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LIFE CYCLE ASSESSMENT OF CASTOR-BASED CONSTRUCTED WETLAND SYSTEMS: A COMPARATIVE STUDY ON BIO-DIESEL AND ERI-SILK COCOON PRODUCTION FOR SUSTAINABLE RICE-MILL WASTEWATER MANAGEMENT

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ABSTRACT

Constructed wetlands (CWs) offer a sustainable method for treating nutrient-rich rice mill wastewater while enabling biomass valorization. This study uses Life Cycle Assessment (LCA) to compare two castor-based CW models—for biodiesel and eri-silk cocoon production—across key impact categories such as human health, ecosystem quality, resource use, energy, water footprint, and compost sustainability. Fine particulate matter formation and global warming dominate environmental impacts, contributing 97% of total damage. Biodiesel production shows higher burdens in global warming (4.94E-07 DALY), fossil resource use (8.49E-03 USD), and eutrophication (8.47E-09 species.yr), mainly due to its energy-intensive processing. Eri-silk production has higher particulate matter formation (2.72E-07 DALY) and fossil resource scarcity (3.63E-03 USD), linked to silkworm rearing. Biodiesel demands more energy (1.28 MJ/kg) and water (0.078 m^3/kg) than eri-silk (0.554 MJ/kg and 0.034 m^3/kg). Compost from the eri-silk system has lower environmental impacts, particularly in eutrophication. The study highlights the need for integrated optimization to balance the eco-sustainability of eri-silk with the economic viability of biodiesel.

No. of Pages: 18 **References: 23**

Keywords: Castor-based Wetland, Eri-silk, Biodiesel, Compost, Life Cycle Assessment, Damage Assessment.

INTRODUCTION

Rice mill wastewater is associated with significant environmental concern due to the large volumes of effluent generated during the rice milling process, particularly in regions where rice is a staple food (Pandhan & S K Sahu; 2011).If not properly treated, it can lead to severe pollution of surface and groundwater resources, affecting both human health and ecosystems (Chen et al., 2023). The effluent typically contains high levels of organic matter, suspended solids, and nutrients, which can degrade water quality and disrupt aquatic life (Kiran & Prasad; 2020)..

The environmental impact of rice mill wastewater requires effective management and treatment strategies to mitigate its adverse effects, caused by virtue of stressed water quality parameters, viz. pH, turbidity, and biochemical oxygen demand (BOD) in affected water bodies(Rahman et al., 2020).In fact, high levels of total dissolved solids (TDS) and other pollutants in the effluent can harm aquatic ecosystems, leading to reduced biodiversity and altered ecosystem functions as well as soil degradation (Adeleye et al 2021; Bharti et al.,2020).

Constructed wetlands (CWs) are increasingly recognized as a sustainable approach to wastewater treatment, offering an eco-friendly alternative to conventional methods.CWs are a cost-effective solution for treating wastewater, requiring lower operational costs compared to traditional systems,

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because of usage of natural processes involving plants, soil, and microorganisms to remove pollutants from sustainability. Besides, they can be decentralized, allowing for localized treatment and minimizing energy consumption (Paul et al., 2015). Their ability to support diverse microbial communities contributes to effective contaminant degradation and nutrient cycling (S Kumar & R Singh 2018; Wang et al., 2023).In fact, specific configurations and plant-microbe interactions enhance the removal of organic micro pollutants for various types ofwastewater, including municipal, agricultural, and industrial effluents.

The castor plant (*Ricinus communis L.*) has been a promising candidate for both wetland remediation and as a cash crop, particularly in areas contaminated with heavy metals, by virtue of its ability to thrive in polluted environments while accumulating and stabilizing toxic substances makes it a valuable asset in phytoremediation efforts (Kataki et al.,2021). Various researchers have demonstrated that the ability of castor to grow in highly contaminated soils, due to its high tolerance and biomass accumulation, which is crucial for effective remediation, it possess significant capacity for phyto-extraction of heavy metals such as copper, lead, and zinc (Flota et al., 2022) Beyond its environmental benefits, castor is also a rich source of ricin oleic acid, making it suitable for biodiesel, offering a renewable alternative to fossil fuels as well as glycerine, which is valuable in pharmaceuticals and cosmetics ,thus providing economic incentives for its cultivation. Hence, the integration of castor cultivation in contaminated sites can lead to sustainable agricultural practices, enhancing soil health while generating income (Deshmukh et al., 2021; Kataki et al., 2021). Even after oil extraction, over 50% of the castor seed remains as de-oiled cake, which can be used as biomass for energy production (Chowdhury & Rahman, 2017).

Yet another domain of economic and sustainable utility of castor leaves is its use as feed for eri silkworms (*Samiacynthiaricini*), which forms a critical aspect of sericulture, influencing both the growth of the silkworms and the quality of silk produced. Research indicates that the nutritional value and health of castor leaves directly affect the productivity of eri silkworms, with various treatments and genotypes showing significant differences in feed efficiency and silkworm performance (Chakraborty & Ray, 2015).

Life Cycle Assessment (LCA) has been globally recognized as an effective tool for sustainability assessment, particularly in evaluating the environmental impacts of products and processes throughout their entire life cycle (K B Aviso, 2024; Novemyanto & Nazri, 2024).There have been extensive studies on LCA-based sustainability assessment of Constructed wetlands and wetland ecosystems, as well as the associated processes (Chen et al., 2023; Kataki et al., 2021; Zhou et al., 2023).

In the present work two pathways of castor-based wetland models are investigated for their sustainability using Life Cycle assessment (LCA), targeting towards two distinct end-products, such as bio-diesel and eri-silk cocoons, with their attendant by-products, namely compost.

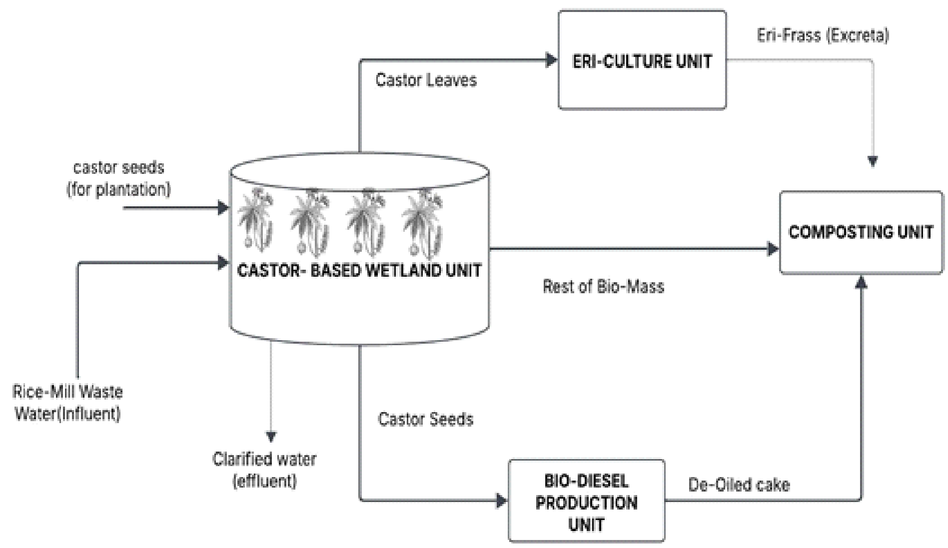


Fig. 1: Integrated the Closed-Loop Castor-Rice Mill wastewater Wetland System.

Since, the castor plants produce various outputs that feed into different units, one of which is its leaves harvested for Eri-Culture Unit, where they serve as food for eri silkworms. These silkworms generate excreta (eri-frass), which is further processed in the Composting Unit to produce nutrient-rich compost. Additionally, the castor seeds also harvested from the wetland unit are sent to the Bio-Diesel Production Unit, where they are processed to extract bio-diesel, a renewable energy source. This extraction process also generates a by-product known as de-oiled cake, which, instead of being discarded, is also sent to the Composting Unit.

Additionally, any residual biomass from the wetland system that is not directly utilized in other processes is also funnelled into the Composting Unit. This ensures that all organic matter is effectively recycled into compost, which can then be used for soil enrichment or reintroduced into the plantation cycle. The entire system is designed to be a circular economy model, where waste from one process becomes an input for another, minimizing environmental impact and maximizing resource efficiency. The integration of wastewater treatment, eri-culture, biofuel production, and composting highlights the framework's sustainability by closing the loop on waste, water, and energy.

Design of Castor-Rice Mill Wastewater (WW) Wetland System

The constructed wetland, being a vital component behind sustainable rice mill waste water management, was designed and construction to handle an inflow rate of 1 kilolitre per day (KLD) of effluent from rice milling operations. The constructed wetland is configured in a rectangular shape, measuring 10 meters in length, 5 meters in width, and 0.5 meters in depth. This design is favoured for its simplicity in construction and maintenance, as well as its effectiveness in facilitating pollutant adsorption through vertical flow mechanisms. The vertical flow design allows for optimal interaction between the wastewater and the plant roots, enhancing the removal of contaminants from the water. The various design specifications are provided in Table-1.

Table 1: Design parameters of wetland system.

S. No	Design Parameter	Values
1.	Wetland Dimensions	50 m^2
2.	Wetland Size	10m (Length) x 5m (Width) x 0.5m (Depth)
3.	Hydraulic Load	1.0 m^3/day
4.	BOD Removal Efficiency	60-90%
5.	TSS Removal Efficiency	70-90%
6.	NH3/NH4 Removal Efficiency	60-80%
7.	TN Removal Efficiency	50-70%
8.	TP Removal Efficiency	50-80%
9.	Retention Time (HRT)	5-10 days
10.	Aspect Ratio (L:W)	2:1
11.	Substrate Composition: Gravel	Coarse (20-40 cm), Fine (10-20 cm)

To prevent groundwater contamination, an impermeable liner made of PVC has been installed at both the base and sides of the wetland. This barrier is essential for containing the wastewater within the system and preventing leachate from impacting surrounding soil and water resources. Additionally, a distribution pipe is strategically placed at the top of the wetland to ensure an even distribution of influent across the surface area. At the bottom, a perforated pipe collects treated effluent, helping to maintain a consistent water level within the wetland. This design feature is vital for sustaining the biological processes necessary for effective wastewater treatment.

