Journal of Cleaner Production 380 (2022) 135153

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

How sustainable are the biodegradable medical gowns via environmental and social life cycle assessment?

Xiang Zhao [a], Jiří Jaromír Klemeš [b], Michael Saxon [c], Fengqi You [a,d,*]

[a] Systems Engineering, Cornell University, Ithaca, NY, 14853, USA
[b] Sustainable Process Integration Laboratory – SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology - VUT Brno, Technická 2896/2, 616 69, Brno, Czech Republic
[c] New York Embroidery Studio, 307 W 36th St. 3rd Floor, New York, NY, 10018, USA
[d] Robert Frederick Smith School of Chemical and Biomolecular Engineering, Cornell University, Ithaca, NY, 14853, USA

ARTICLE INFO

Keywords:
Medical disposable gown
Sanitary landfill
Industrial composting
Life cycle assessment
Landfill gas capture and utilization

ABSTRACT

The growing disposable medical gown consumption due to the COVID-19 pandemic has driven tons of waste to landfills and posed plastic pollution. Investigating the pros and cons of biodegradable gowns over conventional counterparts can guide disposable medical gowns to be environmentally and socially sustainable. This work presents environmental and social life cycle assessments (E− and S-LCA) of biodegradable gowns to compare their environmental and social performances with conventional ones. The E-LCA evaluates the full-spectrum environmental impacts from gown production to end-of-life waste management processes, while the S-LCA assesses their associated influence on economic growth, employment, and worker welfare. The social impacts are evaluated based on the economic input-output analysis results of the economic sectors or gown life cycle stages involved in the gown value chain. Results show that biodegradable gown production poses 10.76% higher ecotoxicity than conventional alternatives contributed by pro-oxidant manufacturing. Integrating the landfill gas (LFG) capture and utilization processes into biodegradable gown waste treatment can reduce 48.81% of life cycle land use and over 5.67% of total greenhouse gas emissions. However, integrating this process in sanitary landfills to treat disinfected gown wastes can increase technical complexity, which enhances 70% of safety risks and 40% frequency of forced labor. Industrial composting biodegradable gowns can reduce over 20.5% of particulate matter formation versus sanitary landfills. Overall, fossil-based gowns possess full-spectrum environmental and social advantages over biodegradable counterparts treated by industrial composting and sanitary landfills. If improving the efficiencies of LFG capture by 85%, biogenic methane oxidation by 43%, and heat generation by 85%, biodegradable gowns can outperform conventional counterparts in reducing GHG emissions and fossil fuel use.

1. Introduction

Global personal protective equipment consumption surge under the current COVID-19 pandemic is now pressing the waste management sectors (Hou et al., 2018), especially for plastic wastes (Klemeš et al., 2020a). Fossil-based disposable medical gowns, which can effectively protect medical workers from virus infection, are environmentally unsustainable by their design (Vozzola et al., 2018). These gowns, frequently treated by landfills (Zhao et al., 2022), can generate plastic debris and intertwine with natural systems with hazards (Hicks et al., 2016). Plastic debris release can undergo natural weathering with age to generate tiny microplastics (Mastellone, 2019; Zhao and You, 2022) and chronic chemicals that harm organisms via easy digestion (Fojt et al., 2022). Compared to conventional gowns, biodegradable counterparts show their environmental advantages in causing less plastic pollution, given their shorter environmental exposure time until complete decomposition (Babaahmadi et al., 2021). Soil organisms can efficiently crack biodegradable gowns in landfills or industrial composting within the short terms (Stegmann et al., 2020) and yield greenhouse gases (GHGs) from non-sequestrated carbons (Kim et al., 2022), so the downstream integration of gas capture technologies, such as the landfill gas (LFG) capture and utilization process (Johari et al., 2012), can keep methane emission to its minimum and benefit the natural environment. Offsite production of the energy and chemicals consumed in these processes can pose a variety of pollution to the ecology and prevent them

* Corresponding author. Robert Frederick Smith School of Chemical and Biomolecular Engineering, Cornell University, Ithaca, NY, 14853, USA.
E-mail address: fengqi.you@cornell.edu (F. You).

https://doi.org/10.1016/j.jclepro.2022.135153
Received 5 October 2022; Received in revised form 27 October 2022; Accepted 9 November 2022
Available online 14 November 2022

Abbreviations

EF 3.0	Environmental Footprints database 3.0
E-LCA	Environmental life cycle assessment
EoL	End-of-life
GDP	Gross domestic productne
GHG	Greenhouse gas
GWP	Global warming potential
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LFG	Landfill gas
IPCC	The Intergovernmental Panel on Climate Change
O&M	Operation and maintenance expenditure
PPE	Personal protective equipment
PSILCA	The Product Social Impact Life Cycle Assessment database
S-LCA	Social life cycle assessment
TEA	Techno-economic analysis
basc	Operation and maintenance expenditure of chemical engineering plant or solid waste treatment sites
ceff	Landfill gas capture efficiency
rl	Social risk impact factor
m	Gown waste mass flow rate
mch	Molecular weight of polypropylene monomer
mco	Molecular weight of carbon dioxide
mm	Plastic carbon content in gowns
mme	Molecular weight of methane
omm	Operation and maintenance expenditure
per	Weight percentage of pro-oxidants in gowns
slcii	Social LCI data
sim	Social impact assessment result
t	Degradation time horizon
vco	Degradation rate of biodegradable gowns
vva	The methane mass flow rate within the landfill gas
vvc	The carbon dioxide mass flow rate within the landfill gas
wh	Average working hours
ws	Worker salaries

from being environmentally benign (Friesenhan et al., 2017). Moreover, the production and end-of-life (EoL) waste treatment of biodegradable gowns can benefit society by creating jobs but also pose social risks corresponding to worker safety (Cetin and Sonmez, 2021). Therefore, understanding these environmental and social performances of biodegradable disposable gowns over conventional ones is critical and requires explicit investigation.

The life cycle assessment (LCA) approach is a powerful tool for a systematic evaluation of the environmental and social impacts and enables achieving the United Nations' sustainable development goals (SDGs) corresponding to gown production, use, and EoL waste disposal (Sala and Castellani, 2019). Existing gown-related LCA studies mainly investigated the environmental sustainability of gown use patterns (Vozzola et al., 2018), including single- and multiple-uses (Van den Berghe and Zimmer, 2011) and novel designs for convenient uses (Burguburu et al., 2022), based on selected environmental indicators corresponding to climate change and energy use. However, the environmental benefits investigated in these studies are not evident in real-world gown use, given the dominant market share of disposable gowns and their low reuse rate in practice (McQuerry et al., 2021). Existing disposable gown studies only identified the environmentally sustainable design (Freund et al., 2022), end-of-life (EoL) waste treatments (Campion et al., 2015), plastic materials (Hicks et al., 2016), and reuse methods (Unger et al., 2016) of fossil-based gowns without investigating the pros and cons of biodegradable counterparts amid plastic pollution mitigation (Tao and You, 2021). To have a full quantified impact of disposable gowns on the environment, it is necessary to assess Environmental Footprints based on the LCA (Klemeš et al., 2020b).

The Social Footprint posed from disposable gown production to EoL waste processing (Bianchini and Rossi, 2021) is also worth to be considered to reflect the associated socio-economic concerns, including domestic economic growth, job creation (Yue et al., 2014), and worker welfare (Kedzierski et al., 2020), from the disposable gowns. In this context, the social life cycle assessment (S-LCA), which accounts for the associated socio-economic and social impacts from the economic interdependencies between economic sectors or industries involved in the product value chain (González et al., 2021), can be applied to evaluate the social impacts caused by the raw material and resource extraction to EoL disposal of gowns (Jørgensen et al., 2008) and stress the sustainability of biodegradable gowns over conventional counterpart. However, the social impact analysis on gown EoL management has not been investigated despite the current S-LCA study that investigated solid waste management's social impacts on labor, health, and salary (Umair et al., 2015) aided by the economic input-output analysis approach (You et al., 2012). Therefore, the potential social and socio-economic effects of the gown across its life cycle remain uninvestigated, though they help understand the pros and cons of biodegradable gowns over conventional counterparts.

Several research challenges need to be addressed to fill the existing knowledge gap in evaluating disposable medical gowns' life cycle environmental and social sustainability across the life cycle. Sanitary landfills and industrial composting are used for gown EoL management after disinfection due to their relatively lower GHG emissions (Anshassi et al., 2021) and capital costs than waste incineration processes typically used for plastic waste processing (Zhao and You, 2021). However, sustainability analyses on these gown EoL managements are still hindered by their life cycle inventory (LCI) data gaps accounting for the environmental and social effects. By collating the environmental- and social LCIs with the well-archived Ecoinvent V3.8 and the Product Social Impact Life Cycle Assessment (PSILCA) Databases, the social and environmental impact assessment can then be performed to investigate the pros and cons of the conventional and biodegradable gowns. Understanding these pros and cons can be reinforced by assessing and comparing their short and long-term environmental consequences, of which evaluation time horizons are still lacking in plastic waste recycling studies.

In this context, this work evaluates the environmental and social impacts posed by conventional and biodegradable disposable medical gowns, both of which are made of polypropylene, to understand the pros and cons of biodegradable gowns over conventional counterparts. A comparative LCA approach is adopted for evaluating and comparing the full-spectrum environmental and social impacts from three gown case studies, which account for conventional and biodegradable gowns treated by sanitary landfills and industrial composting after disinfection, to reflect their pros and cons from environmental and social sustainability perspectives. The social impacts are assessed based on these gowns' economic input-output analysis results to reflect their associated influence on economic growth, employment, and worker welfare. These comparative LCA results can shed light on disposable gowns' environmental and social sustainability. The most influential key technical parameters of the gown life cycle stages are also identified to provide technical and policy insight on enhancing the environmental sustainability of gowns.

Key novelties and findings of this study are summarized below:

(i) Compared to conventional gowns, biodegradable gowns treated by industrial composting with similar extents of worker welfare, domestic economic growth, and employment given in Fig. 11 can raise 16.71% human toxicity arising from chronic leachates, 11.39% GHG emissions from uncaptured CO_2 emissions, and 10.76% of total ecotoxicity related to chemical production for pro-oxidants and their chronic environmental releases illustrated by Fig. 10.
(ii) Adopting the LFG capture and utilization processes within biodegradable gown sanitary landfills can reduce 9.79% GHG emissions and save at least 10% fossil resources by onsite heat and power co-generation (see Fig. 6), which requires extra working hours and raises social risks corresponding to natural disasters, forced labor, and safety compared to industrial composting, as observed in Fig. 7.
(iii) Fossil-based gowns are environmentally and socially sustainable due to a 14.32% reduction in human toxicity (cancer), 10.23% decrement in total GHG emissions, and 9.71% reduction in freshwater ecotoxicity, compared to biodegradable gowns treated by landfills arising from the pro-oxidant production and uncaptured LFG emissions, as indicated by Figs. 10 and 11.
(iv) Improving the LFG capture efficiency above 85% can make biodegradable gowns more environmentally sustainable than conventional gowns by cutting GHG emissions by more than 45% and fossil resource use when biogenic methane oxidation and heat generation efficiencies increase to more than 81% shown by Fig. 13.

Our work investigates the environmental and social sustainability of conventional and biodegradable gowns. Policymakers can refer to the following implications to advocate for improving the environmental and social sustainability of conventional and biodegradable gowns:

(i) Sanitary landfill leachate emission control, innocuous chemical use in pro-oxidant production, and effective disposable gown reuse should be current research needs to alleviate the environmental pressure from medical gowns or generic plastic EoL disposal in landfills.
(ii) Advancing the pro-oxidant synthesis route by reducing solvent use, monitoring LFG oxidation conditions, and meticulously controlling LFG emissions should be incentivized to gain environmental benefits from biodegradable gowns over conventional counterparts.
(iii) Easy operation and safe working conditions should be maintained to limit the labor intensity and other negative social impacts, including safety risks and frequency of forced labor, from the heat and power co-generation in the LFG capture and utilization process that can reduce GHG emissions and save fossil resources.

