ISSN: 0379-5462
IPPTA: Quarterly Journal of Indian Pulp and Paper Technical Association
Vol. 37, E3, 2025, p. 119-124

Life Cycle Assessment – Based Fire Safety Measures in Indian Pulp & Paper Mills: Environmental and Economic Co-Benefits

Dr. Hemant Bherwani*#
Senior Scientist - CSIR-NEERI Nagpur

Pragya Ganvir*
Project Associate-ICSIR-NEERI Nagpur

Dr. Ankit Gupta*#
Principal Scientist- CSIR-NEERI Delhi

Dr. Amit Bansiwal*#
Chief Scientist & Head of Environmental Sustainability and Green Economy (ESGE) - CSIR-NEERI Nagpur

** CSIR-National Environmental Engineering Research Institute (CSIR-NEERI), Nagpur-440020, Maharashtra, India*

 # Academy of Scientific and Industrial Research (AcSIR), Gaziabad-201002, Uttar Pradesh, India

Abstract:

The India's paper and pulp sector is one of the country's most resource and energy intensive industries, consuming high levels of water, energy, and raw materials while emitting significant greenhouse gas (GHGs). Fire incidents in mills worsen these impacts, leading to uncontrolled emissions, production losses, and increased economic costs. This study applies Life Cycle Assessment (LCA) as per ISO 14040 and ISO14044 to evaluate the environmental and economic implications of fire incidents and preventive interventions in an Indian mill. One baseline study and two scenarios were modelled and they are – Fire incident and Fire prevention applied covering cradle-to-gate system boundaries. Impact categories included GWP, AP, EP, ODP, ADP, HTP, POCP and TETP. Results reveal that fire incidents increased GWP from 4358.63 kg CO_2 Eq (Baseline) to 6487.82 kg CO_2 Eq (Fire Incident), while preventive measures reduced it to 2066.1 kg CO_2 eq. The economic interpretation of GWP indicates corresponding costs of ₹15.61 lakh, respectively. LCA demonstrates that implementing fire prevention strategies provides not only safety assurance but also significant environmental and economic co-benefits, aligning industrial safety with sustainability goals.

Keywords: *Life Cycle Assessment, Pulp and Paper Industry, Fire Prevention, Environmental Impact, Sustainability.*

Introduction

India's Pulp and Paper industry contributes sustainability to the manufacturing sector, producing over 15 million tonnes annually and employing more than 0.5 million people [1]. However, it is classified as one of the most energy and water intensive industries in India. The sector's average energy consumption ranges from 34.3 GJ per tonne of paper, with emission intensities averaging 3.4 t CO_2/t paper [2]

Frequent fire incidents within paper mills have emerged as a critical concern. Mills typically process combustible raw materials such as paper stock, pulp dust, and biomass residues, creating high fire vulnerability. Recent large-scale fires, such as the Ghaziabad paper mills fire (2025), have caused extensive property loss and uncontrolled emissions [3].

Traditional environmental assessments overlook such episodic but high-impact events. Therefore, integrating fire safety management within LCA framework can reveal the full extent of environmental and economic damages and demonstrates the benefits of preventive strategies. This study aims to bridge this gap by equating the environmental and economic impacts of fire events and prevention systems in an Indian fire-based paper mill.

2. Materials and Methods

2.1 Methodological Framework

The study followed the ISO 14040 [4] and ISO 14044 [5] Guidelines for the Life Cycle Assessment. A cradle-to-gate system boundary was defined, covering raw material procurement, papermaking, and associated energy and water utilities.

For the purpose of this study, the inventory was developed as a generic, mixed-case scenario based on available literature. It does not represent any specific mill type but rather provides an averaged representation suitable for comparative life cycle assessment.

2.2 Goal and Scope Definition

The Goal was to evaluate and compare the baseline study and operational scenarios:

a)Baseline study: Normal mill operation without fire or prevention.

b)Scenario 1- Fire Incident Included: System performance including emissions and losses during a fire.

c)Scenario 2- Fire Prevention: Inclusion of dust extraction, sprinkler systems, and arc-fault prevention measures.

The Functional Unit was defined as ***1 Tonne*** of finished paper product. This study represents an integrated virgin pulp and paper mill, where both pulping and paper making operations are carried out within the same facility using wood as the primary raw material

2.3 Life Cycle Inventory

Primary Data were obtained from an operational Indian mill and supplemented with open-source secondary datasets.