Plant Selection and Substrate Composition

For this wetland, castor plants (*Ricinuscommunis*) have been selected due to their adaptability to well-drained soils. The substrate used consists of a combination of natural materials aimed at ensuring effective drainage and filtration. Specifically, coarse gravel (20-40 mm) and fine gravel (10-20 mm) are utilized to create a suitable environment for the castor plants while promoting optimal water flow through the system. The density of castor plants is maintained at approximately 4 to 6 plants per square meter for ensuring adequate coverage and maximizing pollutant uptake, thereby enhancing the overall efficiency of the wetland. The plant growth and yield studies are given in Table 2.

Table 2: Plant growth and yield studies.

S. No.	Parameter	Specifications
1.	Plant Height	00 - 300 cm
2.	Number of Leaves per Plant	20 - 96 leaves
3.	Number of Capsules per Plant	18 - 137 capsules
4.	Seed Yield (kg/m2)	0.05 -0.15kg/m^2
5.	Oil Content (%)	40 - 50%
6.	Spike Length (cm)	24.4 - 27.21 cm
7.	Capsule Dry Weight (g/seed)	0.95-1.41 gm
8.	Plant Density	4-6 plants/m^2
9.	Leaf size	15 - 45 cm
10.	Biomass yield per m^2	3.5-9 Kg

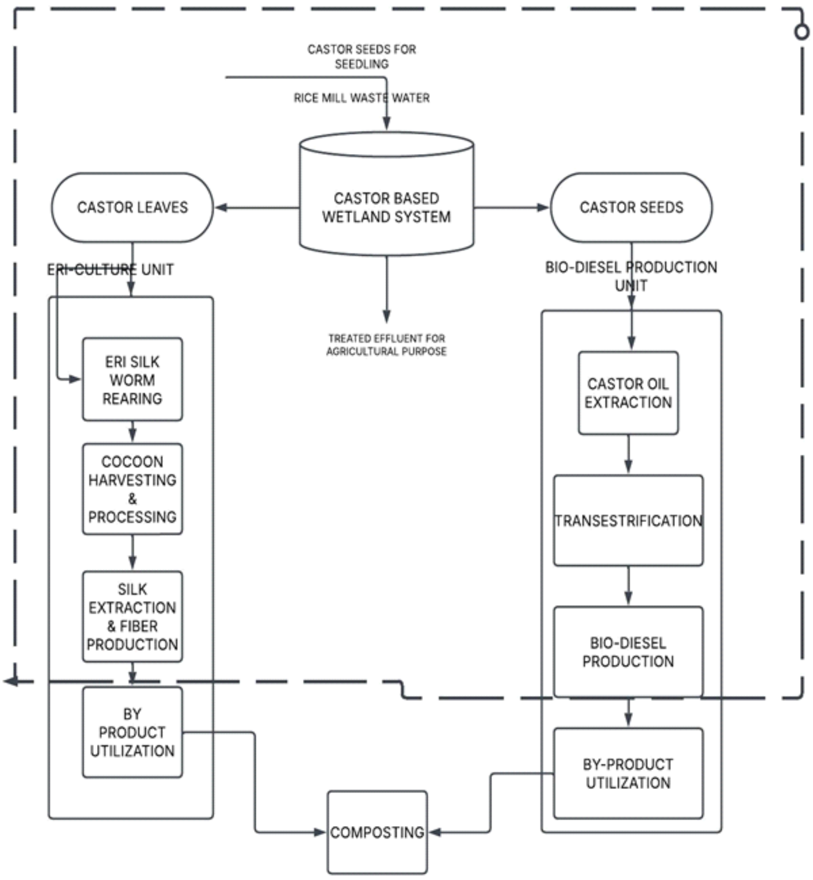
LCA Framework for Wetland System Components

This study employs a comparative Life Cycle Assessment (LCA) approach to evaluate the environmental performance of two distinct castor-based wetland systems, each producing different end products-eri-silk cocoons (Figure 3) and bio-diesel (Figure 4). The LCA focuses on assessing their impacts on human health, ecosystem quality, and resource depletion, considering both short-term and long-term emissions. The study extends to the evaluation of normalized sustainability parameters, a comparative impact assessment of composts derived from both systems, and an analysis of the water footprints associated with these processes. The methodology follows the ISO 14040/14044 guidelines, covering goal and scope definition, life cycle inventory (LCI) using Eco-invent database (Version 3.10), life cycle impact assessment (LCIA), and interpretation using SimaPro 9.6, so as to ensure a rigorous and standardized analysis.

System Boundaries and Functional Units

A cradle-to-grave boundary is established for both systems (batch type, each cycle extending up to 90 days) (Figure 2), incorporating processes from castor cultivation and wastewater treatment to final product generation and waste management. The functional unit is defined as the production of 1 kg of the final product (either bio-diesel or eri-silk cocoons) for a single cycle, in order to enable meaningful comparisons. The study considers multiple impact categories, including human health, ecosystem and resource depletion, along with their sub-categories. The infrastructural set up (for the wetland, process & product handling) as well as usage of products and by-products (viz. treated wastewater, biodiesel, glycerine, eri-silk cocoon and the respective composts) are not included in the present LCA study.

Since, the route for eri-silk production and that for biodiesel generation are dependent on two distinct yields from wetland, namely leaves and seeds, whose productivity of the former affects the latter, because more leaves harvested reduces less yield of seed and thus lesser generation of biodiesel, the two wetland system was studies separately for each of the routes, so as to provide the framework of their integration, based on characteristics of rice mill wastewater as well as available infrastructure. The quality of rice-mill wastewater, which is influent to the wetland system has been pre-treated to a level acceptable for growth of the castor plants, based on the experimental studies carried out in the laboratory of the authors.



Figu. 2: LCA boundary of Castor based Rice-mill waste water wetland system.

System 1: Eri-Silk Production Method Materials and Process Flow

In order to produce eri-silk cocoons as the primary end product, system-1 was deployed (Figure 3), the main inputs and processes being rice-mill wastewater and Castor seeds leading to castor cultivation in wetland basin, while the primary outputs being wetland-treated wastewater, castor biomass (classified as : castor leaves, and rest of the castor biomass). In fact, the eri-worm eggs, which are placed in a rearing unit, where the larvae primarily eat castor leaves yielding progressively unto matured eri-worms, pupae and cocoons, whereas the residues from all

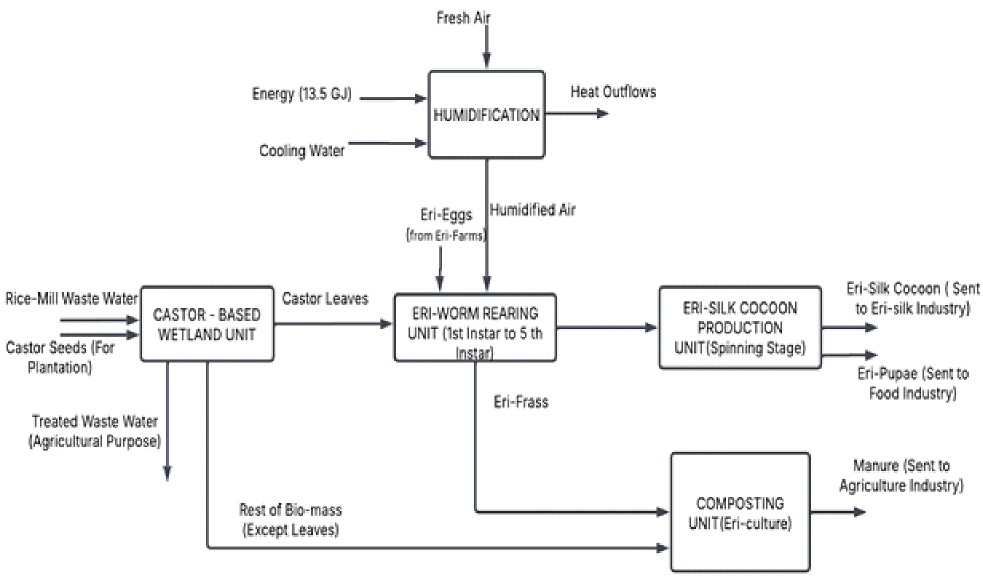


Fig. 3: Flow Diagram of Eri-Culture (Castor based) Unit.

Subsystems being undergone composting to yield organic manure. Hence, this system is primarily comprised of threes subsystems, namely,(1) rearing of eri-worm (up to 5th Instars stage) with a supporting humidification sub-system to maintain an ideal environment for eri-worm development (24–25°C temperature, 75% relative humidity), (2) production of cocoons with development of the pupae, and (3) preparation of compost with a castor-based wetland residues (predominantly consisting of castor non-leafy biomass and eri-frass).Eri-frass refers to an excreta produced by eri-worms after their voracious consumption of castor leaves, as they undergo through five instar stages and are high in nutrients. The next metamorphosed stage of eri-worm is their transformation untoEri-pupae (with the outer layers of spinned-cocoons). Eri-pupae are mostly used as protein supplement, baby-food and even in preparation of biscuits, whereas the eri-silk cocoons are utilized for the eri-silk manufacturing. Now, the circular waste management strategy gets completed by composting the left over biomass (leaves excluded) into organic manure.