2. Material and methods

2.1. Research scope

This comparative LCA study aims to investigate the pros and cons of the biodegradable gown over fossil-based counterparts by holistic environmental and social impact assessments across the entire life cycle confined by the system boundary shown in Figs. 1 and 2. This system boundary includes upstream processes corresponding to the extracting

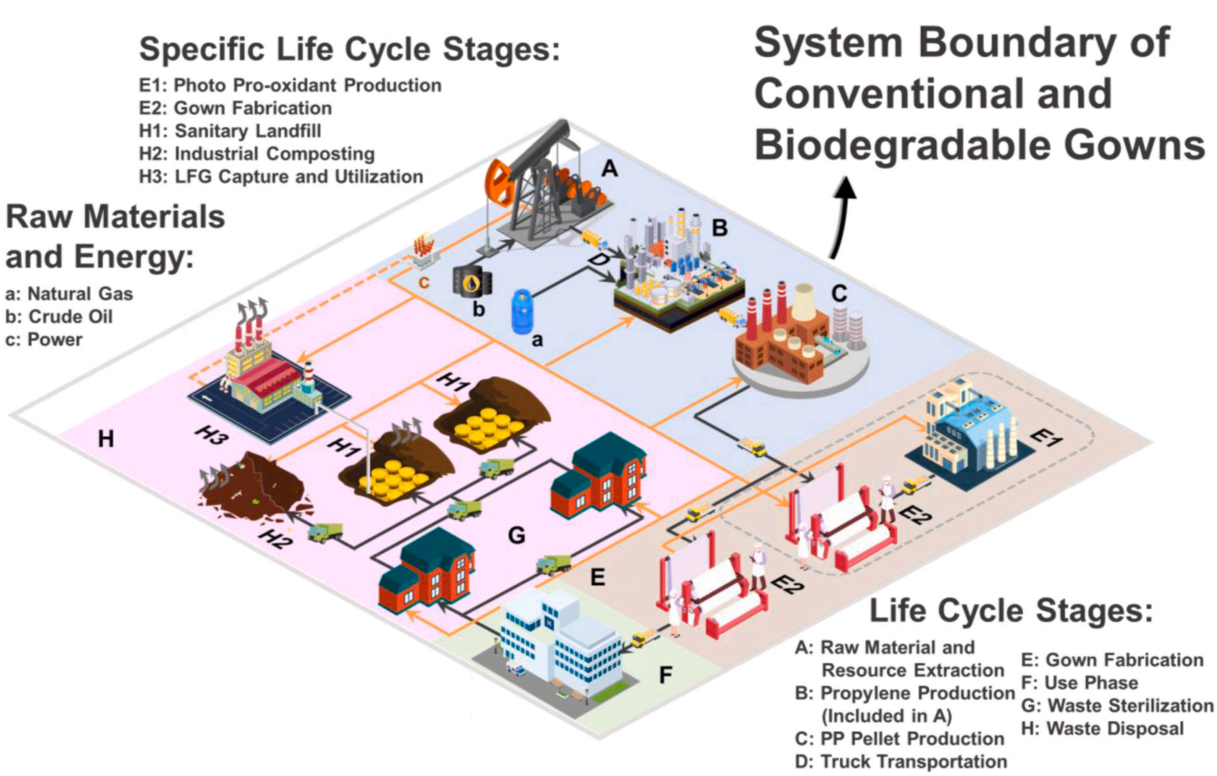

Fig. 1. This comparative LCA study's system boundary corresponds to the conventional and biodegradable gowns. The system boundaries confine the life cycle stages from raw material and resource extraction to EoL disposals, including landfilling for both gowns and biodegradable gown composting. The system boundary of conventional gown waste treated by sanitary landfills covers raw material and resource extraction, propylene production, polypropylene pellet production, truck transportation, gown fabrication, use phase, waste sterilization, and sanitary landfill. Life cycle stages of raw material and resource extraction, propylene production, polypropylene pellet production, truck transportation, photo pro-oxidant production, gown fabrication, use phase, and waste sterilization are all included in the system boundaries of biodegradable gown waste treated by sanitary landfills and industrial composting. These system boundaries also include their specific life cycle stages: LFG capture and utilization for sanitary landfills and industrial composting. The cradle of the conventional and biodegradable gowns are natural gas and crude oil, represented by a and b, respectively, while the c denotes the energy used across the entire gown life cycle.

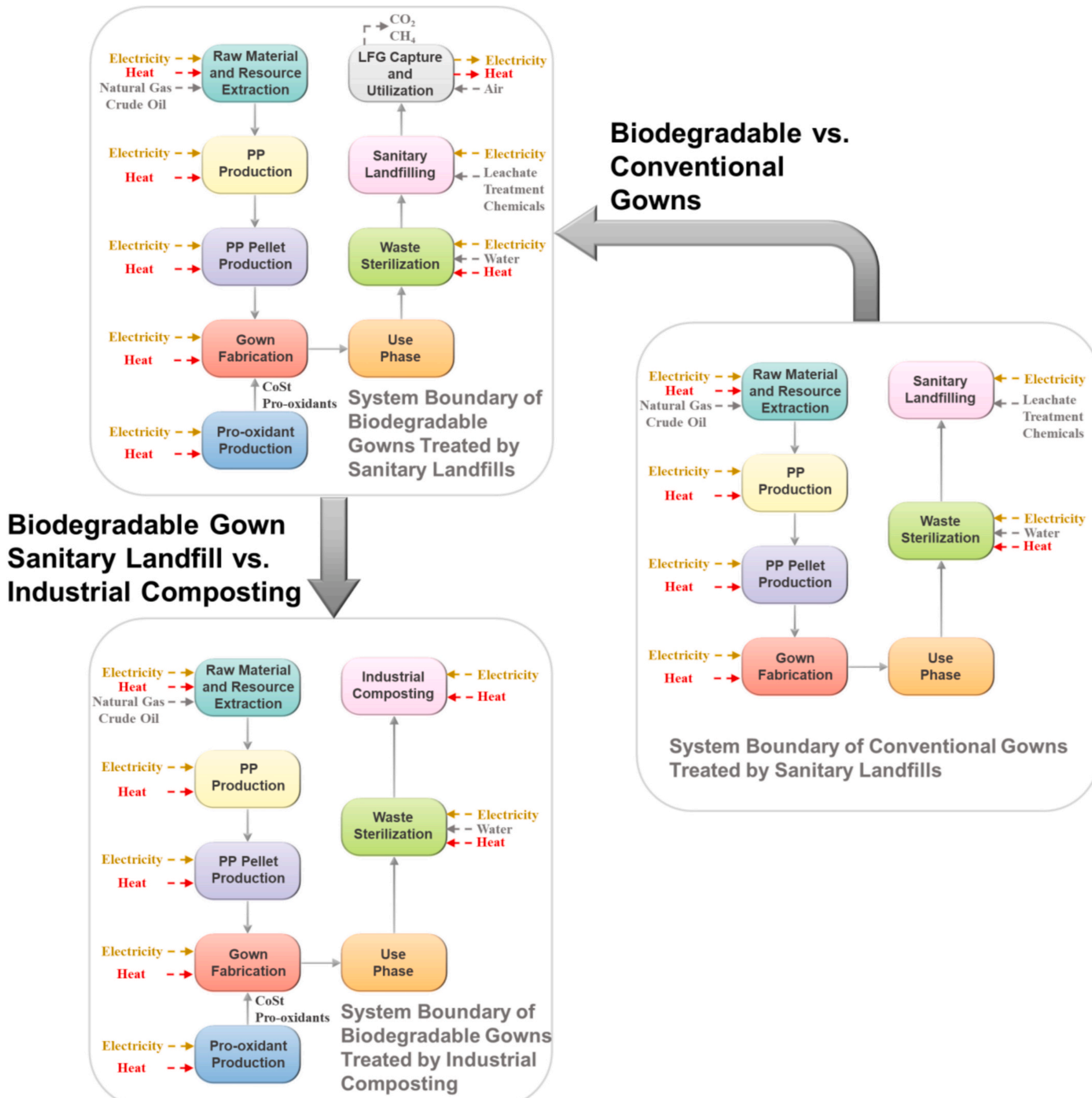

Fig. 2. System boundary flow charts that show detailed life cycle stages of biodegradable and conventional gowns treated by various waste EoL methods: Sanitary landfills and industrial composting.

the raw material and resource, involving the crude oil and natural gas, polypropylene production, gown fabrication, use phase, waste sterilization, and transportation, while the downstream processes are gown EoL disposals. Landfill processes are considered for both biodegradable and conventional gowns, given their wide application in treating plastic waste (Zhou et al., 2014). Due to the negligible LFG emissions within centuries, the LFG capture and utilization processes are not incorporated with conventional gowns (Bora et al., 2020). For biodegradable plastic landfills, the LFG emissions are utilized to generate heat and medium voltage electricity via reciprocal engines (Ogunjuyigbe et al., 2017), and the power generated is then sold to the grid. Meanwhile, composting is another EoL management technology alternative for biodegradable gowns due to its relatively low cost and easy operations compared with landfills (Lou and Nair, 2009). The CoSt photo-prooxidants that catalyze biodegradation used in biodegradable gowns are not considered in conventional gowns (Sable et al., 2021). The functional unit is chosen as one-ton waste gowns treated to fit the research goal of this comparative LCA work and align the mass and energy flow information across the entire gown life cycle (Yang et al., 2018).

2.2. Environmental LCIs

The upstream and downstream processes' mass and energy flow rates were collected as the LCIs, which were then interpreted into environmental impact evaluation results aided by characterization factors extracted from diverse life cycle impact assessment (LCIA) methods. The plastic compartments within biodegradable gowns were nonwoven polypropylene films (Carre, 2008), of which life cycle inventories shown in Table 1 were extracted from the Ecoinvent V3.8 Database. The CoSt pro-oxidants (catalyst), which is synthesized from cobalt acetate, sodium hydroxide, and steric acid at 90 °C, is embedded in the PP film under 120 °C (Asriza and Arcana, 2015) to enable fast degradation of biodegradable gowns to landfill gas (LFG), including methane and CO_2. Table 2 summarizes the energy and chemical use of pro-oxidant production.

The LCI data corresponding to the packaging materials production is included in Table 3 (Vozzola et al., 2020). Besides gown product and package production, the total gown waste transportation load is evaluated (Zhao and You, 2021) based on the road transportation detour factor and distances between the landfilling sites and the medical care locations extracted from New York State Government Website (State, 2022). The medical gown requires disinfection before the EoL waste treatment. Table 4 summarizes the material and energy requirements for pretreating the medical gown wastes via the autoclave steam sterilization process (van Straten et al., 2021).

The downstream processes corresponding to gown EoL disposals account for industrial composting and sanitary landfilling after disinfection. The sanitary landfills' LCIs given in Table 5 are built based on the chemical and energy use data for landfilling infrastructure and operation, leachate treatment, and LFG capture and utilization processes given in Table 6 within 60 years. The LCI data corresponding to sanitary landfills infrastructure, chemical and energy consumption rates, and leachate treatment by wastewater treatment processes are extracted from Demetrious et al. (Wang et al., 2021). Specifically, the LFGs yielded from decomposing biodegradable gowns are mainly CH_4 and CO_2, of which flow rates respectively represented by vvc and vva in Eqs. (1)–(4) are calculated based on the degradation kinetics (Eq. (1)) data given in (Demetrious and Crossin, 2019) for biodegradable plastics. Specifically, the LFG capture efficiency (ceff) is assumed to be 75% (Cudjoe and Han, 2020), and parameters oeff, m, mm, mch, per represent the biogenic methane oxidation efficiency, mass of disposable gown waste, plastic content in biodegradable gowns, monomer molecular weight, and the percentage of pro-oxidants (0.4% wt.%) (Sable et al., 2021) embedded in gowns, respectively. All LFGs are dewatered, treated by siloxane removal processes (Elwell et al., 2018), and used to co-generate medium-voltage electricity at 40.2% and heat at 33% efficiencies (Ogunjuyigbe et al., 2017). The avoided burden approach is applied to account for the environmental benefits from this onsite heat and electricity co-generation, of which environmental impacts are subtracted from the total environmental assessment results.

$$vco = 10^{-7}\cdot\left(1-e^{-0.17121t}\right)+10^{-7}\cdot\left(1+188.143e^{-0.17212t}-189.143e^{-0.17121t}\right) +0.9999\cdot\left(1-1.025e^{-0.00515t}+0.025e^{-0.17121t}\right) \tag{1}$$

$$mm = \frac{m}{mch}\cdot\frac{1}{1+per} \tag{2}$$

Table 1
The LCI model regarding gown production.

Chemical and Energy Input		
Input	Amount per FU	Unit
Textile production, nonwoven polypropylene, spunbond [RoW] (Wrap + gown)	1,000	kg
Market for electricity, high voltage [US-NPCC]	2,777.78	kWh
Market for heat [GLO]	5,420	MJ
Market for tap water [CA-QC]	1	m^3

Table 2
The LCI model regarding pro-oxidants production.

Chemical and Energy Input		
Input	Amount per FU	Unit
Market for stearic acid [GLO]	1.28	kg
Market for sodium hydroxide, without water, in 50% solution state [GLO]	0.42	kg
Market for cobalt acetate [GLO]	0.56	kg
Market for ethanol, without water, in 99.7% solution state, from ethylene [RoW]	33.41	kg
Market for water, decarbonized [US]	0.21	m^3
Market for heat, district or industrial, natural gas [CA-QC]	1,062.78	MJ

Table 3
The LCI model regarding packaging production considers primary, secondary, and tertiary packaging.

Chemical and Energy Input		
Input	Amount per FU	Unit
Market for electricity, high voltage [US-NPCC]	194.32	kWh
Market for heat, from steam, in chemical industry [RoW]	20.68	MJ
Market for heat, district or industrial, natural gas [RoW]	7.79	MJ
Market for diesel [RoW]	3.86	kg
Market for paper, woodfree, uncoated [RoW]	12.46	kg
Market for electricity, high voltage [US-NPCC]	26.83	kWh
Market for polyethylene, low density, granulate [GLO]	55.89	kg
Market for electricity, high voltage [US-NPCC]	5.79	kWh
Market for polyethylene, low density, granulate [GLO]	12.06	kg
Market for folding boxboard carton [RoW]	100.52	kg
Market for packaging film, low density polyethylene	1.33	kg
Market for electricity, high voltage [US-NPCC]	194.32	kWh

Table 4
The LCI model regarding sterilization process, including sterilization bag production and waste sterilization.

Chemical and Energy Input		
Input	Amount per FU	Unit
Market for kraft paper, bleached [GLO]	4.70	kg
Market for high-density polyethylene, granulate [GLO]	3.51	kg
Market for electricity, high voltage [US-NPCC]	43.83	kWh
Market for tap water [CA-QC]	0.92	m^3

Table 5
The LCI model regarding landfill infrastructure and operation.