Fire Prevention:

Table 1: Inventory of Fire Prevention for the production of 1 tonne of finished paper

Raw Materials	Quantity
Raw Fibre (hardwood/wood chips)	2.8 tonne [6]
Steam consumption	12 t steam ~ 26 GJ [7]
Electricity (process + auxiliaries)	1400 kwh [8]
Freshwater (process + cooling)	100 - 350 m^3/t [9]
Sodium hydroxide (NaOH)	~150-420 , ~ 300 kg conservative value [10]
Sodium Sulphide (Na2S)	~40 – 120 kg, assumed ~ 80 kg [11]
CaCO3	~ 50 kg-150 kg [12]
Fuel	3-6 GJ [1]
Sludge	~ 100 – 300 kg [13]
Sprinkler system	~ 0.5. – 1.0 kg [14]
Sprinkler water use	0.1 – 0.5 m3/t [15]
Spark detectors	~ 0.5 - 2 kg [15]
Foam	~ 0.1- 0.5 kg [15]
Baghouse energy	30-80 kwh [16]

During Fire Prevention simulation, freshwater, sprinkler water, and similar sources were considered collectively under single category of total water consumption, and likewise, electricity for the fire pump and baghouse system were combined under total electricity consumption, since the results are obtained in an aggregated form.

Fire Incident:

Table 2: Inventory of Fire Incident for the production of 1 tonne of finished paper

Raw materials	Quantity
Dry woods	2.8 t [6]
Process steam	12 t (~26 GJ) [7]
Electricity	1400 kwh [8]
Fresh water	120 m^3 (typically Indian mill:100-350 m^3/t) [17]
NaOH	~ 300 kg NaOH (conservative working value)
Solid waste (Sludge)	100 – 300 kg paper sludge
Biogenic Co2 from combustion	1628 kg CO_2
Firefighting water (applied + runoff)	36.3 m^3 [18]
Sludge dry	~ 18-72 kg [19]
Diesel	~20 -40 L (~53-106 kg CO2) - assumed

2.4 Process Flowsheet

Based on the Secondary Data, the process flowsheet for the Life Cycle Assessment of 1 tonne of Paper for Baseline study as well as for different Scenarios are shown in Figure 1, 2 and 3 was prepared using GaBi ts software.

