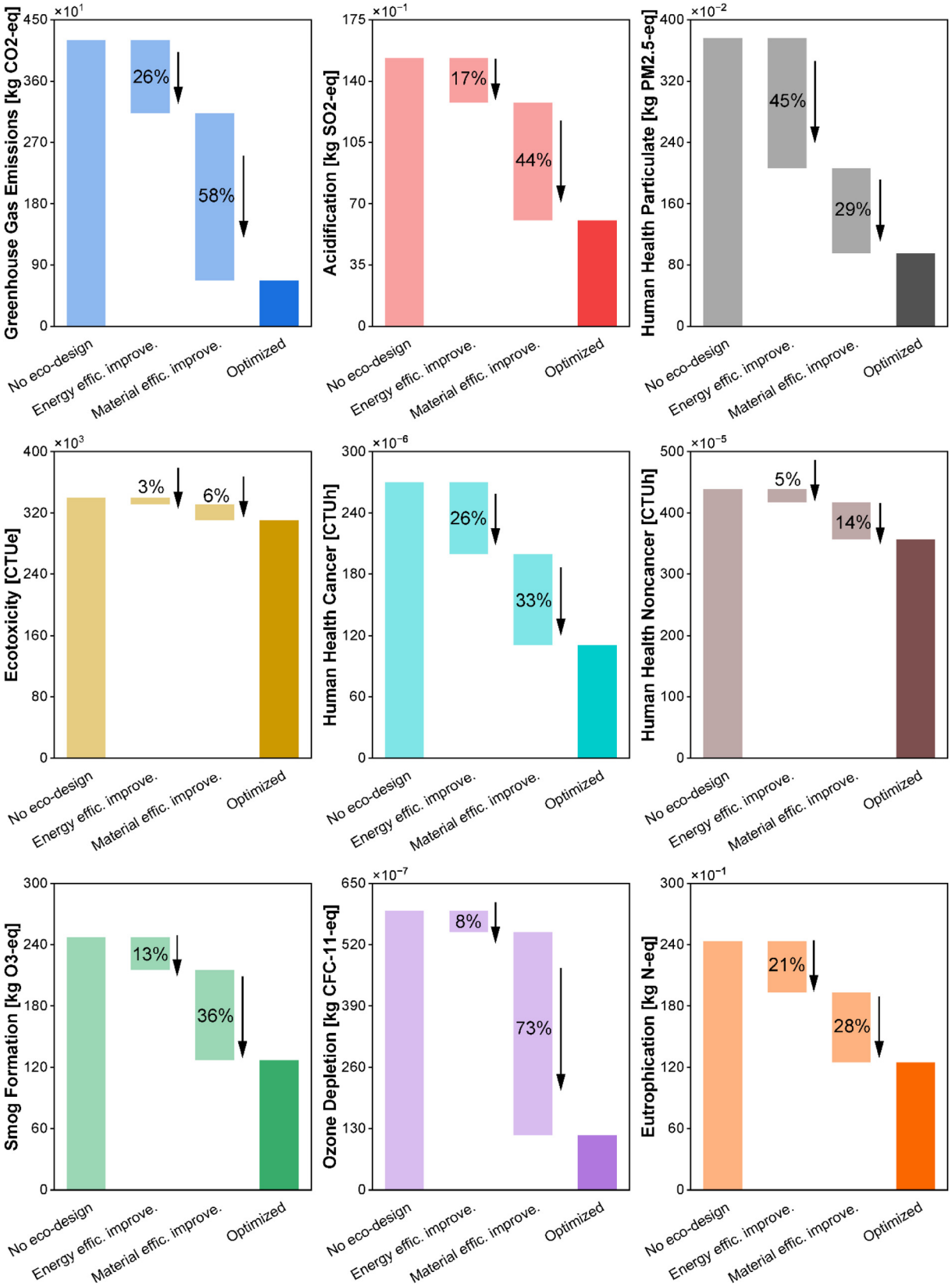

Fig. 5 Effects of eco-design on reducing the environmental impacts of AgNWs production. Energy efficiency improvement refers to the implementation of an industrial reactor with optimized heat loss. Material efficiency improvement involves the recovery of spent solvents (EG, acetone, ethanol) from reaction and washing processes. The optimized bar represents the impact after implementing both material and energy efficiency improvements. The results are based on producing 1 kg of AgNWs. The results of cumulative energy demand are presented in SI Fig. S1.