Chemical and Energy Input		
Input	Amount per FU	Unit
Market for clay [RoW]	0.90	kg
Market for sand [RoW]	0.53	kg
Market for gravel, crushed [RoW]	0.037	kg
Market for polyethylene, high density, granulate, recycled [US]	0.0012	kg
Market for polyethylene pipe, corrugated, DN 75 [GLO]	0.00003	m
Market for polyethylene pipe, corrugated, DN 75 [GLO]	0.00002	m
Market for steel, low-alloyed [GLO]	0.0040	kg
Market for mastic asphalt [GLO]	0.0014	kg
Market for concrete, 35 MPa [RoW]	0.00009	kg
Market for electricity, high voltage [US-NPCC]	0.00075	kWh
Market for diesel, burned in building machine [GLO]	0.023	MJ
Transport, freight, lorry >32 t, EURO6 [RoW]	0.0090	t·km
Lorry, 40 t [RoW]	0.00030	unit
Market for transport, freight, lorry 7.5–16 t, EURO6 [RoW]	0.025	t·km
Lorry, 16 t [RoW]	0.0011	unit

Table 6
The LCI model regarding landfill gas capture and utilization (The negative values represent the avoided offsite electricity and heat co-generation amount).

Chemical and Energy Input		
Input	Amount per FU	Unit
Market for cooling energy [GLO]	2696.73	MJ
Market for electricity, high voltage [US-NPCC]	32.03	kWh
Market for chemical factory, organics [GLO]	5.74E-6	unit
Market for electricity, medium voltage [US-NPCC]	−2357.13	kWh
Steam production, as energy carrier, in chemical industry [RoW]	−10337.10	MJ
Treatment of wood ash mixture, pure, municipal incineration [RoW]	0.00002	kg
Treatment of wastewater, average, capacity 1E9l/y [RoW]	0.0040	m^3
CO_2	1509.64	kg
CH_4	104.02	kg

$$vvc = vco \cdot mm \cdot ceff \cdot mco + vco \cdot mm \cdot oeff \cdot (1 - ceff) \cdot mco \tag{3}$$

$$vva = vco \cdot mm \cdot (1 - oeff) \cdot (1 - ceff) \cdot mme \tag{4}$$

The LCIs of gown waste composting are built based on the energy and chemical consumption rates and chemical compositions of the off-gas emissions, which are assumed to be the average from composting eight biodegradable plastics from relevant literature (Hermann et al., 2011). The flow rate of CO_2 from off-gas is calculated based on the degradation kinetics given by (Sable et al., 2021). The LCIs given in Table 7 are extracted from the industrial composting process data within Ecoinvent V3.8 Database using the cut-off method.

3.1. Environmental impact assessment

These environmental LCI data are then converted into environmental impact evaluation results based on various environmental indicators to determine plastic pollution and its derived environmental impacts on air, water, soil, and ecosystems. The product-level environmental indicators, including Environmental Footprints database 3.0 (EF 3.0) and ReCiPe, are chosen to reflect the life cycle environmental impacts posed by gowns. Three environmental assessment perspectives and their corresponding evaluation time horizons, namely individualist: 20 years, hierarchist: 100 years, and egalitarian: 500 years, are considered in ReCiPe indicators to show the short- and long-term emissions (Huijbregts et al., 2016). Climate change is another vital global issue of plastic EoL management, and the GHG emissions over 20 years, 100 years, and 500 years right after the gown production based on the global warming potential (GWP) indicators extracted from the Intergovernmental Panel on Climate Change (IPCC) 2013 LCIA method (Ford et al., 2012) are evaluated.

3.2. Social LCIs

The social LCIs are built based on the economic input-output analysis results that reflect the economic interdependencies between economic sectors or gown life cycle stages involved in the gown value chain. The TEA methodology is applied to evaluate the operating and maintenance expenses (O&M, represented by symbol: *omm*) of these processes accounting for the plant maintenance cost (*mcc*) and worker salaries (*ws*) given in Eq. (5), by referring to the plastic recycling studies (Zhao and You, 2021). These operating expenditures presented in Eq. (6) are converted into the social LCIs (*slcii*) based on the average working hour (*wh*) as the activity variable (Ciroth and Eisfeldt, 2016), which enables a fair representation of the economic values generated in different sectors and can be collated into the specific share of economic values of each unit process within the gown life cycle (Ciroth and Eisfeldt, 2016). The average working hours (*slcii*) of the gown life cycle stages are evaluated based on those of the U.S. chemical engineering plant and solid waste

Table 7
The LCI model of operating waste gown composting processes

Chemical and Energy Input		
Input	Amount per FU	Unit
market for composting facility, open | composting facility, open | Cutoff, U - GLO	7.41E-06	Unit
market for electricity, low voltage | electricity, low voltage | Cutoff, U - AU	1.23E-01	kWh
market group for electricity, low voltage | electricity, low voltage | Cutoff, U - RNA	2.58	kWh
market group for electricity, low voltage | electricity, low voltage | Cutoff, U - RAS	5.54	kWh
market for electricity, low voltage | electricity, low voltage | Cutoff, U - RU	5.06E-01	kWh
market group for electricity, low voltage | electricity, low voltage | Cutoff, U - Europe without Switzerland	1.77	kWh
market group for electricity, low voltage | electricity, low voltage | Cutoff, U - RAF	3.61E-01	kWh
market group for electricity, low voltage | electricity, low voltage | Cutoff, U - RLA	8.97E-01	kWh
market for electricity, low voltage | electricity, low voltage | Cutoff, U - NZ	2.24E-02	kWh
market for machine operation, diesel,≥74.57 kW, low load factor | machine operation, diesel,≥74.57 kW, low load factor | Cutoff, U - GLO	3.52E-01	h
market for electricity, low voltage | electricity, low voltage | Cutoff, U - AU	1.39E-03	t·km
market group for electricity, low voltage | electricity, low voltage | Cutoff, U - RNA	1.71E-02	unit
market group for electricity, low voltage | electricity, low voltage | Cutoff, U - RAS	8.69E-06	t·km
market for electricity, low voltage | electricity, low voltage | Cutoff, U - RU	2.41E-05	unit
market group for municipal solid waste | municipal solid waste | Cutoff, U - Europe without Switzerland	1.39E-03	kg
market for municipal solid waste | municipal solid waste | Cutoff, U - RoW	1.71E-02	kg
market for municipal solid waste | municipal solid waste | Cutoff, U - IN	8.69E-06	kg
market for municipal solid waste | municipal solid waste | Cutoff, U - CA-QC	2.41E-05	kg
market for municipal solid waste | municipal solid waste | Cutoff, U - CY	6.08E-06	kg
market for wastewater, average | wastewater, average | Cutoff, U - Europe without Switzerland	7.28E-02	m^3
market for wastewater, average | wastewater, average | Cutoff, U - RoW	1.52E-01	m^3
CO_2	3136.58	kg
CH_4	18	kg
N_2O	0.025	kg

treatment sites (*wh*) and their O&M expenditures (*basc*) (Yang and You, 2017).

$$omm = mcc + ws \tag{5}$$

$$slcii = \frac{omm \cdot wh}{basc} \tag{6}$$

3.3. Social impact assessment

The social impacts (*sim*) of gown life cycle stages are then evaluated by scaling these average working hour-based social LCI data (*slcii*) based on a set of specific social risk factors (*rl*) in each social impact indicator, as given in Eq. (7). All these risk factors are defined in the well-archived PSILCA Database that offers transparent and latest social impact analysis data on global regions and their commodity and industry sectors. Three key social impacts of solid waste management sectors (Santos et al., 2019), including worker welfare, employment, and domestic economic growth, are considered in this study from different stakeholder perspectives. The social impacts of the offsite chemical and energy manufacturing required for gown life cycle processes are directly evaluated by the Soca Database. This database aggregates the unit processes given by the Ecoinvent Database by commodity and industry sectors, which are projected to the PSILCA Database to generate the social LCIs and impact assessment results (Eisfeldt, 2017). All the social LCI data are interpreted into S-LCA results in the unit of mid-risk or opportunity working hours, representing the average working hours needed to reduce certain extents of the negative social impacts or gain social benefits.

$$sim = slcii \cdot rl \tag{7}$$

4. Results and discussion

This work investigates gowns' environmental and social sustainability by identifying and comparing environmental hotspots posed by conventional and biodegradable gowns. Three gown case studies corresponding to conventional and biodegradable gowns and their different EoL waste disposal technologies after disinfection are considered in our comparative LCA study and outlined below.

(i) Conventional gowns, of which waste is treated by sanitary landfills (Conventional gown landfills);
(ii) Biodegradable gowns, of which waste is treated by sanitary landfills (Biodegradable gown landfills);
(iii) Biodegradable gowns, of which waste is treated by industrial composting (Biodegradable gown composting).

The full-spectrum environmental performances of these gowns are overviewed and compared based on the EF 3.0 (Saouter et al., 2018), USEtox (Fantke et al., 2017), GWP (Pearce et al., 2014), and ReCiPe indicators (Huijbregts et al., 2016). to identify the environmental hotspot life cycle stages and spaces for sustainability improvement. The arising social impacts of gowns are assessed based on all the indicators relevant to workers, unemployment, and economic development in the PSILCA Database to reflect domestic economic growth, job creation, and worker welfare as typical socio-economic concerns of commodity production and EoL management sectors.

4.1. Conventional gown wastes landfilling

Conventional gowns made from polypropylene are now used pervasively, and their detailed environmental and social analysis aided by the comparative LCA approach can unfold the pros and cons, and future technical innovations of gown disposal towards sustainability. Fig. 3 shows the full-spectrum life cycle environmental impacts of the conventional gown and its waste treated by sanitary landfills based on the EF 3.0 indicators. Offsite production of the packaging materials used for gown product manufacturing, involving low-density polyethylene film, insert paper, and boxboard, is the major contributor to the environmental impacts of gown production, which can pose 57.68% acidification, 60.50% climate change, 89.10% land use, 60.85% freshwater ecotoxicity, 60.19% energy resource use, 61.93% freshwater, 61.61% soil eutrophication, 50.36% human toxicity, 59.36% ionizing radiation, and 58.42% particulate matter formation. Transportation of basic chemicals is another environmental hotspot corresponding to 95.87% non-cancer human toxicity, 88.64% ozone depletion, and 89.67% particulate matter formation effects caused by the direct NO_x and GHG emissions when burning fossil fuels. Moreover, the sanitary landfilling process can pose 9.95% human toxicity related to cancer due to chronic leachate emissions from soil metal ions and 8.64% metal resource depletion caused by manufacturing chemical products used for leachate treatments. These environmental hazards can be reduced if an environmentally sustainable waste disposal technology is implemented for gown EoL management (Zhao and You, 2021).

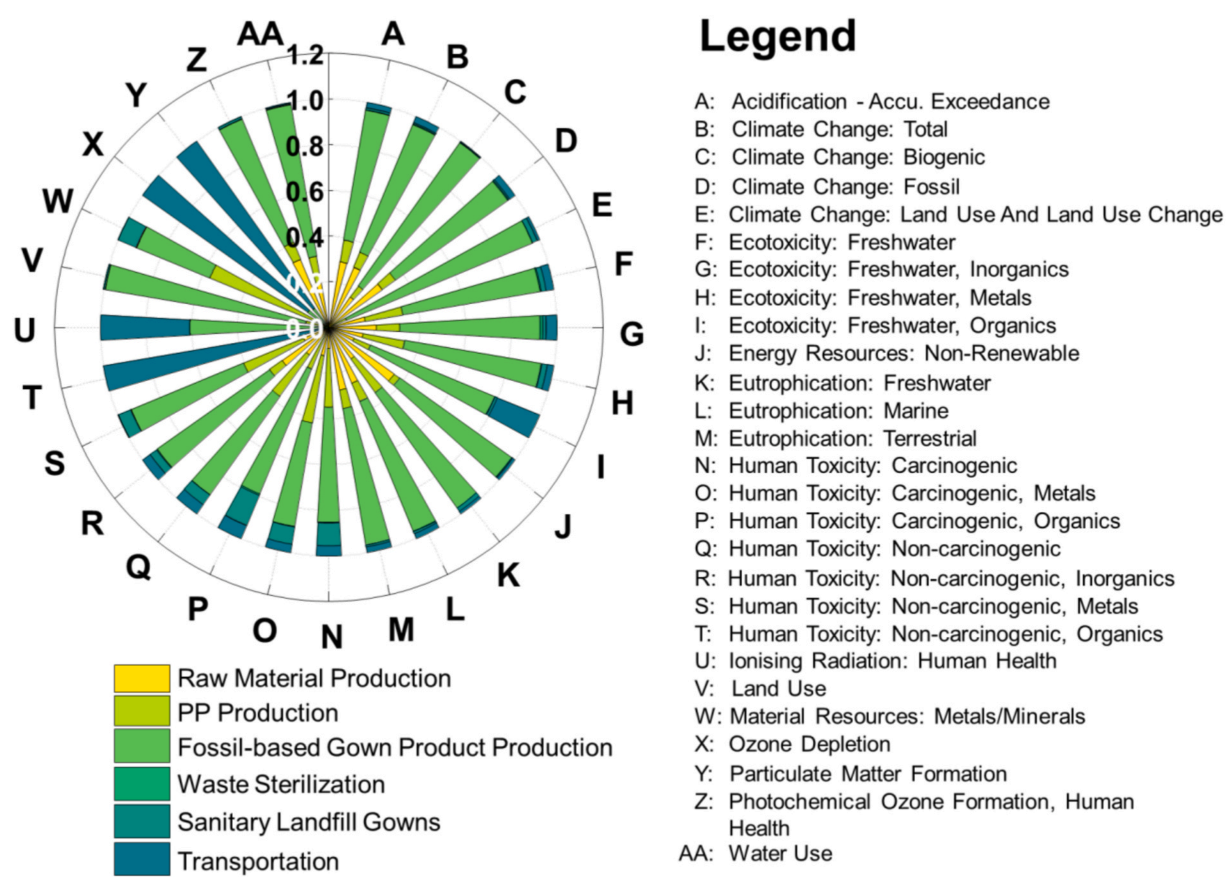

Fig. 3. Environmental profiles of conventional gown treated by sanitary landfills based on EF 3.0 indicators.