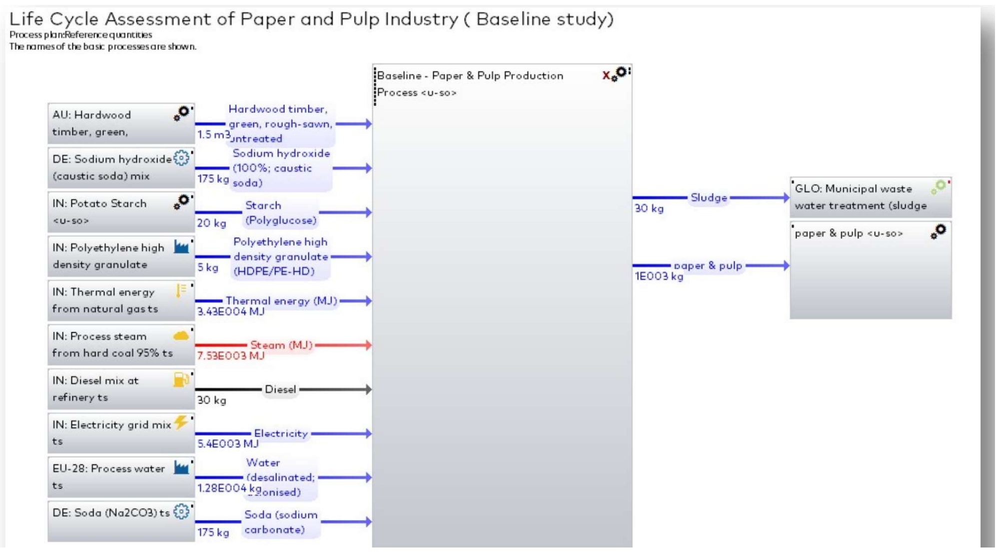

Figure 1: Plan for Baseline study

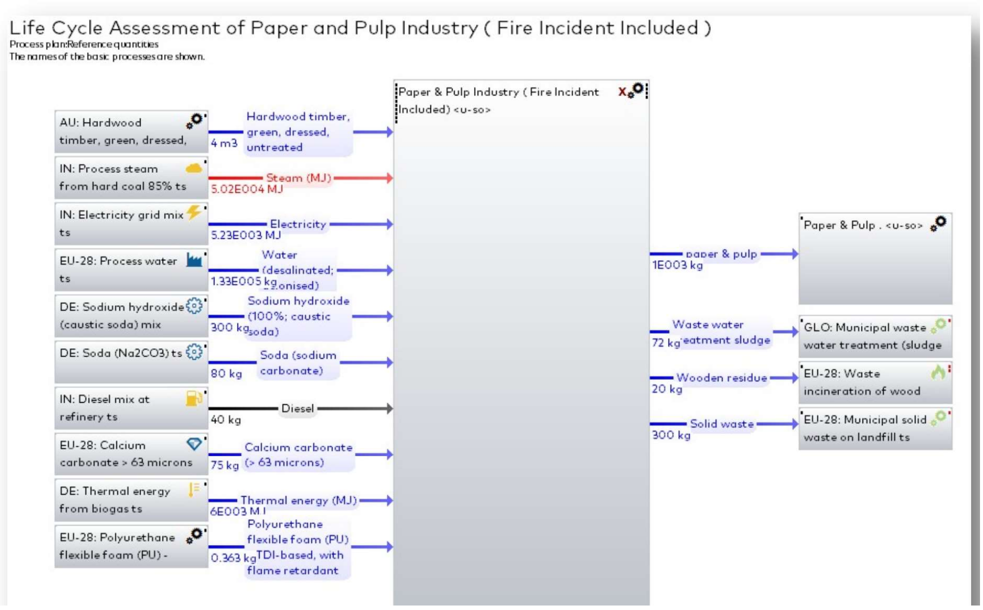

Figure 2: Plan for Fire Incident

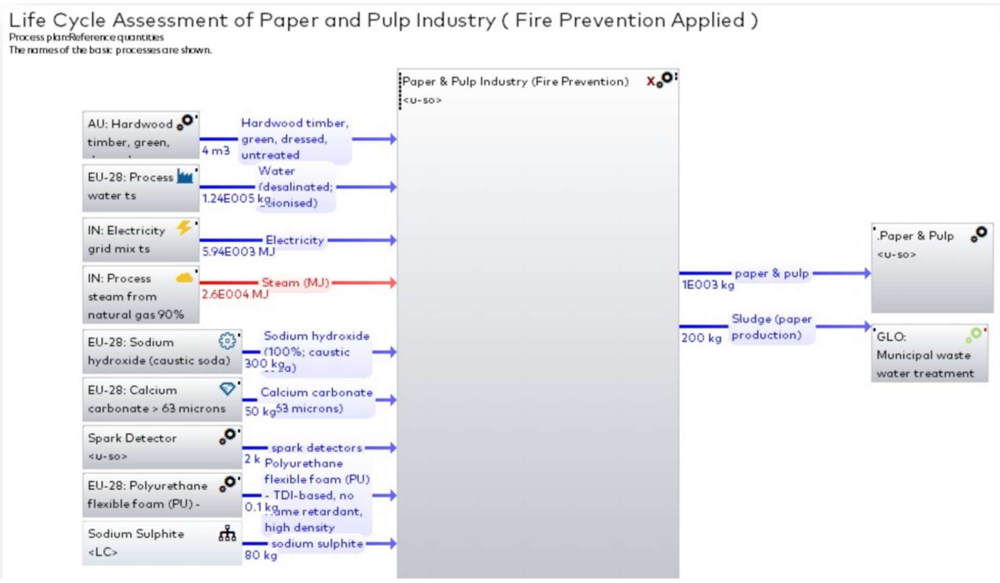

Figure 3: Plan for Fire Prevention Applied

2.5 Life Cycle Impact Assessment

Life Cycle Impact Assessment (LCIA) for Fatty alcohol was carried out using CML-2015 method for various impact categories such as global warming potential, eutrophication potential, human toxicity, etc. The CML method is the methodology of the Centre for Environmental Studies (CML) of the University of Leiden. It is a Life cycle impact assessment methodology used to measure the environmental impacts that are caused by the products or processes.