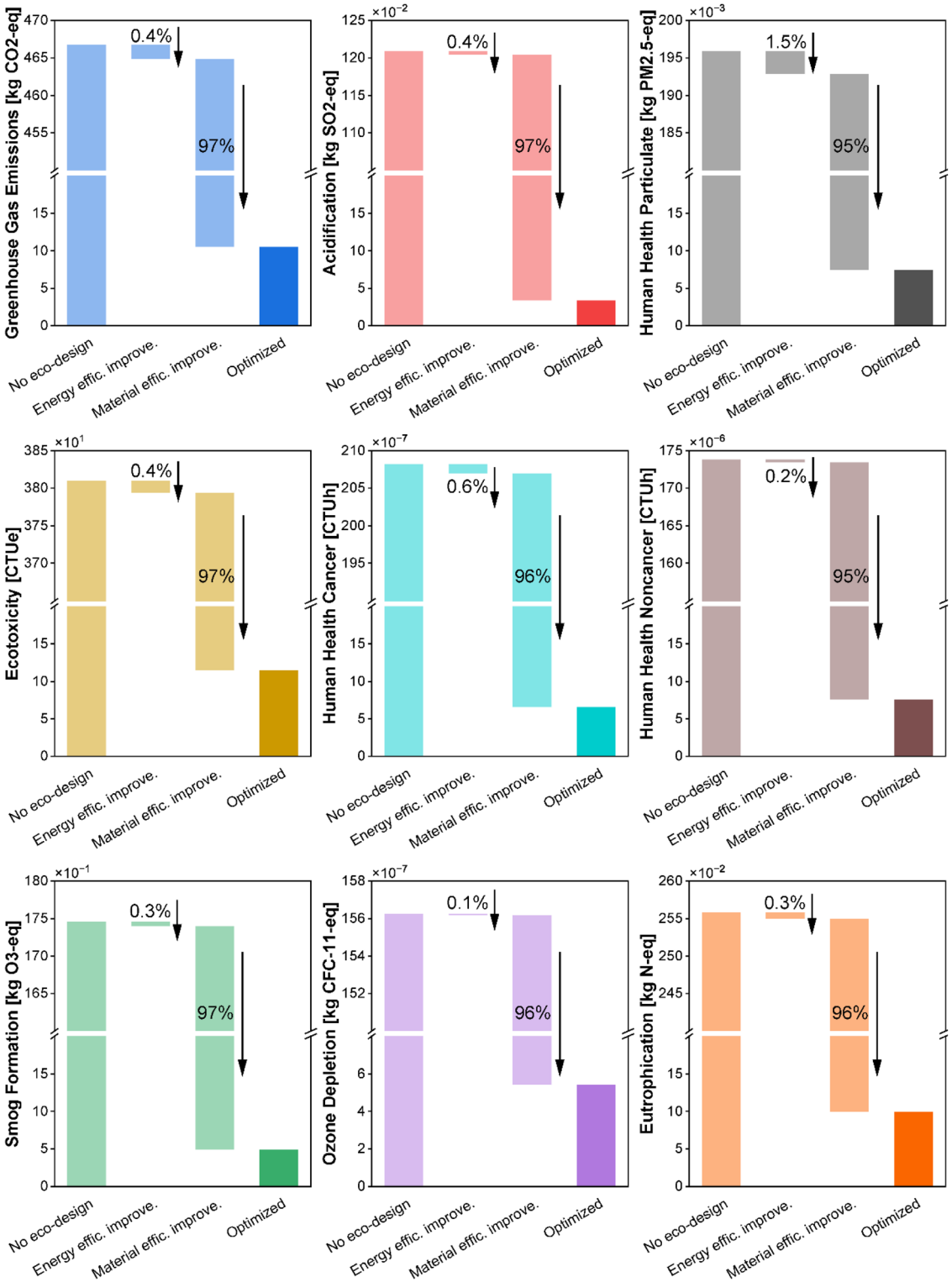

Fig. 6 Effects of eco-design on reducing the environmental impacts of RC substrate production. Energy efficiency improvement refers to optimized process design and the implementation of an industrial reactor with reduced heat loss. Material efficiency improvement involves optimizing the fraction of raw materials and recovering spent solvents (DMAc, acetone), catalyst, and water. The optimized bar represents the impact after implementing both material and energy efficiency improvements. The results are based on producing 1 kg of RC substrate. The results of cumulative energy demand are presented in SI Fig. S1.