Investigation of the environmental sustainability of biodegradable gowns over conventional counterparts can be further reinforced by assessing and comparing the environmental consequences that account for short and long-term environmental emissions. The environmental hotspots shown in Fig. 4, including gown product manufacturing and transportation, are identical to Fig. 3 and not varied from 20 to 500 years. On the other hand, conventional gown landfills only contribute to about 1% of overall environmental impacts. Therefore, conventional gowns should cut their packaging material consumption by using lighter cartons or plastic foams to enhance the environmental sustainability of gowns (Su et al., 2020).

The social impacts of conventional gowns are analyzed to reflect socio-economic concerns corresponding to domestic economic growth, job creation, and worker welfare. Polypropylene raw material production tops other life cycle stages in 16 social impact indicators given Fig. 4 due to the high safety risks in the hard coal mining used for raw materials that discourage workers from staying in this sector and increase its unemployment rate. However, the expanded gown consumption can prompt its raw material production due to COVID-19 (Uddin et al., 2022) and contribute to 90.30% of the overall economic growth measured by domestic product growth (GDP). The incremental gown production, in this context, leads to negative social impacts corresponding to workers' safety, use, and working hours. Specifically, the non-woven polypropylene production process can worsen the natural disaster risks to workers because of the dangerous heating process used for melting the polypropylene granulates for textile manufacturing (Gahan and Zguris, 2000). The sanitary landfilling process, which is technically uncomplex compared to natural gas and crude oil extraction processes, has lower operating and maintenance costs denoted by omm in Eq. (5) (Brunner and Keller, 1972). Therefore, the social impacts (sim) of the waste sanitary landfilling processes evaluated by Eqs. (6) and (7) are lower than the gown upstream processes. Given the less labor intensity, low risks in working environments, and less economic value generated, the social impacts of the waste sanitary landfilling processes are lower than the gown upstream processes.

4.2. Biodegradable gown wastes landfilling

The biodegradable gown can undergo photo-oxidation and be degraded into monomeric gaseous molecules involved in the LFGs, which can be captured and used for onsite heat and mid-voltage electricity generation. Their onsite manufacturing can benefit from offsetting the offsite production and reducing the ensuing environmental burdens. In practice, the environmental benefits of biodegradable gowns still require quantitative estimates and comparison with conventional gowns to substantiate the pros and cons of conventional counterparts.

Environmental burdens of biodegradable gowns treated by sanitary landfills are mainly determined by the emissions from natural gas and crude oil extraction and the landfill and LFG capture and utilization processes. Given the insufficient LFG capture in biodegradable sanitary landfills, the GHG emissions from uncaptured methane can pose 99.48% of life cycle biogenic-based climate change effects, as shown in Fig. 5. The LFG capture and utilization processes also require extra mineral mining for infrastructure and maintenance, which leads to 40.10% of total freshwater ecotoxicity caused by inorganic chemicals and 40.13% of freshwater eutrophication. Moreover, pro-oxidants used for achieving gown's biodegradability are composed of cobalt salt that requires offsite production, which can release toxic cobalt ions within leachate emissions and pose 88.20% of total metal depletion. Additional chronic chemical emissions control, sustainable chemical additive production, and enhancement of LFG capture and utilization efficiencies can enhance biodegradable gowns' environmental sustainability.

The environmental benefits of adopting LFG capture and utilization processes shown in Fig. 5, on the other hand, can be foreseen as reductions of 9.79% of the life cycle climate change effects posed by fossils, 7.08% of GHGs posed by land use, and 16.08% of ionizing radiation effects related to human health. The onsite electricity and heat co-generation can replace their offsite production and decrease their subsequent environmental burdens. Future efficiency improvements on the LFG capture and heat and electricity co-generation can be investigated to help foster these environmental benefits in pursuing the environmental sustainability of biodegradable gowns.

Similar to conventional gowns, the disposal of biodegradable gowns leads to socio-economic concerns corresponding to worker welfare, job creation, and economic growth. Fig. 7 indicates that biodegradable gown production leads to the most serious safety problems, given the toxicity release in the cobalt salt production used for pro-oxidant manufacturing. The integration of LFG capture and utilization can enhance the operating and maintenance costs denoted by omm in Eq. (5) and can worsen the negative social impacts of forced labor, safety

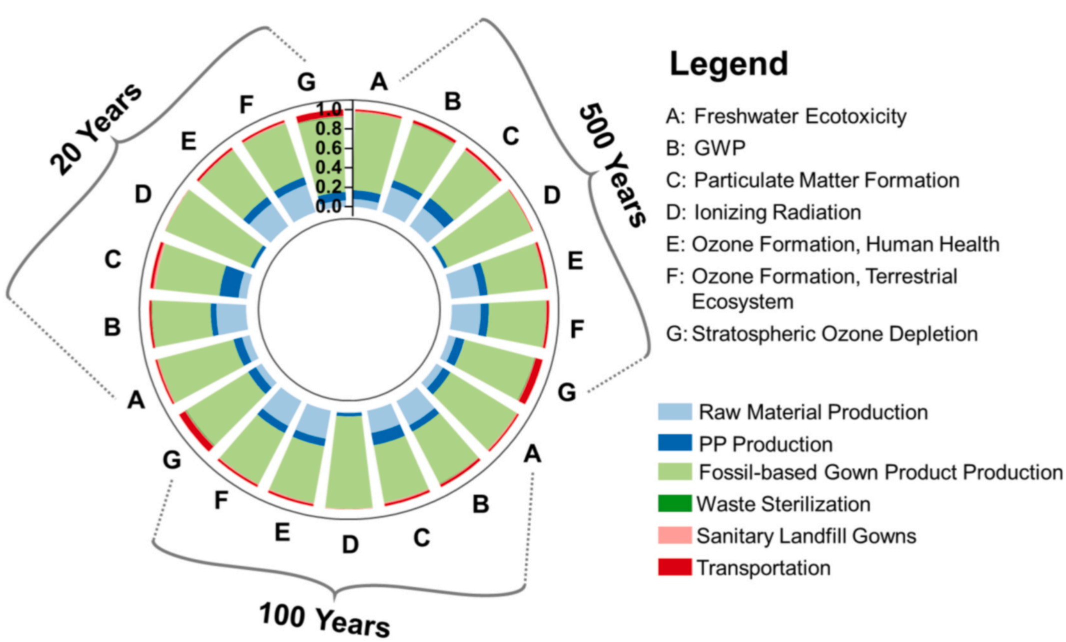

Fig. 4. Environmental profiles of conventional gowns treated by sanitary landfills over 20, 100, and 500 years based on USEtox, GWP, and ReCiPe indicators.

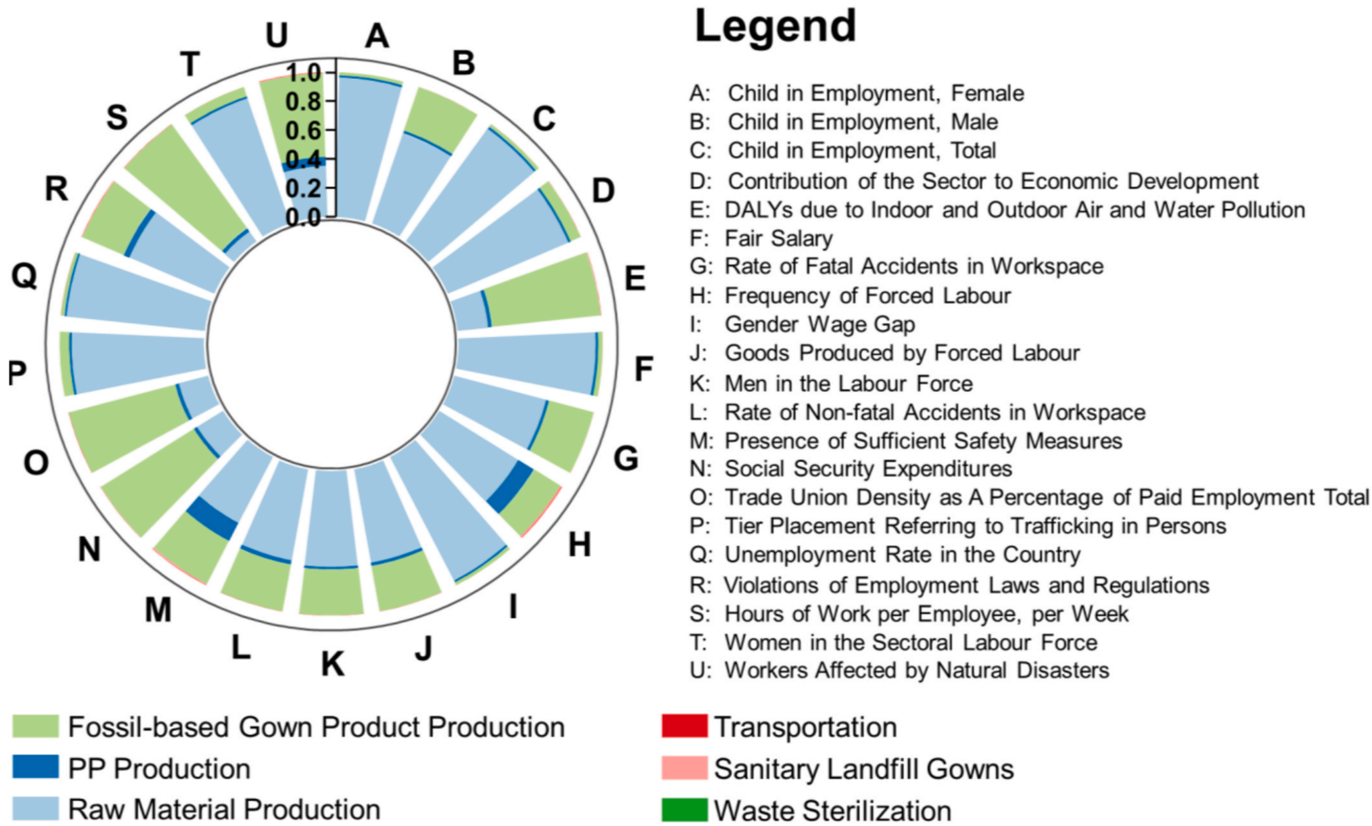

Fig. 5. Social sustainability profiles of conventional gown treated by sanitary landfills.

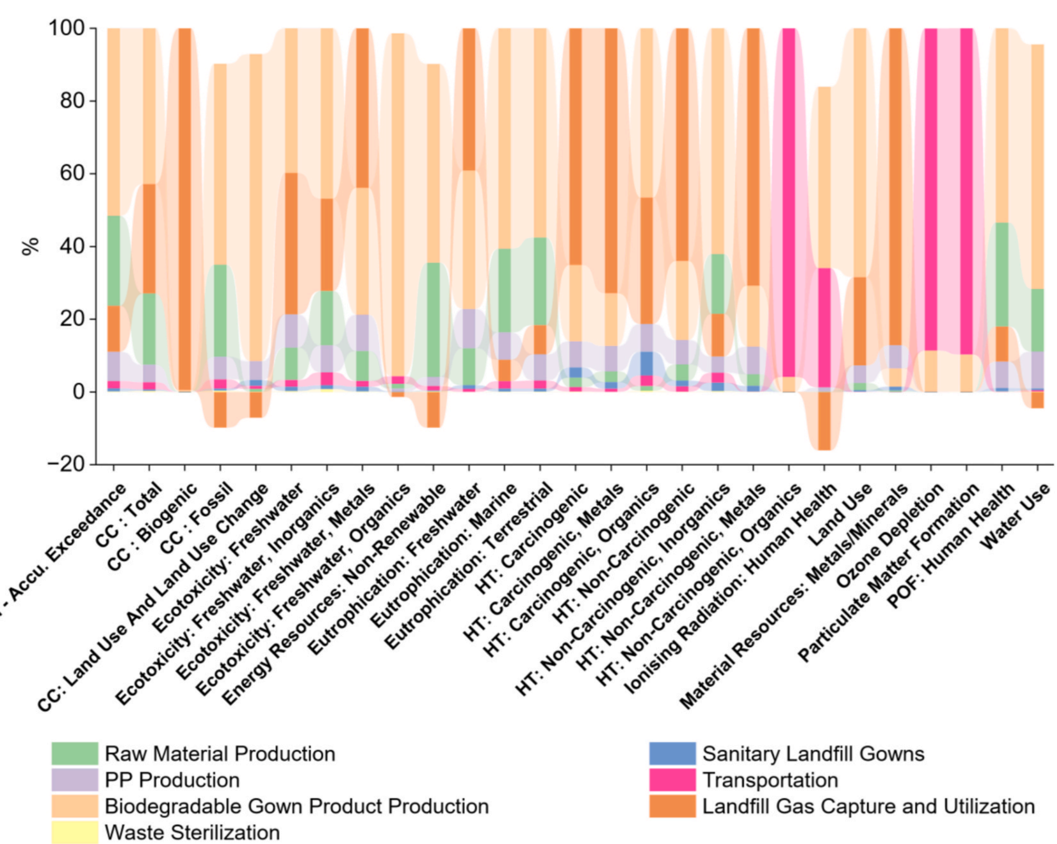

Fig. 6. Environmental profiles of biodegradable gown treated by sanitary landfills based on EF 3.0 indicators.