Table 3: Impact Categories for Paper production

Impact Category	Baseline study	Fire Incident Included	Fire Prevention
Global Warming Potential [kg CO_2-Equiv.]	4358.63	6487.82	2066.1
Acidification Potential [kg SO_2-Equiv.]	39.08136	92.686	65.005
Eutrophication Potential [kg Phosphate-Equiv.]	3.34727	8.343	10.528
Ozone Layer Depletion Potential [kg R11-Equiv.]	1.29e-09	2.95e-7	1.53e-07
Abiotic Depletion fossil [MJ]	7.33e-03	8.72e-03	6.47e-03
Human Toxicity Potential [kg DCB-Equiv.]	1059.94	3119.61	982.995
Photochemical Ozone Creation Potential [kg Ethene-Equiv.]	5.005	14.478	13.461
Terrestrial Eco-toxicity Potential [kg DCB-Equiv.]	8.754	22.772	10.633

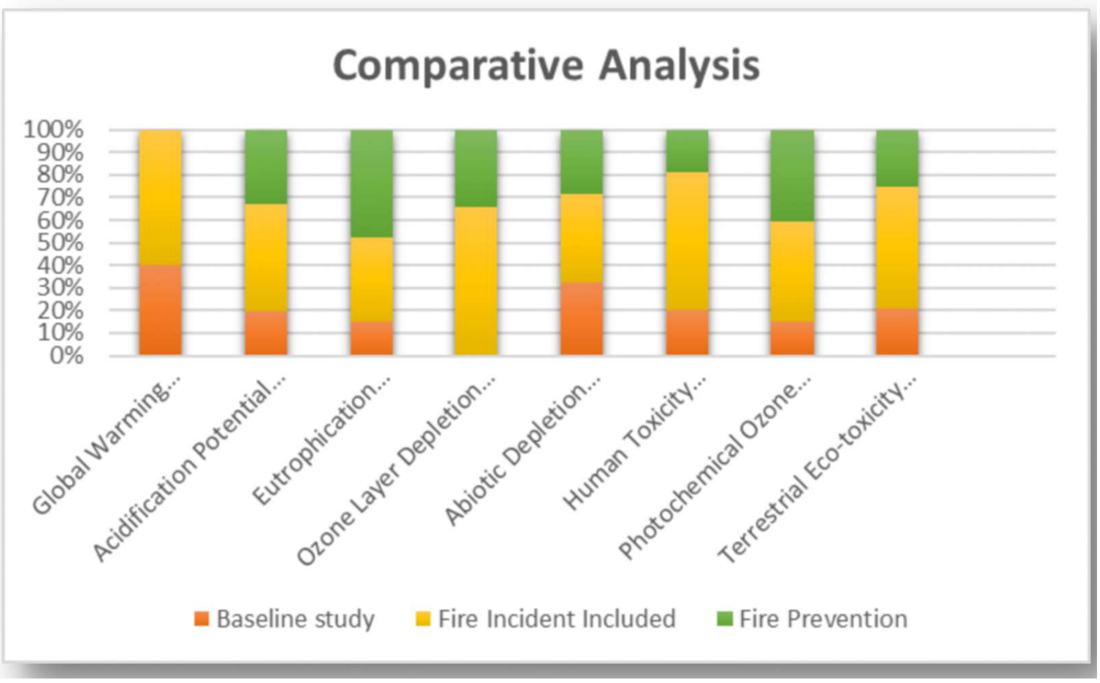

Figure 4: Graphical Comparative Analysis of Impact Categories for Baseline study and Different Scenarios

2.6 Economic Valuation

To quantify the financial equivalence of emissions, social cost of carbon was applied to GWP results. The derived costs were ₹32.95 lakh (Baseline), ₹49.04 lakh (Fire Incident), and ₹15.61 lakh (Fire Prevention). This metric supports decision-making for sustainability safety investments.

3. Results and Discussion

3.1 Environmental Impact Analysis

The Total environmental impacts were distributed among different inputs based on their process use and raw materials. The total environmental impact was calculated across eight categories: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Ozone Depletion Potential (ODP), Abiotic Depletion Potential (ADP) for fossil resources, Human Toxicity Potential (HTP), Photochemical Ozone Creation Potential (POCP), and Terrestrial Eco toxicity Potential (TETP).