System 2: Bio-Diesel Production Route Materials and Process Flow

The bio-diesel system, also referred to as System-2, (Figure 4) starts with the same basic unit as the system-1 :(1) castor-based constructed wetland set up to treat rice mill wastewater. The influent to this sub-system is the castor seeds as well as the rice mill wastewater and the output includes treated wastewater grown-up castor plants, as in the case of System-1. However, the biomass yields form this subsystem is segregated as oil-seed and the rest of the biomass, because here the focus is the oilseed for their usage for biodiesel production (in contrast to castor leaves for their usage in eri-culture as in case of the System-1). The next subsystem involves (2) processing of harvested castor seeds in an oil-extraction unit so as to obtain castor oil, the primary raw material for bio-diesel production, with a portion (roughly 3%) retained for future of castor plantation cycles. This sub-system requires external power for milling the seeds and generates de-oiled cakes along with the castor-oil. The castor-oil so generated needs to undergo (3) trans-esterification process, which in contact with Methanol and catalyst, turns castor oil into bio-diesel as well as glycerin.

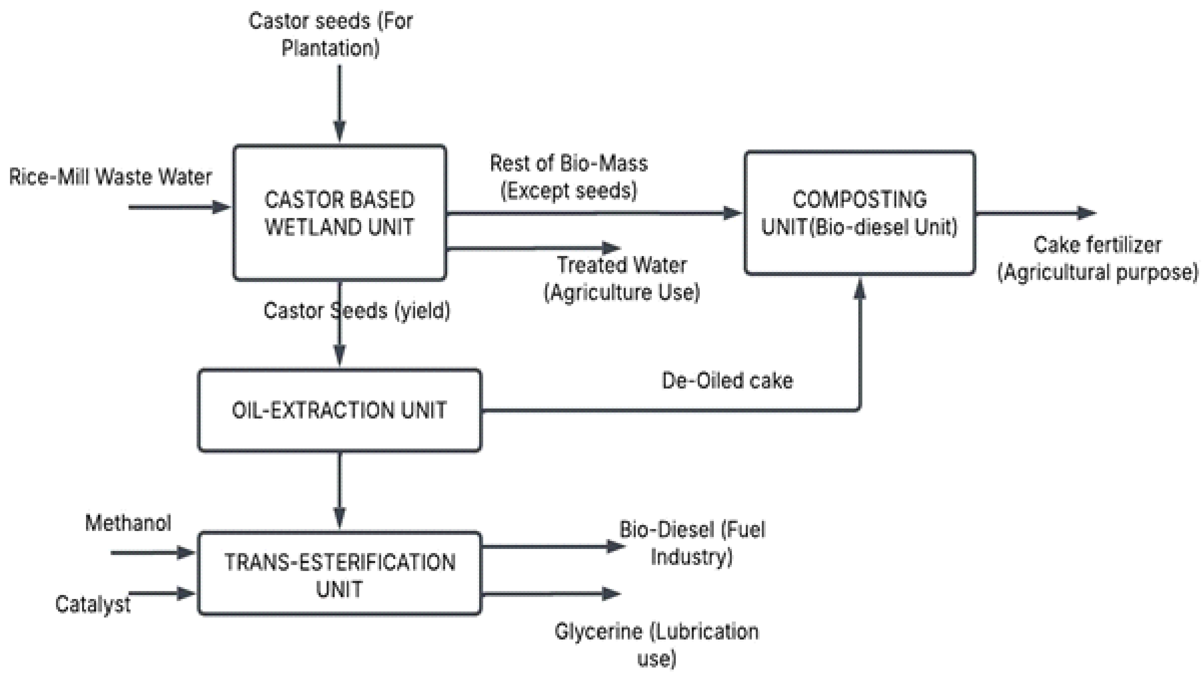


Fig. 4: Flow Diagram of Bio-Diesel (Castor based) Unit.

Byproduct. Finally, the de-oiled cake, a substantial by-product of oil extraction, is (4) composted into organic fertilizer combined with leftover biomass. Hence, the various products generated through the process include treated wastewater, oil-seed (for cultivation for next cycle in the wetland), castor oil (and associated rang of usages), glycerin (utilized for lubricating purposes), bio-diesel (as a substitute to diesel) as well as composted cake fertilizers.

Life Cycle Inventory (LCI) and Information Gathering

LCI phase includes quantification of material flows, energy use, emissions, and waste outputs for both systems, i.e. system-1 & system-2. Site-specific measurements and studies on pilot-plantof experimental castor-wetland units are used for estimating castor biomass yields, wastewater treatment efficiency, energy inputs, and product outputs, composting, bio-diesel production and eri-worm rearing. The emission data associated with all these processes are obtained from Eco-invent database (V 3.10) with special emphasis to India.

Methodology for Life Cycle Impact Assessment (LCIA)

Various impact categories are selected based on their relevance to agriculture-based wetland systems and industrial processing, which are categorized in terms their effects on three primary environmental domains: human health, ecosystem and resources as well as the related subdomains.TheSimapro (9.6) is used to assess comparative environmental impacts, encompassing important areas like water footprint, freshwater eutrophication, human toxicity, global warming potential, and fossil depletion, based on ReCiPe 2016 Midpoint (H) technique.

Comparison of Compost Quality and Environmental Impacts

Both systems generate compost as a by-product, but with varying quality and environmental impact. The compost derived from the eri-worm production system is rich in eri-frass, expected to enhance soil microbial activity and nutrient availability and in contrast, the bio-diesel system is likely to produces de-oiled cake that serves as a fertilizer with higher nitrogen content. The environmental footprint of these composts is compared in terms of greenhouse gas emissions, soil enrichment potential, and overall nutrient retention, using ReCiPe 2016 Midpoint (H) approach.

Water Footprint & Energy Network Analysis

Since, water usage plays a critical role in both systems, assessment of the direct and indirect water footprints across all stages (starting from rice-mill wastewater treatment to product processing) were evaluated using AWARE (V1.06) method. Besides, network analyses for the two components are also carried out to estimate the energy consumption across both the routes of Castor-wetland system.

Sustainability-Magnitude Assessment

The sustainability of each system is assessed using normalized impact scores, which provide insights into the dominant environmental parameters affecting each route. The results are interpreted to determine the relative benefits and drawbacks of eri-silk and bio-diesel production in terms of resource efficiency, emissions reduction, and circular waste management, irrespective of the associated units, so as to ascertain the major environmental hotspots and provide scope for informed sustainable decision-making for castor-based wetland applications by offering a holistic comparison of environmental impacts.

RESULTS AND DISCUSSIONS

Comparative Evaluation of Possible Damages for Different Impact Types

Table.3 provides a comprehensive assessment of comparative evaluation of significant variations across different impact categories as revealed by the short-term and long-term damage assessments components for the eri-silk cocoon and castor-based bio-diesel systems. The long-term impairments typicallyappears to be by and large insignificant or nonexistent, whereas short-term effects predominate in both systems. This distinction is crucial in understanding the immediate versus prolonged environmental and health consequences of each production route.

Table 3: Damage Assessment of Bio-Diesel & Eri-Silk Cocoon (Long-term *vs* Short-term).

IMPACT	Various Category	DAMAGE ASSESSMENT					
		Bio-diesel (Castor -based)			Eri-Silk Cocoon (Castor based)		
		Total	Short-term	Long-term	Total	Short-term	Long-term
Human Health \(DALY)	Global warming, Human health	4.94E-07	4.94E-07	0.00E+00	1.63E-07	1.63E-07	0.00E+00
	Stratospheric ozone depletion	5.60E-11	5.60E-11	7.00E-18	2.40E-11	2.40E-11	3.00E-18
	Ionizing radiation	1.80E-10	1.89E-11	1.62E-10	7.74E-11	8.10E-12	6.93E-11
	Ozone formation, Human health	6.62E-09	6.62E-09	3.10E-15	3.49E-10	3.49E-10	1.32E-15
	Fine particulate matter formation	9.56E-07	9.55E-07	1.94E-10	2.72E-07	2.72E-07	8.32E-11
	Human carcinogenic toxicity	1.63E-07	5.13E-09	1.58E-07	7.00E-08	2.20E-09	6.78E-08
	Human non-carcinogenic toxicity	1.33E-07	1.77E-08	1.16E-07	5.72E-08	7.60E-09	4.96E-08
	Water consumption, Human health	3.93E-10	3.93E-10	0.00E+00	1.69E-10	1.69E-10	0.00E+00
Eco-Systems (species.yr)	Global warming, Freshwater ecosystems	4.07E-14	4.07E-14	0.00E+00	1.34E-14	1.34E-14	0.00E+00
	Ozone formation, Terrestrial ecosystems	2.11E-10	2.11E-10	4.40E-16	5.00E-11	5.00E-11	1.86E-16
	Terrestrial acidification	3.46E-10	3.46E-10	2.60E-16	1.15E-10	1.15E-10	1.10E-16
	Freshwater eutrophication	8.47E-09	8.20E-09	2.73E-10	1.30E-10	1.28E-11	1.17E-10
	Marine eutrophication	6.25E-10	6.25E-10	4.13E-14	1.83E-14	6.07E-16	1.77E-14
	Terrestrial ecotoxicity	8.24E-12	8.18E-12	5.83E-14	3.53E-12	3.51E-12	2.50E-14
	Freshwater ecotoxicity	9.30E-12	7.58E-13	8.55E-12	3.70E-12	3.83E-14	3.67E-12
	Marine ecotoxicity	1.93E-12	1.50E-13	1.78E-12	8.00E-13	3.66E-14	7.63E-13
	Land use	3.41E-09	3.41E-09	0.00E+00	3.13E-11	3.13E-11	0.00E+00
	Water consumption, Terrestrial ecosystem	1.45E-11	1.45E-11	0.00E+00	6.20E-12	6.20E-12	0.00E+00
	Water consumption, Aquatic ecosystems	4.02E-15	4.02E-15	0.00E+00	1.73E-15	1.73E-15	0.00E+00
Resources (USD2013)	Mineral resource scarcity	3.37E-03	3.37E-03	0.00E+00	1.44E-04	1.44E-04	0.00E+00
	Fossil resource scarcity	8.49E-03	8.49E-03	0.00E+00	3.64E-03	3.64E-03	0.00E+00

The category-specific assessment are provided in the subsequent paragraphs.