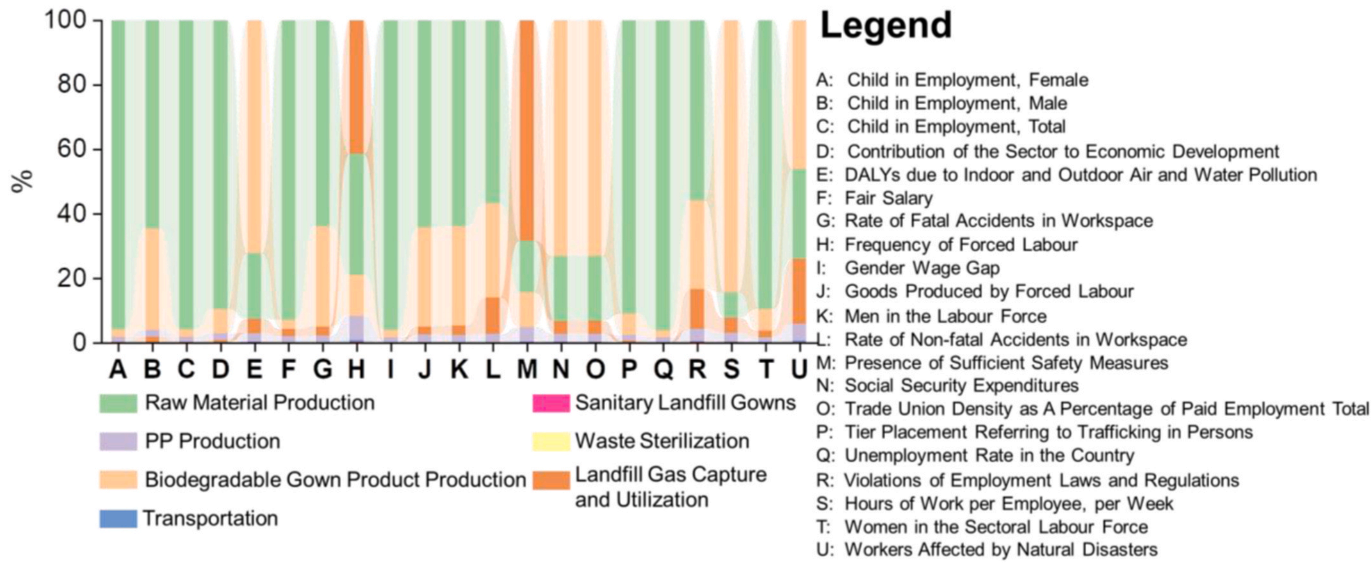

Fig. 7. Social sustainability profiles of biodegradable gown treated by sanitary landfills.

measures, and natural disaster risks (sim evaluated by Eqs. (6) and (7)) due to the additionally unsafe working environment and the high labor intensity in the power plant. On the other hand, the high raw material acquisition rate for gown production can benefit society by contributing to the sector's economic development, shown as the environmental hotspot in Fig. 7.

Overall, biodegradable gowns and their waste EoL treatment via sanitary landfills can embrace both environmental benefits aided by LFG capture, utilization, and hazards from pro-oxidant production. The heat and medium-voltage electricity onsite co-generation from LFG can replace their offsite production to reduce emissions. However, capturing the LFG from biodegradable gown sanitary landfills can also generate environmental problems corresponding to material resource depletion and human toxicity, as shown in Fig. 6. In this context, quantitative estimates and comparison of sanitary landfills' environmental and social performances with other technically viable waste EoL disposal technologies, such as composting, can help provide technical insights on sustaining the gown from their waste disposal sectors.

4.3. Biodegradable gown wastes composting

Besides sanitary landfills, industrial composting used widely in

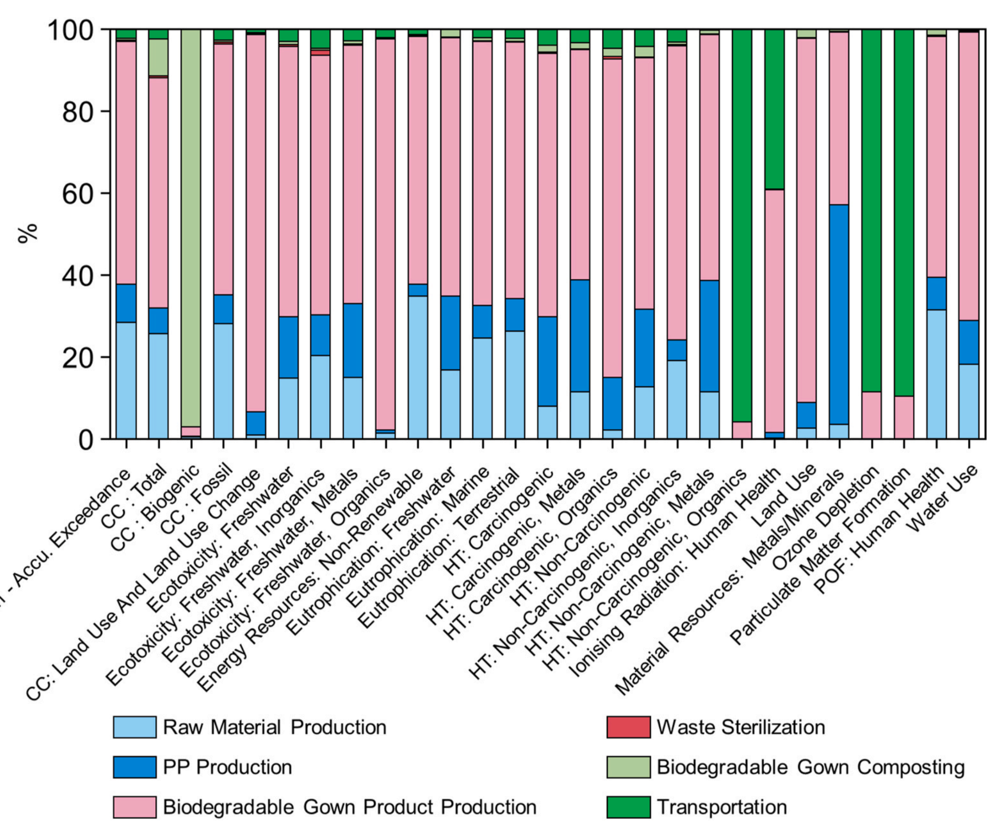

Fig. 8. Environmental profiles of biodegradable gown industrial composting processes based on EF 3.0 indicators.

biomass treatment can also be applied in biodegradable plastics waste management aided by easy and efficient decomposition by soil organisms (Abdelmoez et al., 2021). Given the relatively short degradation time of four years of biodegradable polypropylene materials, composting is considered as another biodegradable gown disposal technology.

Biodegradable gown composting can form biogenic carbon dioxide emissions from polypropylene photo-oxidation aided by pro-oxidants and results in 8.97% and 97.05% of the overall and biogenic life cycle GHG emissions, respectively, as shown in Fig. 8. Given the relatively lower chemical and energy consumption rates and simple infrastructure compared to other EoL management processes (Chin et al., 2022), industrial composting can contribute 2% of the life cycle human toxicity. Besides environmental hazards, biodegradable gown composting poses only 0.06% of the sector to economic development and also requires some safety measures that account for 0.8% of the life cycle impacts on reducing the risks of the toxic chemical emissions from composting, as shown in Fig. 9. Overall, both meticulous chemical emission control (Krzymien et al., 1999) and CO_2 capture processes (Leung et al., 2014) can be integrated with biodegradable gown waste composting to reduce its environmental and social consequences.

4.4. Conventional gown landfilling versus biodegradable gowns composting

The biodegradable gowns' environmental and social sustainability over conventional counterparts is investigated by comparing three proposed gown case studies' life cycle environmental and social impacts. These comparative results can also imply future technical innovations in EoL management sectors and guide the judicious selection of medical gown suppliers from the environmental and social sustainability perspectives.

The comparative life cycle environmental impact results of gown wastes treated by composting versus landfilling given in Fig. 10 demonstrates the pronounced environmental advantages of industrial composting on full-spectrum EF 3.0 impact categories, excluding ecotoxicity, ozone depletion, particulate matter formation, and water use. Since the biodegradable plastic can undergo complete oxidation into CO_2 in industrial composting processes, the uncaptured methane from LFG, which accounts for 25% of total carbons, can pose a much higher GWP than CO_2 emitted from composting and offset the environmental advantages gained from onsite electricity and heat production within landfill sites. Moreover, the extra infrastructures and chemicals used to capture and utilize LFG can worsen these environmental aftermaths. Therefore, industrial composting shows its environmental sustainability in biodegradable gown EoL disposals.

The E-LCA results of the conventional gown treated by landfills and biodegradable gowns managed by industrial composting is then compared to investigate the environmental sustainability of gowns. Fig. 10 displays the higher life cycle environmental impacts of biodegradable gown wastes treated by composting than conventional gowns ending up in landfills based on all full-spectrum EF 3.0 impact categories, especially a 3,567% higher biogenic GHG emissions and 835% higher ecotoxicity effects caused by organic chemical emissions. The uncaptured CO_2 emissions from industrial composting can lead to this higher climate change potential, while the ethanol solvent production used for chemical additive production can increase organic ecotoxicity problems across the entire life cycle of biodegradable gowns. These environmental aftermaths result in 11.39% higher total climate change and 10.76% freshwater ecotoxicity. Industrial composting biodegradable gowns can also increase total human toxicity related to cancer by 16.71% over conventional gown landfilling due to the soluble cobalt metal ions emissions from photo pro-oxidants embedded in biodegradable polypropylene. Therefore, future investigations to reach environmental sustainability on biodegradable gown disposal can focus on capturing the GHG emissions, especially CO_2, from industrial composting processes, leachate emission control, or mitigating emissions from producing pro-oxidants for plasticized gown biodegradation. Reducing the organic solvent use by implementing the solvent recycling process in synthesis can mitigate the ecotoxicity impacts of CoSt pro-oxidant production. Another effective measure is to replace the CoSt pro-oxidants with ecological-benign chemicals in biodegradable gown fabrication. Effective leachate and gas emissions control and innocuous chemical use for material production, in general, can help achieve environmentally sustainable EoL management for not only conventional and biodegradable gowns but also generic plastic materials.

The social impacts of conventional gown landfilling, including those related to workers' welfare, employment, and domestic economic growth, are close to biodegradable gown composting, given the similar labor intensity and economic value generated from landfills and composting. Although integrating the LFG capture and utilization processes with biodegradable gown sanitary landfills can reduce the social impacts of offsite energy production by heat and electricity onsite co-generation, this social impact reduction cannot offset its increment caused by the extra technical complexity and working hours needed. Biodegradable gowns treated by industrial composting and conventional gowns managed by sanitary landfills, in this context, have lower risks of natural disasters and other negative social impacts than biodegradable gowns treated by sanitary landfills.

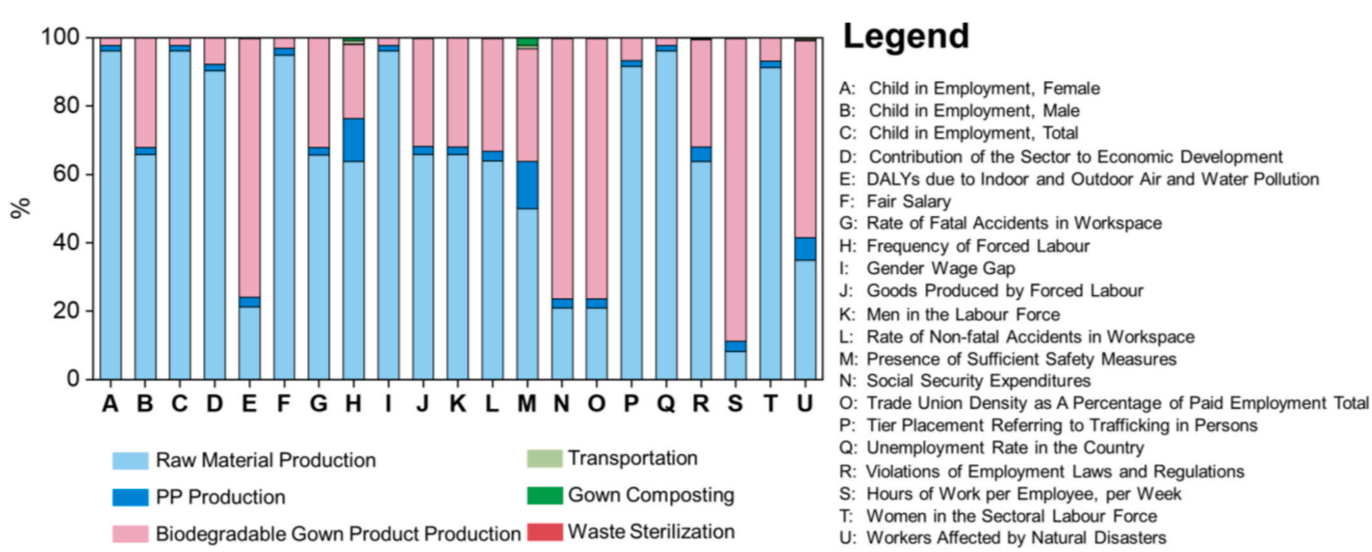

Fig. 9. Social sustainability profiles of biodegradable gown industrial composting processes.