From Table 4, it is clearly seen that the GWP was 4358.63 kg CO2 eq. indicating significant contribution to greenhouse gas emissions. Thermal energy was the highest contributor, responsible for more than half of the total emissions, and also had major impacts on HTP and POCP – showing that heating processes are highly emission-intensive. Electricity was the second highest contributor, significantly affecting AP and HTP, reflecting the fossil-fuel based power mix. Steam generation added emissions mainly from fuel combustion, while chemicals had moderate but non-negligible effects. Freshwater and sludge generation had minimal impacts, indicating that energy use dominates environmental burdens in this process.

Table 4: Contribution of raw materials for different impact categories (Baseline study)

Impact category	GWP(100 kg CO2 eq)	AP(kg co2 eq)	EP (kg po4 eq)	ODP, steady state	ADP fossil (kg Sb eq)	HTP inf (kg DCB eq)	POCP (kg Ethene eq)	TETP inf. (kg of BCB eq.)
Total	4358.63	39.081361	3.347265	1.29E-09	7.33E-03	1059.938	5.005	8.754
Hardwood	-1181.76	3.457	0.788	6.58E-10	3.55E-05	34.94	3.065	1.119
Chemical Input (NaOH,Na2CO3)	470.52	1.707	0.32	2.59E-10	6.94E-03	15.169	0.122	0.387
Freshwater	19.27	0.041	0.013	3.48E-11	1.59E-04	0.846	0.003	0.027
Sludge	0.26	0.000361	0.000265	-	-	0.007	-	0.001
Diesel	16.49	0.126	0.006	5.24E-13	1.35E-06	2.528	0.014	0.027
Electricity	1850.72	23.136	0.979	3.29E-10	1.21E-04	612.195	1.076	5.052
HDPE (Packaging)	9.27	0.052	0.004	3.70E-13	9.24E-07	1.29	0.005	0.01
Steam	820.3	7.089	0.449	3.41E-12	3.75E-06	314.963	0.34	2.062
Thermal energy	2353.56	3.473	0.788	-	6.53E-05	78	0.38	0.069

From Table 5, the GWP during the fire incident was 6487.82 kg CO_2 eq, significantly higher than the baseline value, indicating increased energy use, material loss, and emissions. Steam generation was the dominant source, and showing high impacts across AP, EP and HTP, due to excessive steam production and heat loss during the fire. Electricity was the next major contributor, linked to increased demand during recovery activities. Solid waste and process water together reflecting the additional environmental load from waste management during and after the fire.

Table 5: Contribution of raw materials for different impact categories (Fire Incident Included)

Impact category	GWP(100 kg CO2 eq)	AP(kg co2 eq)	EP (kg po4 eq)	ODP, steady state	ADP fossil (kg Sb eq)	HTP inf (kg DCB eq)	POCP (kg Ethene eq)	TETP inf. (kg of BCB eq.)
Total	6487.82	92.686	8.343	2.95E-07	8.72E-03	3119.61	14.478	22.772
Hardwood	-2529.6	12.699	2.785	3.94E-09	1.27E-04	139.652	10.598	4.181
Soda (Na2CO3)	116.38	0.597	0.111	1.15E-11	2.05E-03	2.524	0.041	0.1
NaOH	369.47	0.693	0.131	4.00E-10	4.20E-03	16.538	0.054	0.289
Thermal energy	131.67	2.86	0.632	-	5.29E-04	8.908	0.097	-2.778
CaCO3	2.97	0.007	0.001	2.16E-07	-	2.212	0.001	0.004
Solid waste	243.81	0.068	0.246	-	3.53E-06	0.987	0.061	0.41
Foam	1.29	0.003	-	1.28E-08	1.12E-05	0.053	-	0.009
Process water	200.79	0.432	0.132	3.62E-10	1.65E-03	8.816	0.031	0.279
Waste wood	33.43	0.013	0.003	5.84E-08	-1.00E-06	0.14	0.001	0.008
Waste water	0.63	0.001	0.001	-	-	0.016	-	0.002
Diesel	21.98	0.168	0.008	-	1.80E-06	3.37	0.019	0.036
Electricity	1791.5	22.395	0.948	3.18E-09	1.17E-04	592.605	1.042	4.89
Steam	6103.5	52.75	3.345	-	2.71E-05	2343.789	2.533	15.342

From Table 6, it is clearly seen that, GWP during the fire prevention was 2066.1 kg CO2 Eq. Major Contributors were Electricity and steam generation, highlighting energy consumption as the dominant hotspot. Other significant inputs included NaOH and process water with moderate effects on AP and HTP. Minor materials such as CaCO3, foam, and sludge contributed negligibly across all impact categories. Overall, fire prevention measures effectively reduced total emissions and toxicity compared to baseline and fire-incident scenarios.