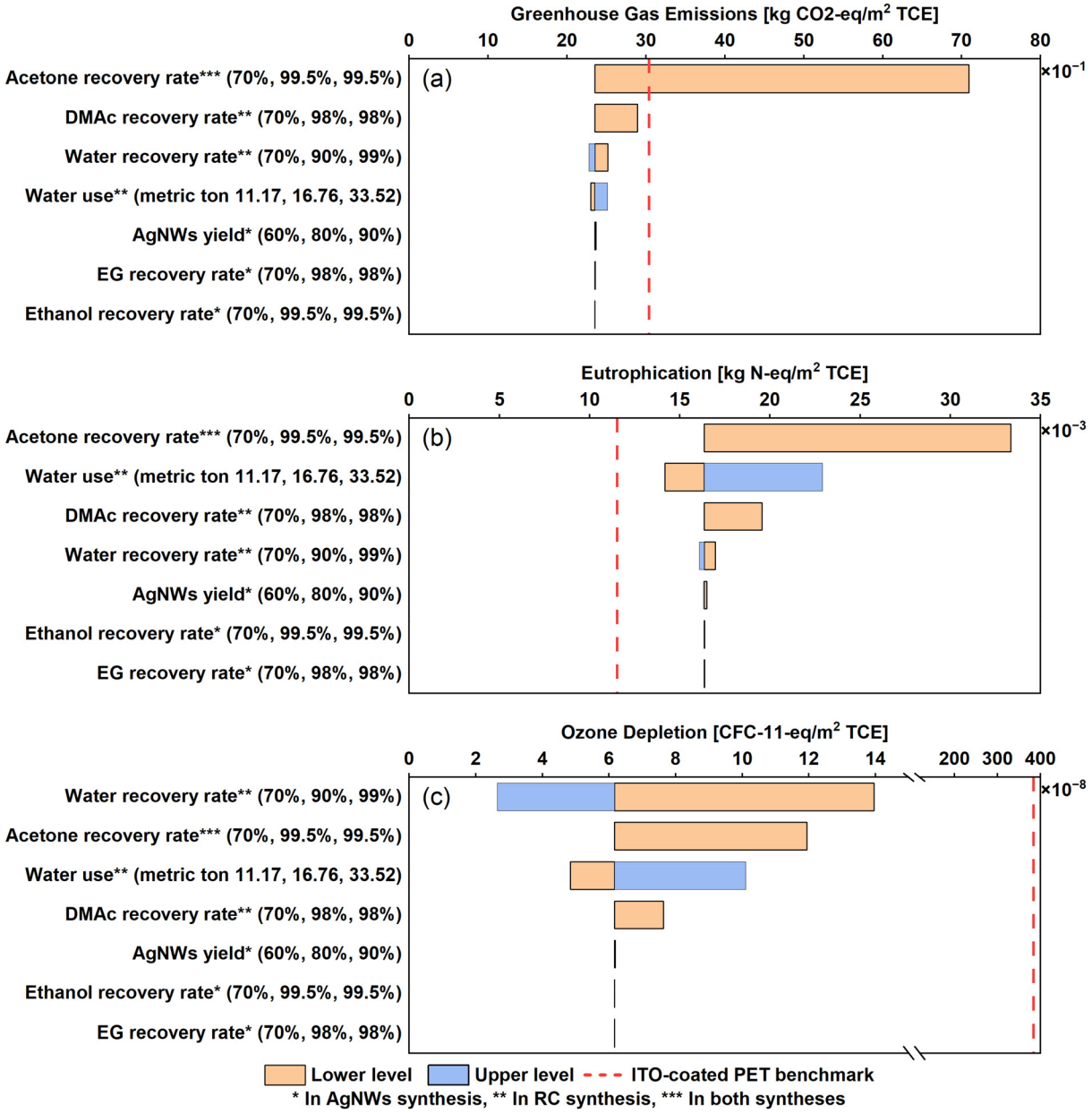

Fig. 7 Sensitivity of key eco-design factors on (a) greenhouse gas emissions, (b) eutrophication potential, and (c) ozone depletion of AgNWs-coated RC films. EG denotes ethylene glycol.

solvent type. Acetone recovery rate is the most critical factor. A low recovery rate (such as 70%)[49] results in substantial increases in several impacts, such as GHG emissions, acidification, human health particulate, photochemical smog formation, and human health cancer and noncancer, making AgNWs-coated RC films more environmentally burdensome than ITO-coated PET films. For other solvents, the changes in DMAc recovery rate have a smaller impact compared to those of the acetone recovery rate, but they are larger than the variations in the recovery rates of ethanol and ethylene glycol, which have minimal effects on results. For other impact categories, including eutrophication, ozone depletion, and ecotoxicity, the variations of eco-design factors change the absolute values of the results but not the comparative conclusions between AgNWs-coated RC and ITO-coated PET films.

Water usage and recovery rates are other influential factors. Water recovery rate means the percentage of wastewater that is treated and reused, while water usage refers to the consumption of freshwater. Higher water recovery rate and lower water usage in RC synthesis contribute to lower environmental impacts, though the extents differ by category. For example, water usage variations lead to much larger changes in eutrophication and human health noncancer than the water recovery rate, while the trends are opposite for other impacts such as ozone depletion, where water recovery rate is more important in driving the variations of the results.