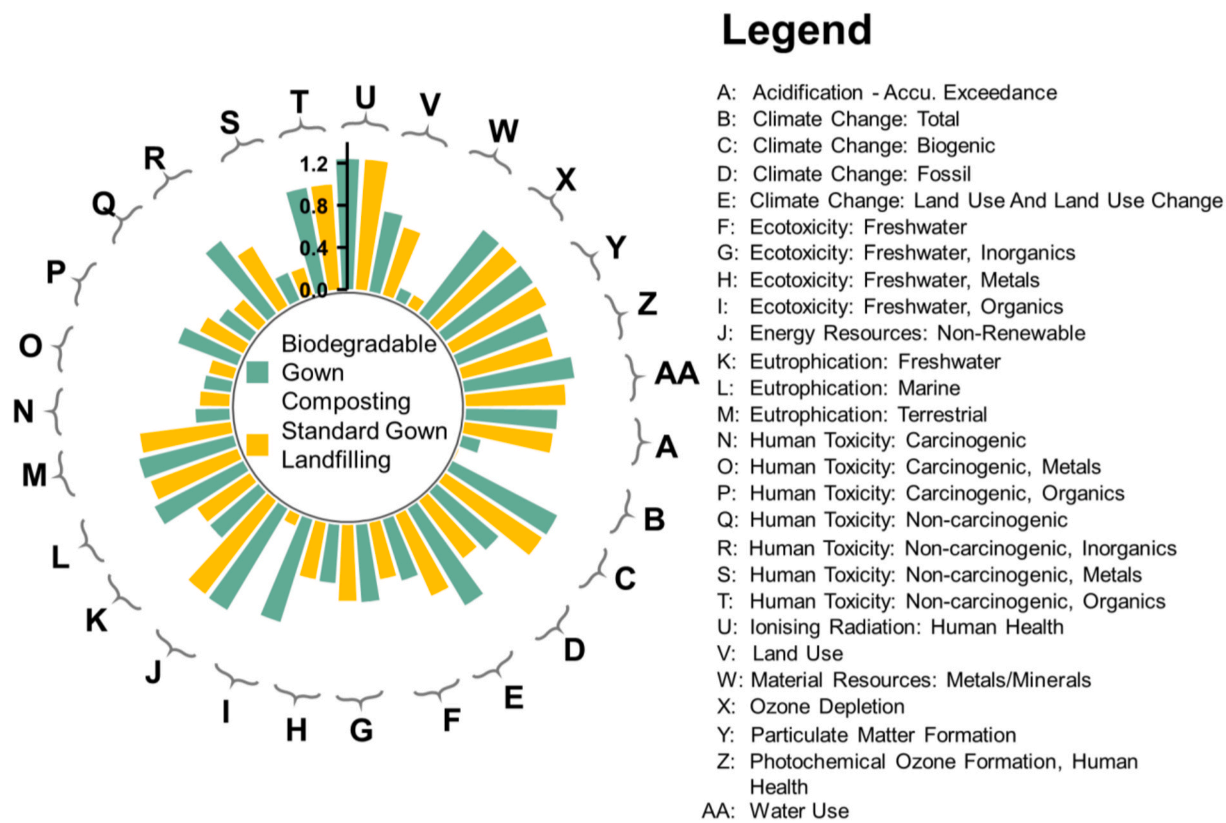

Fig. 10. Comparative environmental assessment results of conventional and biodegradable gowns. Each bar represents the impact evaluation results of biodegradable gown composting or conventional gown landfilling versus biodegradable gown landfilling used widely in gown EoL disposal.

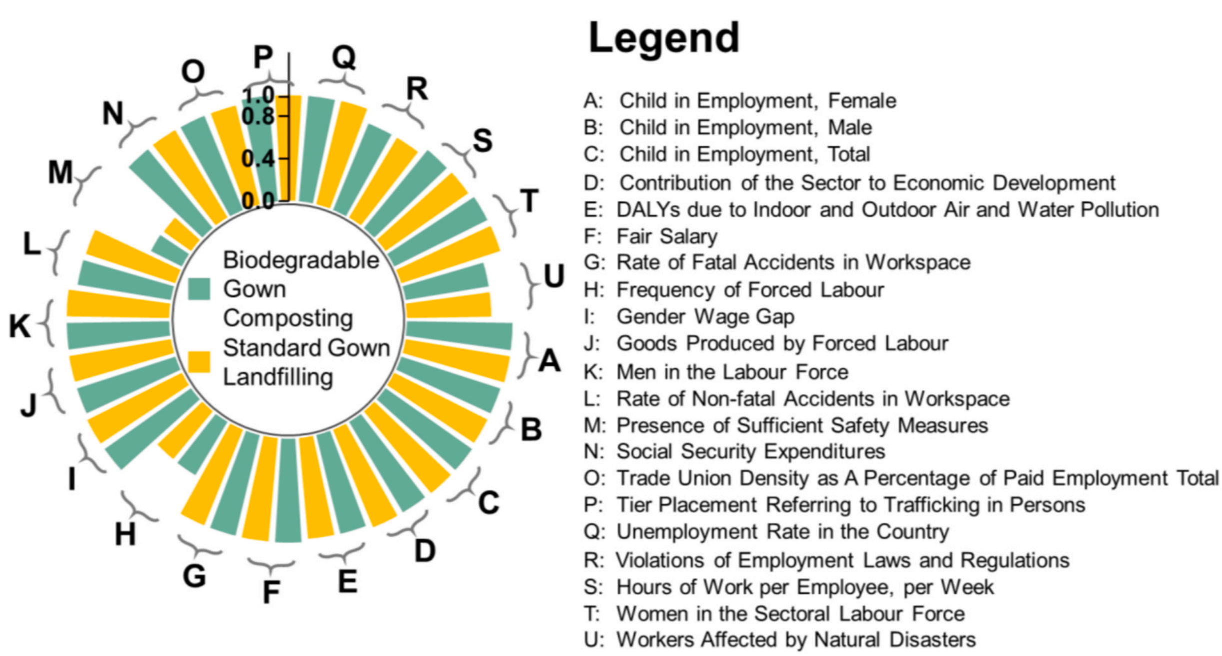

Fig. 11. Comparative social sustainability assessment results of conventional and biodegradable gowns. Each bar represents the impact evaluation results of biodegradable gown composting or conventional gown landfilling versus biodegradable gown landfilling used commonly in gown EoL disposal.

4.5. Sensitivity analysis

Identifying the most influential key technical parameters on the environmental performances of the gowns pinpoints how they can become more environmentally sustainable. The key technical parameters of LFG capture and utilization processes corresponding to the efficiencies of biogenic methane oxidation (De Visscher and Van Cleemput, 2003), LFG capture (Benavides et al., 2020), power use (Wanichpongpan and Gheewala, 2007), heat generation (Wanichpongpan and Gheewala, 2007), and power generation are accounted for to generate the sensitivity analyses results. The environmental sensitivity analyses results were generated from changing the key parameters, including efficiencies of biogenic methane oxidation (*oeff*), landfill gas capture (*ceff*), power use, heat generation, and power generation, as well as transportation distance and composting energy use given in Eqs. (3) and (4) in subsection 2.2. Generic technical parameters for the gown life cycle stage, including the total transportation distance, are also considered to evaluate their influence on the full-spectrum EF 3.0-based environmental effects. Fig. 12 identifies the biogenic methane oxidation efficiency as the most influential technical parameter, especially for global warming, ionizing radiation, and ozone depletion effects, because this technical parameter determines the direct methane emission rate from sanitary landfilling biodegradable gowns. An increment of biogenic methane oxidation efficiency can decrease the climate change effects of methane within LFGs from biodegradable gown sanitary landfilling. Once the oxidation efficiency increases to one, all LFGs, including methane that pose intense climate change effects, are completely oxidized into CO_2 and reduce 48.69% of overall climate change impacts measured by GWP_{100} and 238% ionizing radiation impacts. Varying the LFG capture efficiency to 80% (Range: 60%–100%) can result in decrements of 5.04% ozone depletion and 8.63% ionizing radiation effects. The effects of other technical parameters investigated are not pronounced, given their relatively minor contribution to the overall life cycle environmental effects of gowns. Overall, the technical parameters of the LFG capture and utilization, including the efficiencies of LFG capture, biomethane oxidation, and energy generation, can influence the environmental sustainability of biodegradable gowns.

Therefore, technical improvement in environmentally sustaining disposable medical gowns should focus on tuning the technical parameters of LFG capture and utilization in sanitary landfills. When the LFG capture efficiency improves to or above 85%, as shown in Fig. 13, the biodegradable gown treated by sanitary landfills can outperform the conventional gowns up to an 8.4% lower climate change effects and 12.4% lower fossil resource use via increasing the processing heat generation efficiencies to 85% and biogenic methane oxidation efficiencies to 43%. A higher LFG capture efficiency of 95% can enhance the onsite heat and electricity co-generation rates and increase environmental benefits by decreasing above 32.4% climate change and 17.4% fossil resource scarcity effects. Future LFG capture and utilization technology should improve LFG capture efficiencies to above 85% by optimizing the LFG gas collection operations and improving the LFG well design of the gas collection (Yazdani et al., 2015).

Overall, our study investigated the environmental and social impacts of conventional and biodegradable disposable gowns to show their pros and cons from the life cycle sustainability perspective and provided technical insights on further improving environmental sustainability.

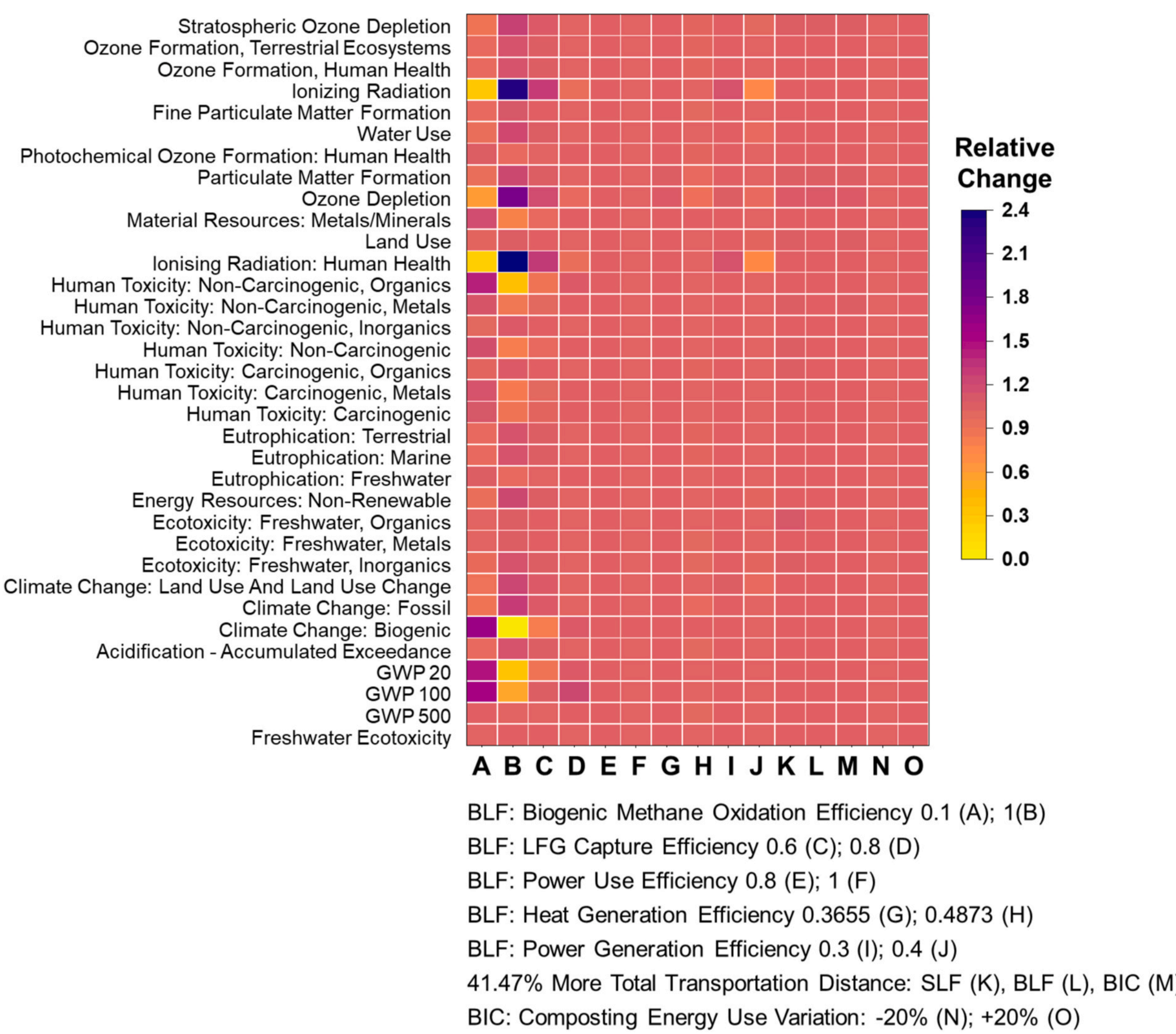

Fig. 12. Environmental sensitivity analysis results based on the full-spectrum environmental performances of biodegradable gowns in USEtox, GWP, and ReCiPe indicators. BLF, SLF, and BIC represent the biodegradable gown waste landfilling, conventional gown waste landfilling, and biodegradable gown industrial composting, respectively. The *x*-axis denotes the environmental impact evaluation scenarios as presented in brackets in the lower legend.