For instance, chemicals like sodium sulphite are included as part of the generic inventory, but their use is not tied to a specific pulping typ. this approach allows the LCA to reflect an average case applicable to a broad range of paper mills rather than a single process.

Table 6: Contribution of raw materials for different impact categories (Fire Prevention)

Impact category	GWP(100 kg CO2 eq)	AP(kg co2 eq)	EP (kg po4 eq)	ODP, steady state	ADP fossil (kg Sb eq)	HTP inf (kg DCB eq)	POCP (kg Ethene eq)	TETP inf. (kg of BCB eq.)
Total	2066.1	65.005	10.528	1.53E-07	6.47E-03	982.995	13.461	10.633
Hardwood	-2529.8	12.7	2.785	3.94E-09	1.27E-04	139.663	10.599	4.181
Sodium Sulphite	101.96	22.718	5.765	6.22E-11	5.64E-04	79.407	1.269	0.174
CaCO3	1.98	0.005	-	1.44E-07	-	1.475	0.001	0.003
Foam	0.32	0.001	-	3.83E-09	1.57E-06	0.018	-	0.001
Process water	187.35	0.403	0.123	3.38E-10	1.54E-03	8.226	0.029	0.26
NaOH	284.27	0.8	0.112	8.51E-10	4.05E-03	14.996	0.059	0.364
Sludge	1.76	0.002	0.002	-	4.81E-07	0.046	-	0.004
Electricity (Grid)	2035.95	25.451	1.077	3.62E-10	1.33E-04	673.468	1.184	5.588
Steam (NG)	1982.31	2.925	0.664	-	5.50E-05	65.696	0.32	0.058

3.2 Comparative Environmental Analysis

Comparative analysis is performed to clearly understand the difference in environmental impacts between Baseline study and different scenarios, such as fire incident, and fire prevention. It helps to identify which processes or events cause the highest environmental burden, evaluate the effectiveness of preventive measures, and support informed decision-making for safety and sustainability, by quantifying reductions or increases in impact categories. Table 7, provides a clear actionable insight into two scenarios, fire prevention improve overall environmental performance.

Table 7: Comparative Environmental analysis of fire prevention vs fire incident

Impact Categories	GWP	AP	EP	ODP	ADP	HTP	POCP	TETP
% Reduction (Fire Prevention vs Fire Incident	68.15% ↓	29.84 % ↓	-26.20% ↓	48.14 % ↑	25.80 % ↓	68.49 % ↓	7.02 % ↓	53.31% ↓

3.3 Economic Interpretation

While Life Cycle Assessment (LCA) quantifies environmental impacts in physical terms (e.g., kg CO2 Eq), these numbers alone often fail to communicate the real world cost implications to industry decision makers. Therefore, an economic interpretation was performed to translate the environmental burdens – specifically the global warming potential (GWP) into their corresponding economic equivalents (INR). This Translation was based on the social cost of carbon framework, which represents the estimated monetary value of damages caused by emitting one additional tonne of CO2 into the atmosphere. Applying this approach helps link environmental sustainability with financial accountability.

The results are summarized below:

Table 8: Economic Interpretations of baseline study and different Scenarios

Impact Category	unit	Estimated Cost (USD)	Cost in INR	Baseline study	Fire Incident Included	Fire Prevention Applied
Global Warming Potential (GWP)	100 kg CO_2 eq	$9.00	₹ 756	₹ 32,95,124	₹ 49,04,792	₹ 15,61,972

The findings in Table 8, indicates a Substantial economic escalation associated with fire incidents. The total GWP-related economic cost during a fire incident increased to ₹ 49.04 lakh compared to ₹ 32.95 lakh in baseline operation – representing a 49% cost increase. Conversely, when preventive measures were implemented, the cost declined to ₹15.61 lakh, reflecting a 52% reduction compared to baseline and nearly 68% savings compared to the fire incident scenario.

The economic interpretation thus bridges the gap between environmental science and business decision – making. By converting GWP into monetary terms, the study demonstrates that:

- Fire incidents impose hidden financial costs through uncontrolled emissions, resource losses, and extended downtimes.
- Fire prevention investments yield measurable returns, reducing both GHGs emissions and operational costs.