Assessment of Damage Potential related to Human Health for the Castor-based wetland Systems

For human health-related impacts (Figure 5 & 6), both bio-diesel and eri-silk cocoon systems exhibit only short-term damage for global warming, ozone formation, particulate matter formation, and water consumption, with long-term values being negligible. For instance, the biodiesel production shows almost four-fold higher short-term effects of global warming on human health (i.e., 4.94E-07 DALY), compared to its counterparts for eri-silk production system (i.e., 1.63E-07 DALY); whereas the long-term component is nil in both the cases, indicating the greenhouse gas emissions and the resulting health costs are mostly immediate in nature (rather than appreciably protracted over time). In the similar line, the short-term implications of fine particulate matter generation by biodiesel (9.56E-07 DALY) is about four-fold of the short-term fine particulate.

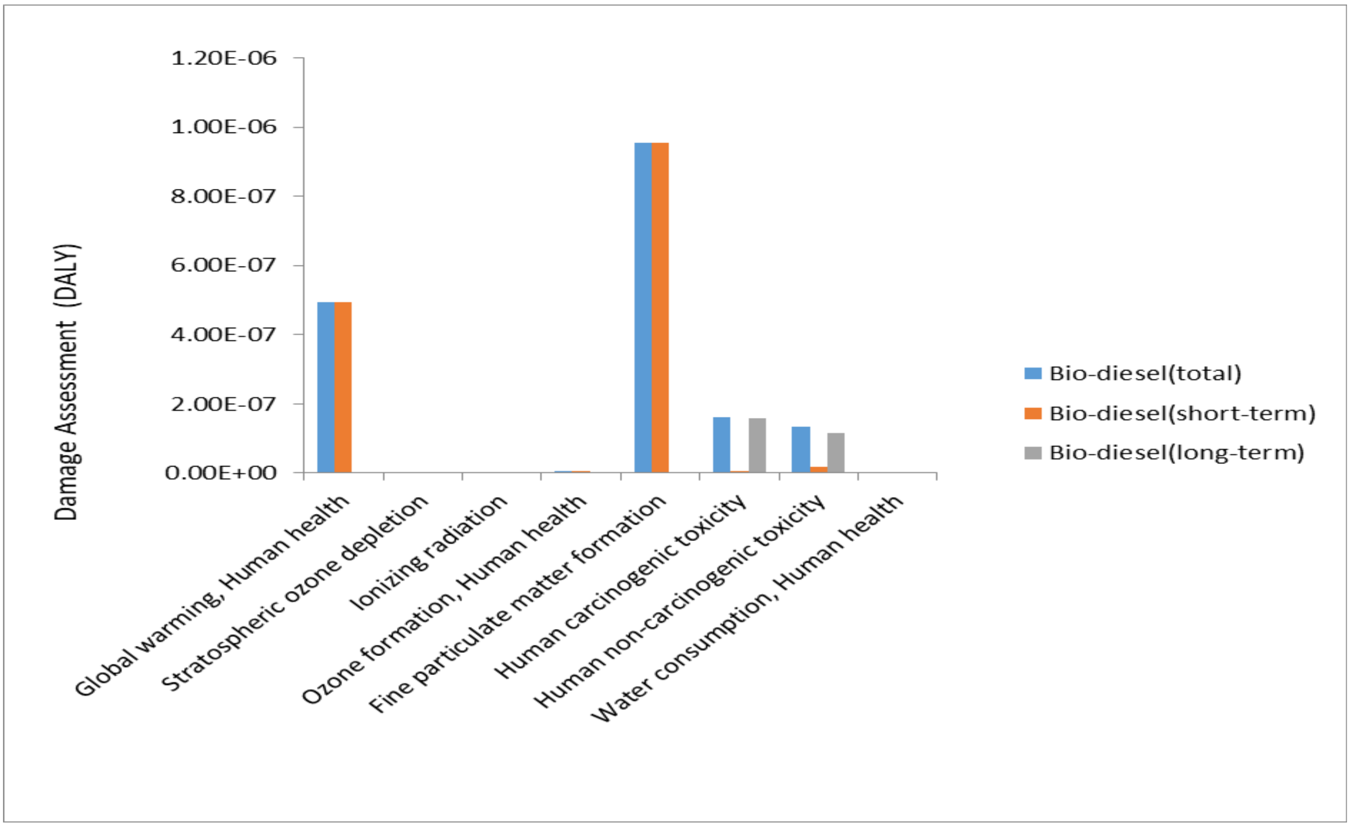


Fig. 5: Damage Assessment with Regard to Human Health for Biodiesel Castor Wetland Systems.

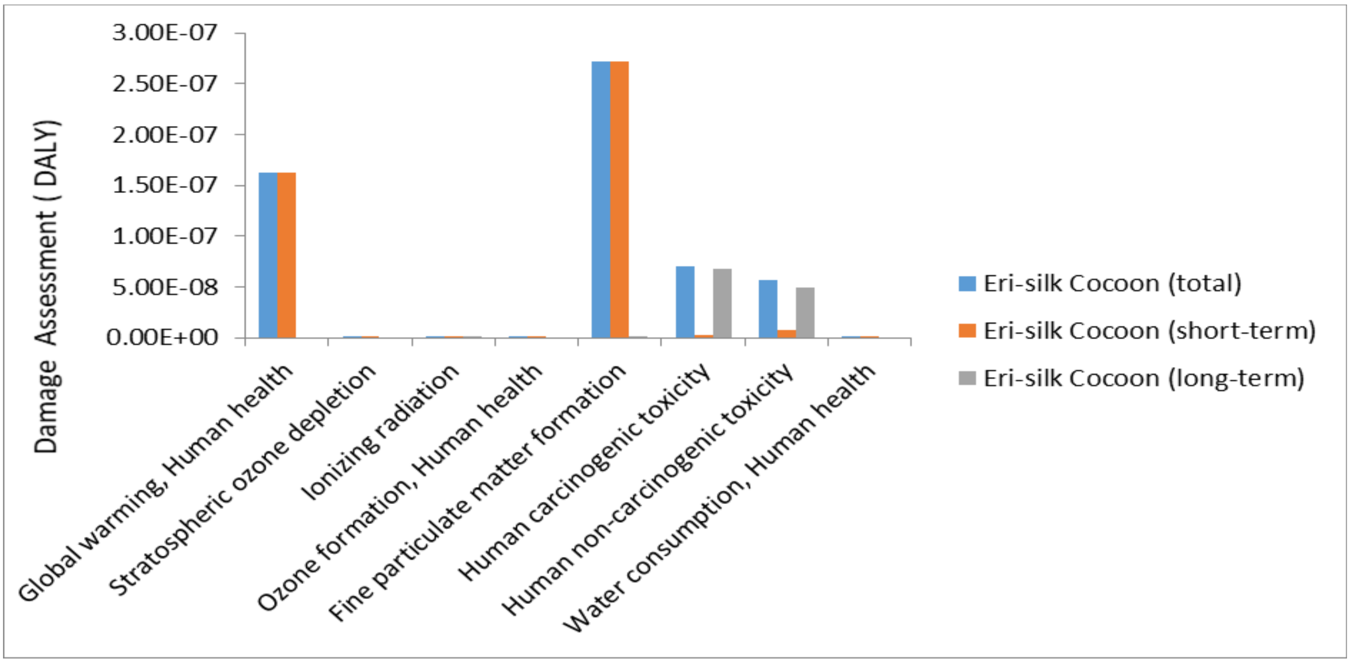


Fig. 6: Damage Assessment with Regard to Human Health for Eri Silk Castor Wetland Systems.

Matter generation for eri-silk production (2.72E-07 DALY), which constitutes a significant cause of respiratory disorders, whereas the long-term effects are negligible. This pattern seems to suggest that emissions produced during the production of gasoline or the rearing of silk contribute to air pollution mostly in the short term rather than over time.

It may also be noted that, with regard totoxicity effects, a slight long-term component is observed for both systems, but with varying magnitudes indicating that the magnitude of chemical exposure from bio-diesel processing has longer-lasting consequences. We can see that the human carcinogenic toxicity for bio-diesel (1.36E-07 DALY total) includes a small long-term impact (1.58E-07 DALY), whereas eri-silk cocoon production (7.00E-08 DALY total) has a lower long-term toxicity impact (6.78E-08 DALY).non-With regard to carcinogenic toxicity,bio-diesel (1.16E-07 DALY) is an order to high with regard to that associated with production of eri-silk Cocoon (4.96E-08 DALY). It is also evident that the pollutants from both processes have some degree of long-term health effects, although the bio-diesel pathway is more noticeable.

Assessment of Damage Potential related to Ecosystem for the Castor-based wetland Systems

For ecosystem-related impacts, most categories are dominated by short-term effects, with minimal long-term contributions (Figure 7 & 8). For instance, terrestrial acidification shows significant short-term impacts of 3.46E-10 species.yr for bio-diesel and 1.15E-10 species.yr for eri-silk, while their long-term contributions are almost negligible (2.06E-16 species.yr and 1.10E-16 species.yr, respectively). It is also observable that both the systems' (i.e., biodiesel-system&eri-system) acidifying emissions and fertilizer runoff have a short-term impact on ecosystems with limited long-term durability. Similarly, the long-term component of freshwater eutrophication in bio-diesel is higher by an order (8.47E-09 species.yr) compared to that caused by production of eri-silk cocoons' (1.30E-10 species.yr), although both of the cases it is negligible. However, there are several categories, such as terrestrial ecotoxicity and marine eutrophication, wherein there is aslight long-term effects, probably associated with lingering chemical and waste product residues from these systems.