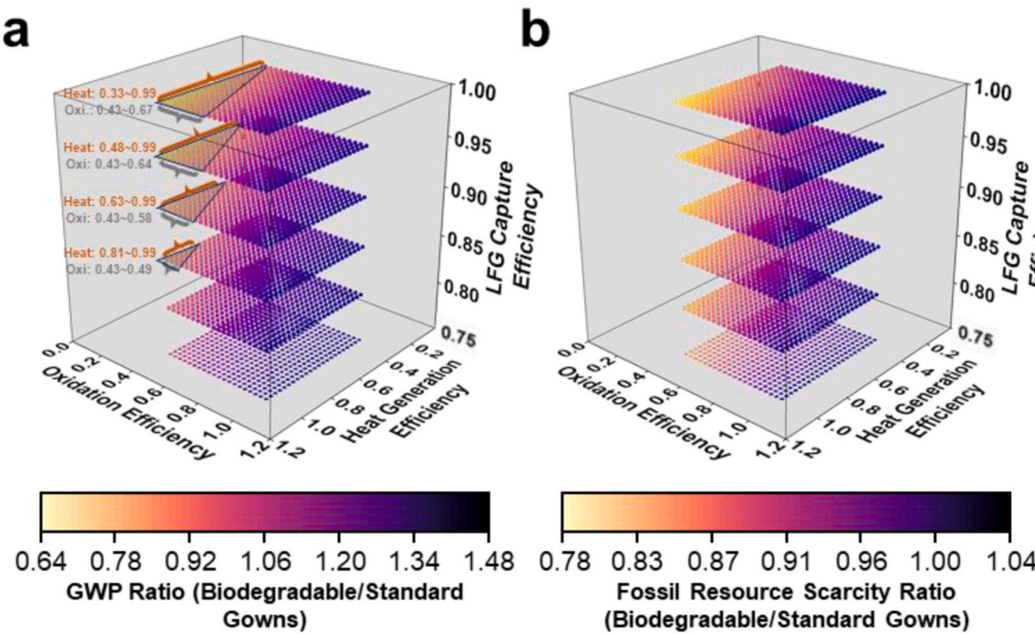

Fig. 13. Environmental sensitivity analysis results on the key technical parameters of sanitary landfills, including the efficiencies of LFG oxidation, heat generation, and LFG capture, to unveil the technological improvement needed for achieving environmental sustainability of biodegradable gowns compared to conventional counterparts: **a,** Sensitivity analysis results based on GWP indicator; **b,** Sensitivity analysis results of fossil resource scarcity impacts. The values (intervals) near brackets represent the efficiencies of heat generation and biogenic methane oxidation required for biodegradable gown landfilling to outperform conventional gowns treated by sanitary landfills. The grey surfaces confine the efficiency ranges of biogenic methane oxidation and heat generation, enabling biodegradable gowns to outperform conventional counterparts in environmental sustainability.

Current conventional gowns treated by sanitary landfills are more environmentally sustainable than biodegradable counterparts but still have safety risks in polypropylene raw material production and gown fabrication processes. Easy operation and safe working conditions should be ensured in gown production to maintain high environmental sustainability with minimum social risks. On the other hand, the biodegradable gowns will be more environmentally advantageous than conventional counterparts if meticulously tuning the biogenic methane oxidation efficiency to exceed 45% and heat generation efficiency to more than 81% in the landfill gas (LFG) capture and utilization processes. Both environmental and social sustainability can then be maintained if further reducing the social risks via uncomplex operations in the LFG capture and utilization processes.

Our study only considered the widely-used end-of-life waste management processes within the gown life cycle rather than the advanced plastic recycling processes (Chin et al., 2022), like chemical recycling and upcycling, that can further improve environmental sustainability. Moreover, process optimization over the gown life cycle processes should be performed to determine the optimal technical parameters in achieving minimum pollution and social risks related to gowns. These future research directions require explicit investigation to improve the gown environmental and social sustainability to pursue sustainability development goals (SDGs).

5. Conclusion

This work performed comparative LCAs on gowns to understand the pros and cons of biodegradable gowns over conventional counterparts in achieving SDGs. The full-spectrum environmental impacts across the entire life cycle of gowns corresponding to three gown case studies were evaluated by accounting for conventional and biodegradable gowns treated by sanitary landfills and industrial composting after disinfection. The social impacts were assessed based on these gowns' economic input-output analysis results to reflect their associated influence on economic growth, employment, and worker welfare. Our study showed that biodegradable gowns managed by sanitary landfills deviated from SDG 3 (Good Health and Well-being) by worsening 14.32% human toxicity (cancer), SDG 13 (Climate Action) by increasing 10.23% GHG emissions, and SDG 14 (Life Below Water) by posing 9.71% more freshwater ecotoxicity compared to fossil-based gowns because of the uncaptured LFGs and producing the pro-oxidant used in biodegradable gowns. Reducing the organic solvent use in synthesis or replacing the CoSt pro-oxidants with the ecological-benign chemicals in biodegradable gown fabrication can mitigate these ecotoxicity impacts. The uncaptured LFG emissions could be reduced by incorporating the LFG capture and utilization processes within biodegradable gown sanitary landfills, alleviating 9.79% GHG emissions and saving at least 10% of fossil fuel resources aided by onsite heat and power co-generation. However, this process caused negative life cycle social impacts corresponding to natural disasters, forced labor, and safety when gaining the environmental benefits of biodegradable gowns. The most influential key technical parameter of the gown life cycle environmental impacts was then identified to pinpoint the technological improvement needed to make biodegradable gowns more environmentally and socially advantageous over conventional counterparts. An improvement of the LFG capture efficiency to above 85% could cut the life cycle GHG emissions and fossil resource use of biodegradable gowns to lower than those of conventional gown landfills when tuning the biogenic methane oxidation efficiency to exceed 45% and heat generation efficiency to more than 81%. Future studies should then investigate how to maintain easy operation and safe working conditions in LFG capture and utilization to minimize the negative social impacts of biodegradable gowns. Effective leachate and gas emissions control and innocuous chemical use for material production, in general, require future investigation to help achieve environmentally sustainable EoL management for conventional and biodegradable gowns and generic plastic materials. Advanced plastic recycling processes, like chemical recycling and upcycling, improve the environmental sustainability of gowns and can further be applied to gown waste processing to improve the gown environmental and social sustainability to pursue sustainability development goals (SDGs).

CRediT authorship contribution statement

Xiang Zhao: Methodology, Conceptualization, Software, Formal analysis, Data curation, Visualization, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition. **Jiří Jaromír Klemeš:** Writing – review & editing. **Michael Saxon:** Writing – review & editing, Funding acquisition. **Fengqi You:** Methodology, Conceptualization, Software, Formal analysis, Data curation, Visualization, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgment

This work was partially supported by the National Science Foundation (NSF) CAREER Award (CBET-1643244) and the Cornell Center for Materials Research (CCMR) with funding from the NSF MRSEC program (DMR-1719875) and New York State Empire State Development's Division of Science, Technology, and Innovation (NYSTAR) and also by the Grant Agency of the Czech Republic under Project No. 21–45726L in collaboration with the Slovenian Research Agency (J7-3149). The authors gratefully appreciate the helpful discussions with and suggestions from Dr. John P. Sinnott at CCMR.

References

Abdelmoez, W., Dahab, I., Ragab, E.M., Abdelsalam, O.A., Mustafa, A., 2021. Bio-and oxo-degradable plastics: insights on facts and challenges. Polym. Adv. Technol. 32 (5), 1981–1996. https://doi.org/10.1002/pat.5253.

Anshassi, M., Sackles, H., Townsend, T.G., 2021. A review of LCA assumptions impacting whether landfilling or incineration results in less greenhouse gas emissions. Resour. Conserv. Recycl. 174, 105810 https://doi.org/10.1016/j.resconrec.2021.105810.

Asriza, R.O., Arcana, I.M., 2015. Synthesis of cobalt stearate as oxidant additive for oxo-biodegradable polyethylene. In: AIP Conference Proceedings. AIP Publishing LLC, 070007. https://doi.org/10.1063/1.4930711.

Babaahmadi, V., Amid, H., Naeimirad, M., Ramakrishna, S., 2021. Biodegradable and multifunctional surgical face masks: a brief review on demands during COVID-19 pandemic, recent developments, and future perspectives. Sci. Total Environ. 798, 149233 https://doi.org/10.1016/j.scitotenv.2021.149233.

Benavides, P.T., Lee, U., Zarè-Mehrjerdi, O., 2020. Life cycle greenhouse gas emissions and energy use of polylactic acid, bio-derived polyethylene, and fossil-derived polyethylene. J. Clean. Prod. 277, 124010 https://doi.org/10.1016/j.jclepro.2020.124010.

Bianchini, A., Rossi, J., 2021. Design, implementation and assessment of a more sustainable model to manage plastic waste at sport events. J. Clean. Prod. 281, 125345 https://doi.org/10.1016/j.jclepro.2020.125345.

Bora, R.R., Wang, R., You, F., 2020. Waste polypropylene plastic recycling toward climate change mitigation and circular economy: energy, environmental, and technoeconomic perspectives. ACS Sustain. Chem. Eng. 8 (43), 16350–16363. https://doi.org/10.1021/acssuschemeng.0c06311.

Brunner, D.R., Keller, D.J., 1972. Sanitary Landfill Design and Operation. Environmental Protection Agency, Office of Water and Waste Management, Environmental Protection Agency, USA.

Burguburu, A., Tanné, C., Bosc, K., Laplaud, J., Roth, M., Czyrnek-Delêtre, M., 2022. Comparative life cycle assessment of reusable and disposable scrub suits used in hospital operating rooms. Cleaner Environmental Systems 4, 100068. https://doi.org/10.1016/j.cesys.2021.100068.

Campion, N., Thiel, C.L., Woods, N.C., Swanzy, L., Landis, A.E., Bilec, M.M., 2015. Sustainable healthcare and environmental life-cycle impacts of disposable supplies: a focus on disposable custom packs. J. Clean. Prod. 94, 46–55. https://doi.org/10.1016/j.jclepro.2015.01.076.

Carre, A., 2008. Life Cycle Assessment Comparing Laundered Surgical Gowns with Polypropylene Based Disposable Gowns. RMIT University, Melbourne, Australia, p. 84.

Cetin, Y., Sonmez, A., 2021. Cost Analysis of Disposable/reusable Surgical Drapes Used in Turgut Ozal Medicine Center. http://161.9.164.68/xmlui/handle/11616/55585?show=full. (Accessed 15 March 2022).

Chin, H.H., Varbanov, P.S., You, F., Sher, F., Klemeš, J.J., 2022. Plastic Circular Economy Framework using Hybrid Machine Learning and Pinch Analysis. Resour. Conserv. Recycl. 184, 106387. https://doi.org/10.1016/j.resconrec.2022.106387.

Ciroth, A., Eisfeldt, F., 2016. PSILCA—a product social impact life cycle assessment database. In: Database Version, vol. 1. GreenDelta, Berlin, Germany, pp. 1–99.

Cudjoe, D., Han, M.S., 2020. Economic and environmental assessment of landfill gas electricity generation in urban districts of Beijing municipality. Sustain. Prod. Consum. 23, 128–137. https://doi.org/10.1016/j.spc.2020.04.010.

De Visscher, A., Van Cleemput, O., 2003. Simulation model for gas diffusion and methane oxidation in landfill cover soils. Waste Manag. 23 (7), 581–591. https://doi.org/10.1016/S0956-053X(03)00096-5.

Demetrious, A., Crossin, E., 2019. Life cycle assessment of paper and plastic packaging waste in landfill, incineration, and gasification-pyrolysis. J. Mater. Cycles Waste Manag. 21 (4), 850–860. https://doi.org/10.1007/s10163-019-00842-4.

Eisfeldt, F., 2017. Soca V. 1 Add-On: Adding Social Impact Information to Ecoinvent. Description of Methodology to Map Social Impact Information from PSILCA 1. GreenDelta, Berlin, Germany.

Elwell, A.C., Elsayed, N.H., Kuhn, J.N., Joseph, B., 2018. Design and analysis of siloxanes removal by adsorption from landfill gas for waste-to-energy processes. Waste Manag. 73, 189–196. https://doi.org/10.1016/j.wasman.2017.12.021.

Fantke, P., Bijster, M., Guignard, C., Hauschild, M.Z., Huijbregts, M., Jolliet, O., Kounina, A., Magaud, V., Margni, M., McKone, T.E., 2017. USEtox® 2.0 Documentation (Lyngby, Denmark), Version 1.00.

Fojt, J., Denková, P., Brtnický, M., Holátko, J., Řezáčová, V., Pecina, V., Kučerík, J., 2022. Influence of poly-3-hydroxybutyrate micro-Bioplastics and polyethylene terephthalate Microplastics on the soil organic matter Structure and soil water properties. Environ. Sci. Technol. 56 (15), 10732–10742. https://doi.org/10.1021/acs.est.2c01970.

Ford, J.D., Vanderbilt, W., Berrang-Ford, L., 2012. Authorship in IPCC AR5 and its implications for content: climate change and Indigenous populations in WGII. Clim. Change 113 (2), 201–213. https://doi.org/10.1007/s10584-011-0350-z.

Freund, J., Gast, K., Zuegge, K., Hicks, A., 2022. Environmental considerations in the selection of medical staplers: a comparative life cycle assessment. J. Clean. Prod. 371, 133490 https://doi.org/10.1016/j.jclepro.2022.133490.