This research considers ITO-PET films as the benchmark due to the dominance of commercial ITO in the market of transparent conductive coatings.[60,61] Although other emerging technologies, such as carbon nanotube-based and graphene composite-based TCEs,[62,63] have been proposed, they currently possess low technology readiness levels and remain in an early stage of development. Since this study focuses on sustainable scale-up strategies of TCEs for flexible displays, these emerging technologies are not included as benchmarks due to the lack of comprehensive scaling-up analyses with eco-design optimizations. The method presented in this study can be used to address this gap in future research. Moreover, there are potential practical challenges during scale-up that must be addressed by future industrial and research efforts. For example, although the polyol method is the most widely used approach for AgNWs synthesis, the nucleation and growth steps are sensitive to uniform mass and heat transfer, which become more challenging in large-scale batch production. Thus, it is essential to develop effective process strategies to maintain AgNWs quality in terms of size and morphology.[64,65] In the production of RC substrate, scaling up the gas-sparging process will require precise control of bubble size and gas flow rate to enable efficient separation of acetone from the DMAc/LiCl co-solvent system.[66] Large-scale ion exchange resin is also more prone to channeling and mass transfer hindrance, increasing operational complexity.[67] Furthermore, while using a higher cellulose concentration (~15%) can reduce the consumption of solvent and water, it also increases the viscosity of the solution, leading to poorer mass and heat transfer and, consequently, potential cellulose degradation during dissolution and regeneartion.[55] Therefore, optimal mixing conditions and precise temperature control will need to be determined and validated at the industrial scale. These challenges highlight the need for further research to refine LCI data, which can be integrated into the eco-design framework of this study to facilitate large-scale process optimization.

This study presents a sustainability-informed scale-up method for the cradle-to-gate production of emerging AgNWs/RC-based TCE. The use and EoL stages are still under investigation and should be addressed in future research to enable holistic cradle-to-grave analyses. For example, while the biodegradability of RC films in soil has been reported in previous lab-scale studies,[68,69] their degradation in natural environments, as well as the associated GHG and other emissions, remain unknown. Future analyses should consider factors such as device lifetime, bio- or enzymatic degradation of RC substrates, and silver recycling potential when relevant data become available. In addition to environmental impacts, cost is another important factor for the market acceptance of emerging TCEs. Although silver is more readily available than indium, its price is higher (USD 804 *vs.* 220 per kilogram in the U.S. in 2021).[8] Therefore, future studies should conduct techno-economic analyses (TEA) to quantitatively compare the cost performance of AgNWs-RC and ITO-PET films, considering capital investments and operational costs, such as feedstock, energy, and labor costs. The LCI data presented in this study can lay the foundation for future TEA studies and large-scale analysis for the current and future TCE industry.

4. Conclusion

In this study, experimental measurements, process modeling, and the Green Chemistry (GC) Principles were incorporated to assess the environmental performances of lab-scale AgNWs-coated RC films and the eco-design strategies for scaling up. The results indicate that current AgNWs-coated RC films exhibit worse environmental performance than ITO-coated PET films, primarily due to the impacts from RC synthesis. Nevertheless, this can be significantly improved through eco-design scenarios, which reveal the importance of spent solvent recovery, water recycling, and heat loss optimization during RC synthesis to achieve better environmental performance of AgNWs-coated RC films than ITO-coated PET. As an *ex-ante* study, there are several uncertainties in technology scale up. The sensitivity analysis evaluated the impacts of uncertainties associated with key eco-design parameters and identified waste acetone recovery as the most critical factor. Additionally, this research mainly focused on solvent use, aligning with the GC Principle 1 (waste prevention). Future studies can explore the GC Principle 5 by identifying safer alternatives to hazardous solvents such as DMAc, which is classified as a substance of very high concern due to its reproductive toxicity.[70] Moreover, since RC substrates are bio-based and degradable, future studies should explore the biogenic carbon during biomass growth and end-of-life treatment of AgNWs-coated RC films. The approaches presented in this study can be utilized by future researchers to assess the potential environmental implications of alternative solvents and end-of-life scenarios.

Conflicts of interest

There are no conflicts to declare.

Data availability

All relevant data that support the findings of this research are available within the article and its supplementary information (SI). Supplementary information is available. See DOI: https://doi.org/10.1039/d5gc03167b.

The background life cycle inventory data of upstream materials and energy for producing transparent conductive electrodes are from the ecoinvent database (https://ecoinvent.org/), which requires a license for access.

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2134664. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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