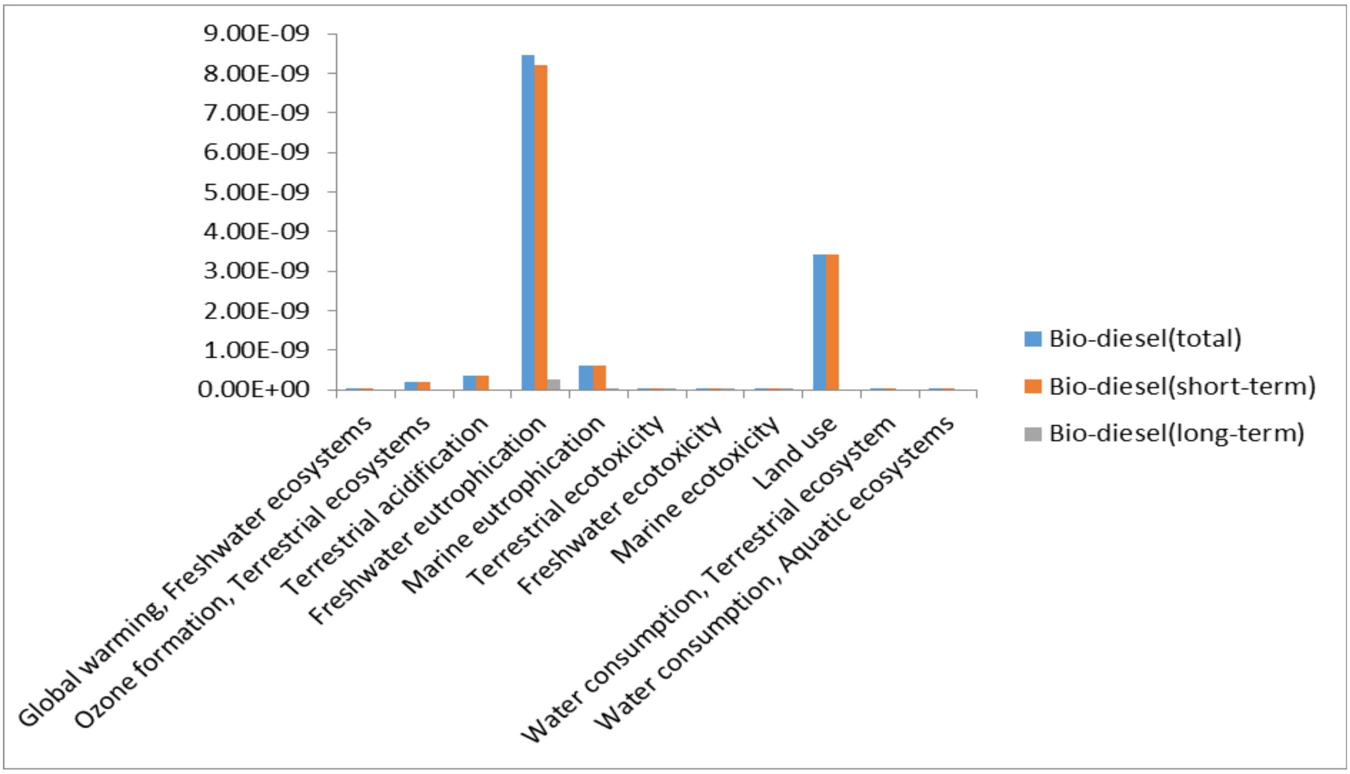


Fig. 7: Damage Assessments with Regard to Ecosystem for Biodiesel Castor Wetland Systems.

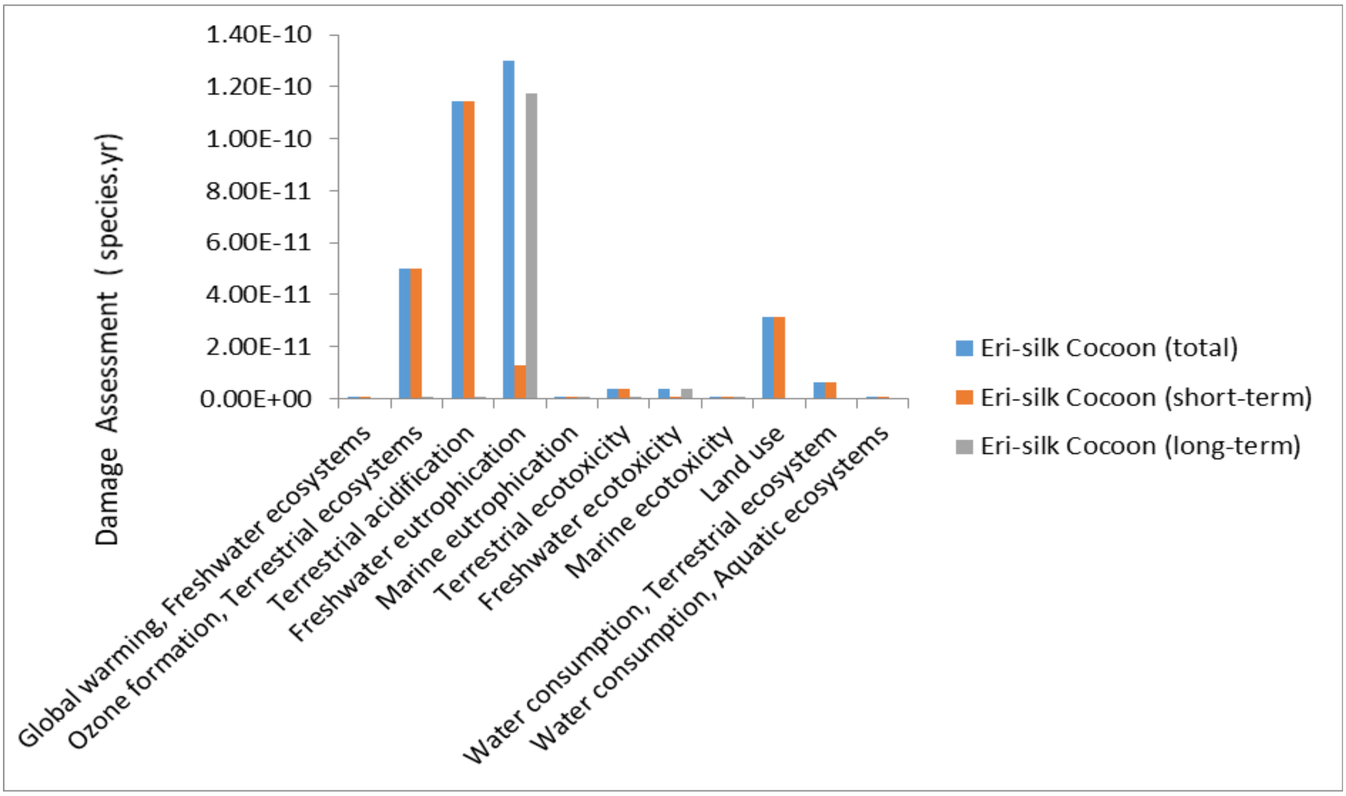


Fig. 8: Damage Assessment with Regard to Ecosystem for Eri Silk Castor Wetland Systems.

Assessment of Damage Potential related to Resource Depletion for the Castor-based wetland Systems

Resource depletion impacts also exhibit short-term dominance. Mineral resource scarcity for bio-diesel (3.37E-03 USD) and eri-silk (1.44E-04 USD) remains short-term, with no significant long-term impact (Figure 9 & 10). So also the case of fossil resources scarcity, which is predominantly short term depletion, with almost two and half times damage potentials in case of biodiesel system (8.49E-03 USD) than the eri-silk system (3.64E-03 USD). Hence, in all these cases, steps to mitigate short-term resource depletion necessitates scope for improvisation, especially with regard to bio-diesel system.