In Essence, this approach reframes fire safety as an investment in climate resilience and operational efficiency, rather than as a regulatory obligation. The study shows that protecting the environment and saving money are not opposite goals – they actually support each other.

4. Conclusion

This study establishes that integrating fire preventive measures into paper mill operations yield measurable environmental and economic co-benefits. The Life Cycle Assessment revealed that:

- Fire incidents can raise carbon footprints by upto 49% significantly worsening overall sustainability.
- Preventive systems reduce GWP, AP, and EP by over 50%, aligning Indian mills closer to global best practices.
- Economic analysis demonstrates that prevention measures reduce equivalent GHG-related costs by more than ₹17 lakh per functional unit (1 tonne) compared to a fire event.

Therefore, fire safety investments must be recognized as sustainability investments-enhancing compliance, reducing emissions, and ensuring long-term economic resilience.

Bibliography

[1] National Productivity Counsil, "Manual on Pulp and Paper Sector: Green House Gases Emission Reduction Pulp and Paper Sector," National Productivity Council, Government of India, (2017).

[2] Ravi Prakash. Ashok Kumar Pandey, "Energy Conservation Opportunities in Pulp & Paper Industry," Scientific Research, vol. 7, pp. 89-99, (2018).

[3] Avishek kumar, "Earthmovers punch hole in paper mill wall as firemen battle for 12 hours to douse blaze in Ghaziabad," The Times Of India, pp. 1-2, july 08, (2025).

[4] "ISO 14040 - Environmental management - Life cycle assessment - Principles and framework," International Organization for Standardization, (2006).

[5] "ISO 14044 - Environmental management — Life cycle assessment — Requirements and guidelines," International Organization for Standardization, (2006).

[6] Food and Agriculture Organization "Non Wood And Recycled Fibre : The Context In Which Their Utilization Is Developing," FAO, (1998).

[7] "Technology Compendium on Energy Saving Opportunities in the Pulp & Paper Industry," Shakti Sustainable Energy Foundation, (2013).

[8] "the pulp and paper industry addressing the need for energy efficiency," Paper mart , (2018). [Online].

[9] Kapoor, S.K., Y.V. Sood, K.S. and Pandey, H., "Reducing water consumption in the pulp and paper mills,," IIPTA Journal, vol. 6, no. 163-163, pp. 111-116, (1993-94).

[10] E. Brannvall, "The limits of Deligniufication in kraft cooking," BioResources, vol. 12, pp. 1-15, (2017).

[11] E. K. Vakkilainnen, "The Kraft Chemical Recovery Process," TAPPI Proceedings, pp. 1-8, (2008).

[12] KSR MURTHY, K. Kalyana Sundaram, "Paper Making Raw-Material-Techno Economics," IPPTA (Indian Pulp and Paper Technical Association), Vols. Vol. IX, No. 3, p. 222–225.

[13] Haile, A., Gelebo, G.G., Tesfaye, T., Mengie, W., Mebrate, M.A., Abhuhay, A., & Limeneh, D.Y. , "Pulp and paper mill wastes: utilizations and prospects for high value-added biomaterials," Bioresources and Bioprocessing, vol. 8, no. 1, pp. 1-35, (2021).

[14] H. E. S. Bhd, "Fire Protection for Paper and Pulp Plants," Hegel - Fire Engineering Team, (2021). [Online]. Available: https://www.hegelengineering.com/single-post/fire-protection-for-paper-and-pulp-plants.

[15] A. X. R. Consulting, "Estimating Fire Protection Water Demands," Property Risk Consulting Guidelines, PRC.14.1.1.0, vol. N/A, (2020).

[16] I. CPE Filters, "A Guide to Maximizing Energy Efficiency in Industrial Dust Collection Systems," CPE Filters, Inc., (2024).

[17] N. Gune, "Total Water Management in Pulp & Paper Industry with Effluent Discharge: Focus on Achieving 'Zero Discharge' Status," IPPTA (Indian Pulp and Paper Technical Association), Vols. Vol. 12, No. 4, pp. 124–137, 142, (2000).

[18] Hickey, Harry E., "Water Supply Systems and Evaluation Methods," vol. 2, p. ~188, (2008).

[19] M. P. M. Limited, "Risk Assessment Report (Mohit Paper Mills Limited)," Environmental Clearance / Risk Assessment Division (Government / Indian regulatory body), (2018).