Friesenhan, C., Agirre, I., Eltrop, L., Arias, P.L., 2017. Streamlined life cycle analysis for assessing energy and exergy performance as well as impact on the climate for landfill gas utilization technologies. Appl. Energy 185, 805–813. https://doi.org/10.1016/j.apenergy.2016.10.097.

Gahan, R., Zguris, G.C., 2000. A review of the melt blown process. In: Fifteenth Annual Battery Conference on Applications and Advances (Cat. No. 00TH8490). IEEE, pp. 145–149. https://doi.org/10.1109/BCAA.2000.838396.

González, A., Sendra, C., Herena, A., Rosquillas, M., Vaz, D., 2021. Methodology to assess the circularity in building construction and refurbishment activities. Resources, Conservation & Recycling Advances 12, 200051. https://doi.org/10.1016/j.rcradv.2021.200051.

Hermann, B., Debeer, L., De Wilde, B., Blok, K., Patel, M.K., 2011. To compost or not to compost: carbon and energy footprints of biodegradable materials' waste treatment. Polym. Degrad. Stabil. 96 (6), 1159–1171. https://doi.org/10.1016/j.polymdegradstab.2010.12.026.

Hicks, A., Reed, R., Theis, T., Hanigan, D., Huling, H., Zaikova, T., Hutchison, J., Miller, J., 2016. Environmental impacts of reusable nanoscale silver-coated hospital gowns compared to single-use, disposable gowns. Environ. Sci. Nano 3 (5), 1124–1132. https://doi.org/10.1039/C6EN00168H.

Hou, P., Xu, Y., Taiebat, M., Lastoskie, C., Miller, S.A., Xu, M., 2018. Life cycle assessment of end-of-life treatments for plastic film waste. J. Clean. Prod. 201, 1052–1060. https://doi.org/10.1016/j.jclepro.2018.07.278.

Huijbregts, M.A., Steinmann, Z.J., Elshout, P.M., Stam, G., Verones, F., Vieira, M., Hollander, A., Zijp, M., van Zelm, R., 2016. ReCiPe 2016: a Harmonized Life Cycle Impact Assessment Method at Midpoint and Endpoint Level Report I: Characterization. National Institute for Public Health and the Environment, the Netherlands.

Johari, A., Ahmed, S.I., Hashim, H., Alkali, H., Ramli, M., 2012. Economic and environmental benefits of landfill gas from municipal solid waste in Malaysia. Renew. Sustain. Energy Rev. 16 (5), 2907–2912. https://doi.org/10.1016/j.rser.2012.02.005.

Jørgensen, A., Le Bocq, A., Nazarkina, L., Hauschild, M., 2008. Methodologies for social life cycle assessment. Int. J. Life Cycle Assess. 13 (2), 96–103. https://doi.org/10.1065/lca2007.11.367.

Kedzierski, M., Frère, D., Le Maguer, G., Bruzaud, S., 2020. Why is there plastic packaging in the natural environment? Understanding the roots of our individual plastic waste management behaviours. Sci. Total Environ. 740, 139985 https://doi.org/10.1016/j.scitotenv.2020.139985.

Kim, T., Bamford, J., Gracida-Alvarez, U.R., Benavides, P.T., 2022. Life cycle greenhouse gas emissions and water and fossil-fuel consumptions for polyethylene furanoate and its coproducts from wheat straw. ACS Sustain. Chem. Eng. 10 (8), 2830–2843. https://doi.org/10.1021/acssuschemeng.1c08429.

Klemeš, J.J., Van Fan, Y., Tan, R.R., Jiang, P., 2020a. Minimising the present and future plastic waste, energy and environmental footprints related to COVID-19. Renew. Sustain. Energy Rev. 127, 109883 https://doi.org/10.1016/j.rser.2020.109883.

Klemeš, J.J., Van Fan, Y., Jiang, P., 2020b. The energy and environmental footprints of COVID-19 fighting measures–PPE, disinfection, supply chains. Energy 211, 118701. https://doi.org/10.1016/j.energy.2020.118701.

Krzymien, M., Day, M., Shaw, K., Zaremba, L., 1999. An investigation of odors and volatile organic compounds released during composting. J. Air Waste Manag. Assoc. 49 (7), 804–813. https://doi.org/10.1080/10473289.1999.10463845.
Leung, D.Y., Caramanna, G., Maroto-Valer, M.M., 2014. An overview of current status of carbon dioxide capture and storage technologies. Renew. Sustain. Energy Rev. 39, 426–443. https://doi.org/10.1016/j.rser.2014.07.093.
Lou, X., Nair, J., 2009. The impact of landfilling and composting on greenhouse gas emissions–a review. Bioresour. Technol. 100 (16), 3792–3798. https://doi.org/10.1016/j.biortech.2008.12.006.
Mastellone, M.L., 2019. A feasibility assessment of an integrated plastic waste system adopting mechanical and thermochemical conversion processes. Resour. Conserv. Recycl. X 4, 100017. https://doi.org/10.1016/j.rcrx.2019.100017.
McQuerry, M., Easter, E., Cao, A., 2021. Disposable versus reusable medical gowns: a performance comparison. Am. J. Infect. Control 49 (5), 563–570. https://doi.org/10.1016/j.ajic.2020.10.013.
Ogunjuyigbe, A., Ayodele, T., Alao, M., 2017. Electricity generation from municipal solid waste in some selected cities of Nigeria: an assessment of feasibility, potential and technologies. Renew. Sustain. Energy Rev. 80, 149–162. https://doi.org/10.1016/j.rser.2017.05.177. New York State Statewide COVID-19 Hospitalizations and Beds. https://health.data.ny.gov/Health/New-York-State-Statewide-COVID-19-Hospitalizations/jw46-jpb7. (Accessed 25 April 2022).
Pearce, W., Holmberg, K., Hellsten, I., Nerlich, B., 2014. Climate change on twitter: topics, communities and conversations about the 2013 IPCC working group 1 report. PLoS One 9 (4), e94785. https://doi.org/10.1371/journal.pone.0094785.
Sable, S., Ahuja, S., Bhunia, H., 2021. Biodegradation kinetic modeling of pro-oxidant filled polypropylene composites under thermophilic composting conditions after abiotic treatment. Environ. Sci. Pol. 28 (17), 21231–21244. https://doi.org/10.1007/s11356-020-11766-0.
Sala, S., Castellani, V., 2019. The consumer footprint: monitoring sustainable development goal 12 with process-based life cycle assessment. J. Clean. Prod. 240, 118050 https://doi.org/10.1016/j.jclepro.2019.118050.
Santos, A.C., Mendes, P., Teixeira, M.R., 2019. Social life cycle analysis as a tool for sustainable management of illegal waste dumping in municipal services. J. Clean. Prod. 210, 1141–1149. https://doi.org/10.1016/j.jclepro.2018.11.042.
Saouter, E., Biganzoli, F., Ceriani, L., Versteeg, D., Crenna, E., Zampori, L., Sala, S., Pant, R., 2018. Environmental Footprint: Update of Life Cycle Impact Assessment Methods–Ecotoxicity Freshwater, Human Toxicity Cancer, and Non-cancer. European Union, Luxembourg.
Stegmann, P., Londo, M., Junginger, M., 2020. The circular bioeconomy: its elements and role in European bioeconomy clusters. Resour. Conserv. Recycl. X6, 100029 https://doi.org/10.1016/j.rcrx.2019.100029.
Su, Y., Duan, H., Wang, Z., Song, G., Kang, P., Chen, D., 2020. Characterizing the environmental impact of packaging materials for express delivery via life cycle assessment. J. Clean. Prod. 274, 122961 https://doi.org/10.1016/j.jclepro.2018.11.042.
Tao, Y., You, F., 2021. Can Decontamination and Reuse of N95 Respirators during COVID-19 Pandemic Provide Energy, Environmental, and Economic Benefits? Appl. Energy 304, 117848. https://doi.org/10.1016/j.apenergy.2021.117848.
Uddin, M.A., Afroj, S., Hasan, T., Carr, C., Novoselov, K.S., Karim, N., 2022. Environmental impacts of personal protective clothing used to combat COVID-19. Adv. Sustain. Syst. 6 (1), 2100176 https://doi.org/10.1002/adsu.202100176.
Umair, S., Björklund, A., Petersen, E.E., 2015. Social impact assessment of informal recycling of electronic ICT waste in Pakistan using UNEP SETAC guidelines. Resour. Conserv. Recycl. 95, 46–57. https://doi.org/10.1016/j.resconrec.2014.11.008.
Unger, S.R., Campion, N., Bilec, M.M., Landis, A.E., 2016. Evaluating quantifiable metrics for hospital green checklists. J. Clean. Prod. 127, 134–142. https://doi.org/10.1016/j.jclepro.2016.03.167.
Van den Berghe, A., Zimmer, C., 2011. Life Cycle Assessments of Single-Versus Multiple-Use Surgical Gowns. Minnesota Technical Assistance Program, University of Minnesota, Minneapolis, MN. http://www.sustainabilityroadmap.org/pims/pdfs/pim247_lifecycle_assessment_disposable_versus_reusable.pdf. (Accessed 10 June 2020).
van Straten, B., Ligtelijn, S., Droog, L., Putman, E., Dankelman, J., Weiland, N., Horeman, T., 2021. A life cycle assessment of reprocessing face masks during the Covid-19 pandemic. Sci. Rep. 11 (1), 1–9. https://doi.org/10.1038/s41598-021-97188-5.
Vozzola, E., Overcash, M., Griffing, E., 2018. Environmental considerations in the selection of isolation gowns: a life cycle assessment of reusable and disposable alternatives. Am. J. Infect. Control 46 (8), 881–886. https://doi.org/10.1016/j.ajic.2018.02.002.
Vozzola, E., Overcash, M., Griffing, E., 2020. An environmental analysis of reusable and disposable surgical gowns. AORN J. 111 (3), 315–325. https://doi.org/10.1002/aorn.12885.
Wang, Y., Levis, J.W., Barlaz, M.A., 2021. Life-cycle assessment of a regulatory compliant US municipal solid waste landfill. Environ. Sci. Technol. 55 (20), 13583–13592. https://doi.org/10.1021/acs.est.1c02526.
Wanichpongpan, W., Gheewala, S.H., 2007. Life cycle assessment as a decision support tool for landfill gas-to energy projects. J. Clean. Prod. 15 (18), 1819–1826. https://doi.org/10.1016/j.jclepro.2006.06.008.
Yang, M., Tian, X., You, F., 2018. Manufacturing ethylene from wet shale gas and biomass: comparative technoeconomic analysis and environmental life cycle assessment. Ind. Eng. Chem. 57 (17), 5980–5998. https://doi.org/10.1021/acs.iecr.7b03731.
Yang, M., You, F., 2017. Comparative techno-economic and environmental analysis of ethylene and propylene manufacturing from wet shale gas and naphtha. Ind. Eng. Chem. 56 (14), 4038–4051. https://doi.org/10.1021/acs.iecr.7b00354.
Yazdani, R., Imhoff, P., Han, B., Mei, C., Augenstein, D., 2015. Quantifying capture efficiency of gas collection wells with gas tracers. Waste Manag. 43, 319–327. https://doi.org/10.1016/j.wasman.2015.06.032.
You, F.*, Tao, L., Graziano, D., Snyder, S.W., 2012. Optimal Design of Sustainable Cellulosic Biofuel Supply Chains: Multiobjective Optimization Coupled with Life Cycle Assessment and Input-Output Analysis. AIChE J. 58, 1157–1180. https://doi.org/10.1002/aic.12637.
Yue, D., Slivinsky, M., Sumpter, J., You, F., 2014. Sustainable design and operation of cellulosic bio-electricity supply chain networks with life cycle economic, environmental and social optimization. Ind. Eng. Chem. Res. 53, 4008–4029. https://doi.org/10.1021/ie403882v.
Zhao, X., Klemeš, J.J., You, F., 2022. Energy and environmental sustainability of waste personal protective equipment (PPE) treatment under COVID-19. Renew. Sustain. Energy Rev. 153, 111786. https://doi.org/10.1016/j.rser.2021.111786.
Zhao, X., You, F., 2021. Consequential life cycle assessment and optimization of high-density polyethylene plastic waste chemical recycling. ACS Sustain. Chem. Eng. 9 (36), 12167–12184.
Zhao, N., You, F., 2021. Food-energy-water-waste nexus systems optimization for New York State under the COVID-19 pandemic to alleviate health and environmental concerns. Appl. Energy 282, 116181. https://doi.org/10.1016/j.apenergy.2020.116181.
Zhao, X., You, F., 2021. Waste Respirator Processing System for Public Health Protection and Climate Change Mitigation under COVID-19 Pandemic: Novel Process Design and Energy, Environmental, and Techno-economic Perspectives. Appl. Energy 282, 116129. https://doi.org/10.1016/j.apenergy.2020.116129.
Zhao, X., You, F., 2021. Waste High-Density Polyethylene Recycling Process Systems for Mitigating Plastic Pollution through Sustainable Design. AIChE J 67, e17127. https://doi.org/10.1002/AIC.17127.
Zhao, X., You, F., 2022. Life Cycle Assessment of Microplastics Reveals Their Greater Environmental Hazards than Mismanaged Polymer Waste Losses. Environ. Sci. Technol. 56 (16), 11780–11797. https://doi.org/10.1021/acs.est.2c01549.
Zhou, C., Fang, W., Xu, W., Cao, A., Wang, R., 2014. Characteristics and the recovery potential of plastic wastes obtained from landfill mining. J. Clean. Prod. 80, 80–86. https://doi.org/10.1016/j.jclepro.2014.05.083.