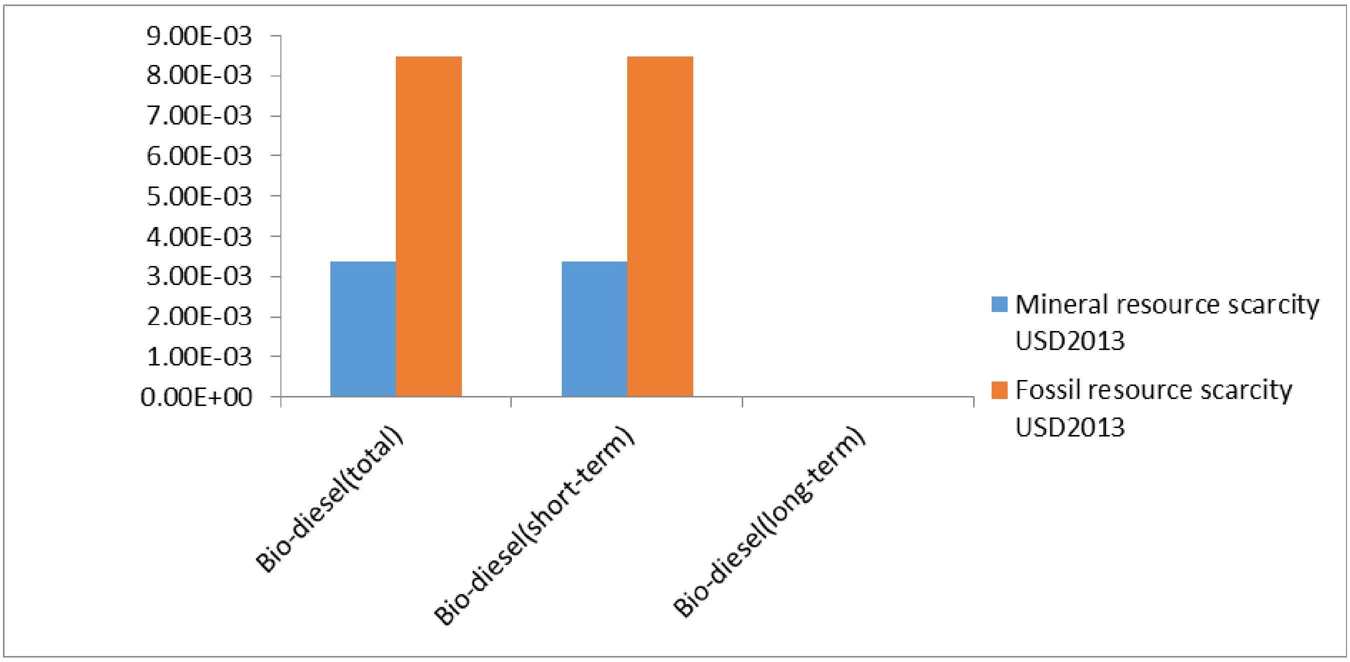


Fig. 10: Damage Assessment with Regard to Ecosystem for Eri Silk Castor Wetland Systems.

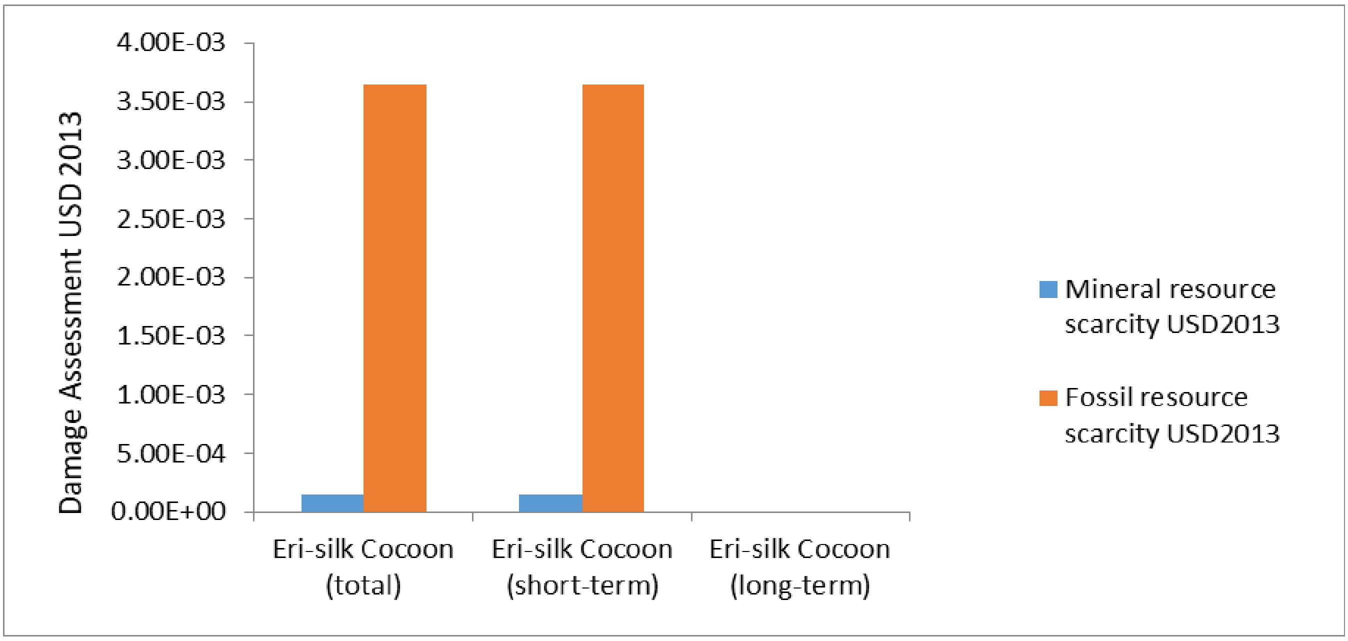


Fig. 10: Damage Assessment with Regard to Ecosystem for Eri Silk Castor Wetland Systems.

As we can see with the present study, the effects of bio-diesel and eri-silk cocoon systems on resource categories, ecosystems, and human health are primarily short-term. It may be noted that, when they do occur, the long-term effects are mostly linked to toxicity-related consequences, like toxicity that can cause cancer in humans and non-carcinogenic effects, as well as small contributions to ecosystem deterioration. In fact, in comparison to eri-silk, bio-diesel production typically seems to have more short- and long-term effects, especially in the areas of resource depletion and health. Given the preponderance of short-term consequences, mitigation methods ought to concentrate on waste management and immediate emissions in order to reduce their environmental impact.

Comparative Evaluation of Damage Potential for Various Impact Types

In order to identify the main effect categories in each system, normalization procedure was deployed with regard to the respective contributions of eri-silk cocoon and bio-diesel systems on the human health, ecosystem and resource depletion (Figure 11).Supporting the findings of the previous impact assessment, demonstrating enhanced production of biodiesel (for both short-term and long-term global warming) and associated greenhouse gas emissions, the normalized study also reveals the excessively large contribution of global warming (human health), especially for bio-diesel. The eri-silk cocoon system also contributes to this category, although to a much less or degree. With regard to the generation of fine particulate matter, both systems do have fairly comparable normalized scores, indicating need of careful consideration production pathways leading to the hazards to respiratory health and the deterioration of air quality.

Both the systems show a considerable standardized score with regard to human carcinogenic, with eri-silk cocoon pathway showing relatively higher toxicity. The health effects of exposure to harmful compounds during the growing or processing of silk may be might besevere than those of bio-diesel generation.
Similarly, human non-carcinogenic toxicity is also slightly higher for eri-silk, implying that non-cancerous health effects—potentially from chemical residues in silk processing—are of concern. On the other hand, categories related to marine and freshwater ecotoxicity, terrestrial acidification, and eutrophication show relatively higher contributions in bio-diesel, indicating that the fuel production pathway has a greater influence on ecosystem degradation.

Since the eri-silk production necessitates a large amount of land for the breeding of silkworms and the growth of castor plants, in case of the eri-silk cocoon system, land use stands out as a category that makes a substantial contribution. On the other hand, when adjusted, the impact of bio-diesel production is less noticeable. On being compared, water use efficiency

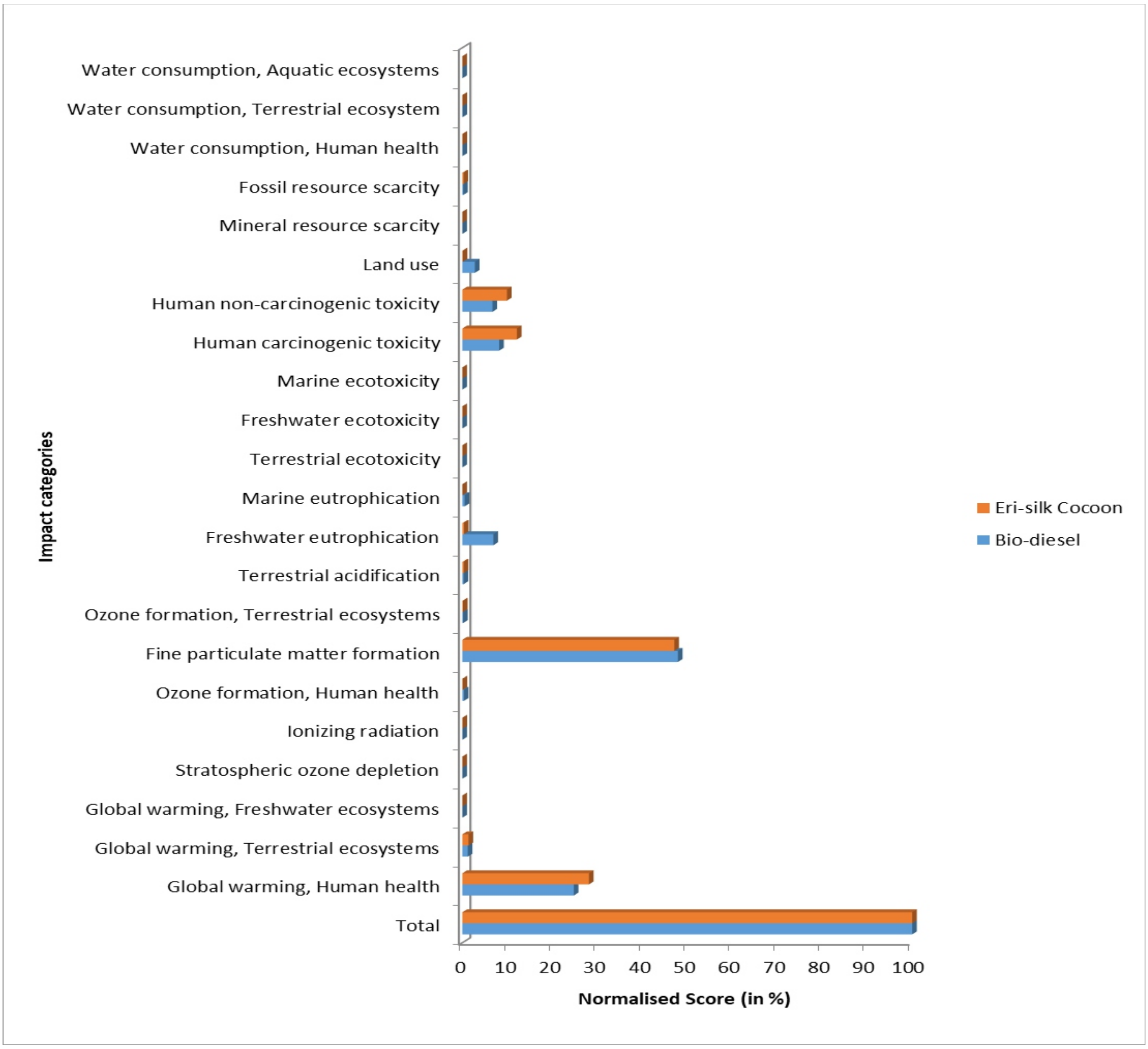


Fig. 11: Normalized Damage Assessment of Castor Wetland Systems.

in these processes does not appear to be a significant environmental burden because water consumption in terrestrial, aquatic, and human health ecosystems are small in both systems.

Although, both systems, resource scarcity—including mineral and fossil resources—displays comparatively lower normalized scores. Nonetheless, bio-diesel has a marginally greater scarcity of fossil resources, which emphasizes the need for energy inputs and resource extraction to produce fuel. This is to be expected as the synthesis of bio-diesel requires methanol and other processing chemicals. Overall, the normalized ratings show that the impact profile of both systems is dominated by categories relating to human toxicity, fine particulate matter production, and global warming. The eri-silk cocoon system has greater effects on land usage and human toxicity, whereas bio-diesel has a greater impact on ecosystem-related categories like acidification and eutrophication. These findings do highlight the necessity for tailored mitigation techniques addresses certain effect categories pertinent to each system.

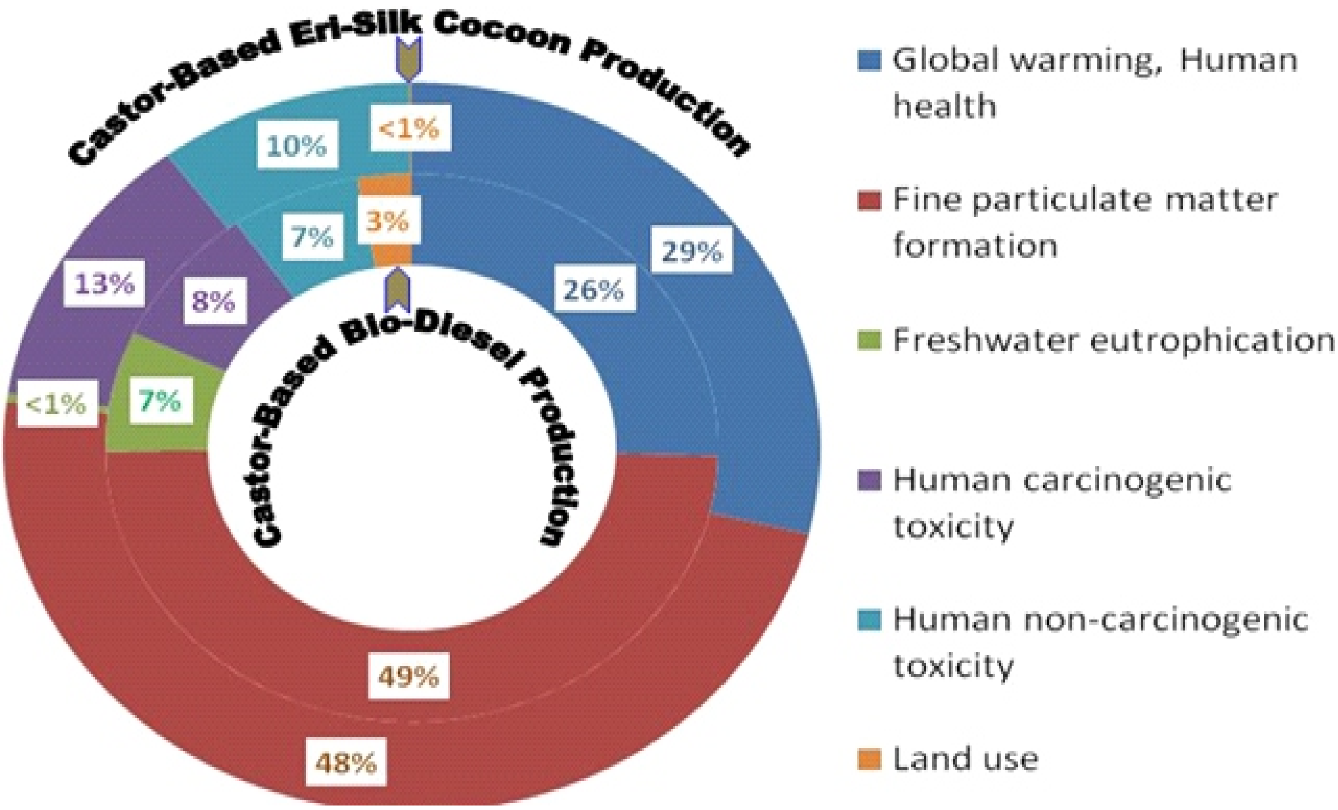


Fig.12: Environmental Hotspot Assessment of Castor Wetland Systems

A Hierarchical Evaluation of key impact categories are highlighted (figure 12) by the hierarchical assessment of environmental hotspots for the production of eri-silk cocoons and castor-based bio-diesel, which covers 97% of all normalized damage. Both these systems are dominated by fine particulate matter generation, which accounts for over half of the overall damage (49% for bio-diesel and 48% for eri-silk). This suggests that combustion and farming practices are major sources of air pollution.

The production of biodiesel (29%) is more affected by global warming (human health) than eri-silk (10%), most likely as a result of greenhouse gas emissions from fuel processing and agricultural inputs.. For bio-diesel, fertilizer runoff causes significant freshwater eutrophication (7%) but eri-silk has little effect (<1%). On the other hand, because of the space needed for silk rearing, the land use impact of eri-silk (3%) is greater than that of bio-diesel (<1%). On aggregation, human carcinogenic and non-carcinogenic toxicity account for 20% of biodiesel and 18% of eri-silk, indicating potential dangers of chemical exposure in both processes. In general, eri-silk also exhibits larger land use and toxicity implications, whereas bio-diesel displays higher greenhouse gas emissions and nutrient runoff.

Castor Wetland Systems' Water Footprints

The figure 13 water footprint evaluation measures the overall amount of freshwater used in castor-based wetland systems for the production of biodiesel and eri-silk cocoons. According to the findings, the water footprint of producing bio-diesel is substantially larger (0.078 m^3, 70%) than that of producing eri-silk cocoons (0.034 m^3, 30%). This implies that the production of eri-silk, which mostly consists of the cultivation of castor leaves and the raising of silkworms, requires less water than bio-diesel processing, which comprises the irrigation of castor crops, oil extraction, and transesterification. The reason behind such disparity, in case of the bio-diesel pathway, could be usage of more water during industrial processing steps like oil refining and bio-diesel conversion. The process of producing eri-silk, on the other hand, is fairly water-efficient, requiring less water for post-harvest processing even if it also depends on castor leaves.

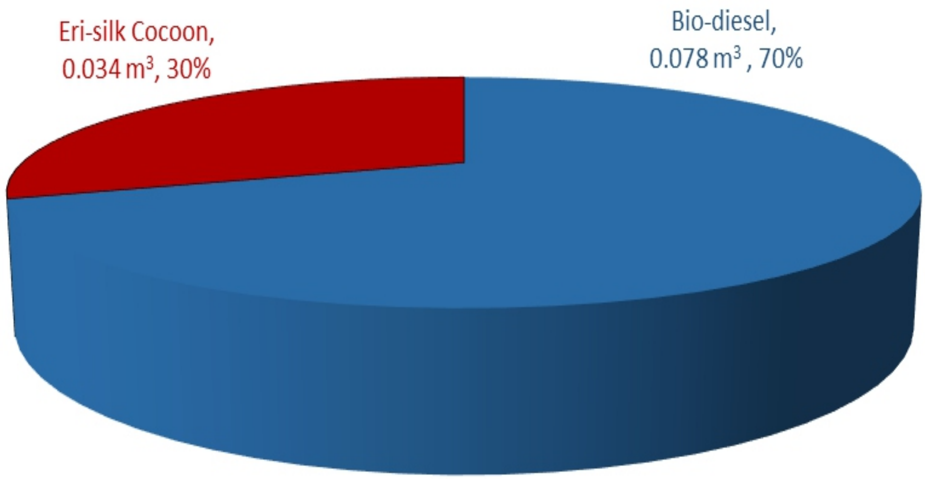


Fig. 13: Water Footprint Assessment of Castor Wetland Systems.

The striking difference in water useas observed herein does also fit with the larger sustainability evaluation, demonstrating that resource-intensive operations like chemical processing and oil extraction leading to incremental the environmental burden as well. In order to improve water-use efficiency and lessen the depletion of freshwater resources, this analysis emphasizes the necessity of better water management techniques, especially during the manufacture of biodiesel.

Energy Flow Assessment in Eri-Silk Cocoon and Bio-Diesel Production Systems

Figure 14illustrate the energy demands associated with the production of eri-silk cocoons and bio-diesel from castor seeds, highlighting differences in their energy intensities and production complexities.

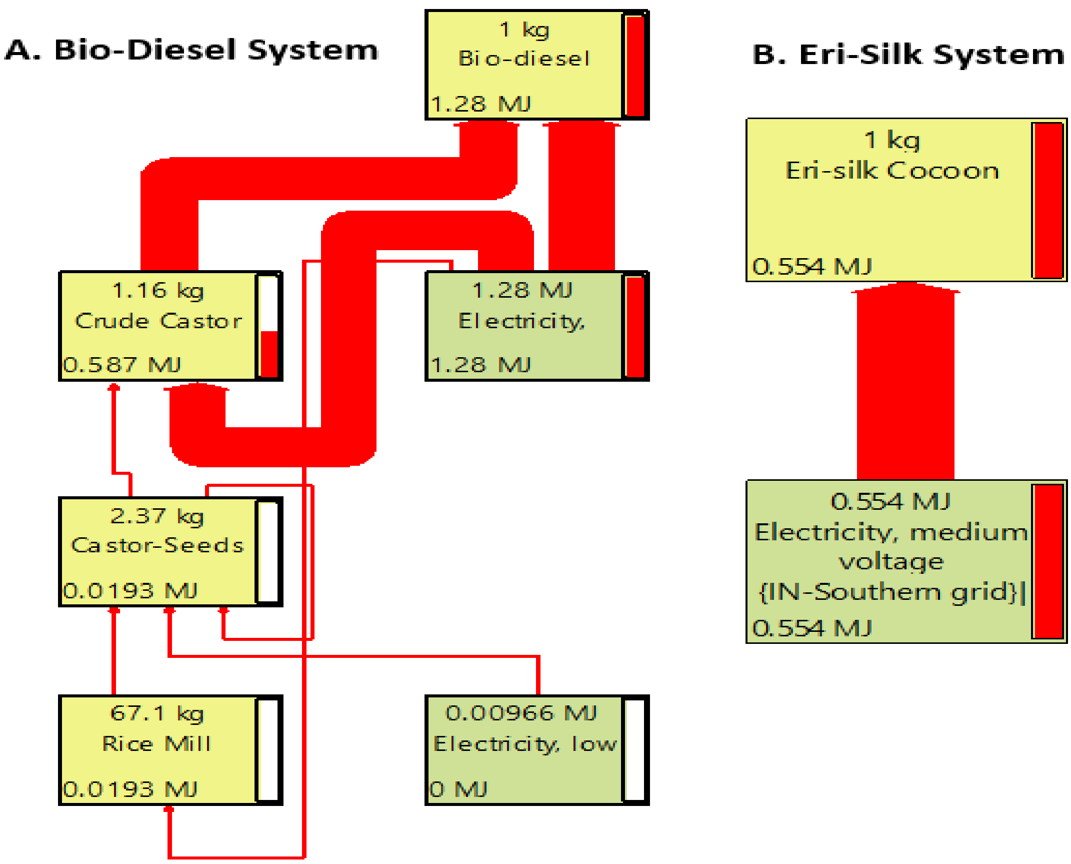


Fig. 13: Water Footprint Assessment of Castor Wetland Systems.

The study (Figure 14-A) demonstrates a fairly complex energy flow for bio-diesel production, amounting to a total energy demand of 1.28 MJ per kg of output.

In fact, at each step of this process (viz. processing seeds, extracting crude castor oil, and refining the finished bio-diesel) there is incrementalloading of energy input to the system, with crude castor oil extraction accounts for the biggest portion of energy usage (0.587 MJ), followed byancillary energy demands from seed processing and auxiliary electrical inputs.

On the other hand, the energy inputs needed to produce 1 kg of eri-silk cocoons (Figure 14-B), i.e., 0.554 MJ of electricity, is mostly related to the power needed to maintain ideal conditions in silk manufacturing, with no additional energy requirement (for fuel or raw material processing, unlike biodiesel-system) as shown in the diagram as a straight red bar indicating a relatively simple and direct energy flow. The simplicity of this process implies a reduced reliance on fossil fuels or additional processing steps, which could help to reduce environmental impacts in terms of carbon emissions and resource depletion.

Impact Assessment of Composts generated from the Castor wetland systems

Since compost is one of the common by-product of both the systems, a comparative impact assessment is likely to shed more light on the effect of the common-sink. The impact assessment study of compost derived from the biodiesel production system and the eri-silk production system highlights significant differences in their environmental burdens (Figure 15), where in the bar graph displays the normalized percentage contributions of both compost kinds across a number of impact categories. When compared to compost from the biodiesel system, compost from the eri-silk system continuously and persistently performs better environmentally and contributes less to major environmental problems.

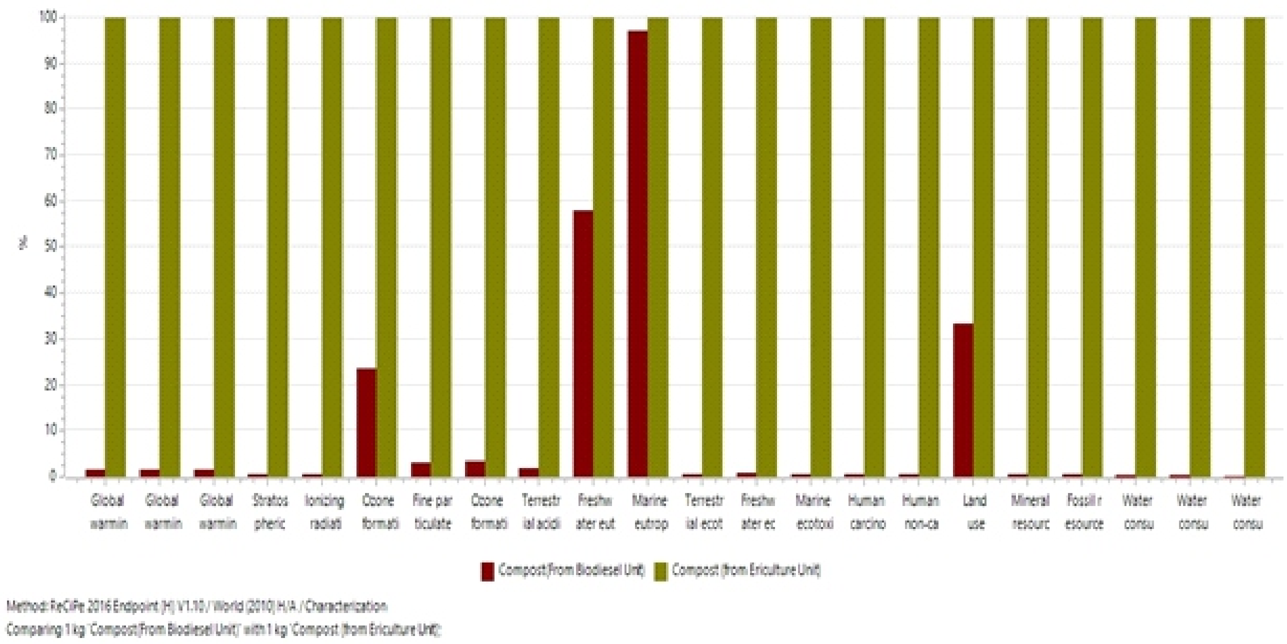


Fig. 15: Impact Assessment of Composts generated by the Castor Wetland Systems.

Compost from the eri-silk system shows dominance across nearly all impact categories, suggesting that it has lower environmental damage compared to its counterpart from the biodiesel system. This is likely due to the relatively low energy intensity of eri-silk production, as previously noted, which translates into fewer emissions and resource depletion impacts in the compost phase. Since the inputs needed for eri-silk production are much less dependent on fossil fuels and resource extraction, the compost's negligible contributions to global warming, stratospheric ozone depletion, ionizing radiation, and water consumption reflect its more sustainable lifecycle.

On the contrast, in case of the biodiesel production system, the compost generated shows significant environmental consequences (esp. freshwater eutrophication, marine eutrophication, and land use effect). Higher ecosystem degradation through enhanced marine and freshwater eutrophication ratings (esp. through nitrogen and phosphorus runoff) are probably contributed by nutrient-loaded waste streams associated with biodiesel system. Hence, even in the compost-front, castor-based biodiesel has a greater impact due to the higher energy and material inputs needed for manufacture, such as seed processing and oil extraction. These findings imply that compost from the manufacture of eri silk might be a more environmentally benign byproduct, especially in applications of the circular economy where waste valorization is a top concern.

These revelations offer more support for the idea that eri-silk production is a more environmentally friendly and sustainable option. However, from techno-economic robustness, biodiesel system is more reliable and cash-generating because of higher demand of biodiesel & glycerin as well as less sensitive than eri-culture (wherein improper handling of the worms can keep the system a standstill) thereby necessitating a proper blend of the two system, wherein adequate leaves to be reserved after harvesting the leaves for growth of eri-worm, so as to maintain the growth of the castor plant to yield seeds, adequate for oil-production as well as plantation for the forthcoming cycles. Together, the results highlight how crucial it is to consider the full life cycle of bio-based systems because, depending on where they come from, even waste-derived products can have serious effects on the economic and environmental sustainability.

CONCLUSION

The present work offers a thorough comparative life cycle assessment (LCA) of two castor-based wetland models, namely, the production of bio-diesel (with higher potential for global warming, fossil depletion, and eutrophication) and the production of eri-silk cocoons (with a stronger impact on land usage and human toxicity), both the systems being dominated by short-term impacts (with toxicity categories alone largely responsible for long-term environmental hazards). On overall assessment, the manufacturing of eri-silk is relatively more environmentally friendly in terms of emissions, energy as well as water-footprint compared to biodiesel-system. However, sensitivity of the former system and techno-economic robustness of the later system necessitates the scope of an integrated hybrid approach that combines the lower ecological impact of eri-silk production with the biofuel potential of castor and this forms a significant finding from this study. Through the optimization of energy efficiency, resource allocation, and wastewater treatment, such a unified system could improve environmental performance while lowering individual trade-offs. To further increase the sustainability of bio-based wetland systems, future research should concentrate on possible nutrient recovery, hybrid process design, proportioning of leaf and seed harvest, and the integration of composts from the two systems, and so forth.

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