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Acidification potential estimation for small hydropower using LCA methodology in India

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Small hydropower (SHP) systems are widely considered environmentally sustainable, but they still contribute to emissions during the construction and maintenance phase. This study evaluates the life cycle acidification potential of different SHP projects in India using life cycle assessment (LCA) techniques. SO_{2eq} emissions from these projects vary between 0.065 and 0.325 g/kWh, depending on the project type—run-of-river, canal-based, or dam-toe—as well as their respective size (capacity) and location. The predictive models developed here accurately estimate these emissions and provide practical tools for minimizing environmental impacts in for the prediction of future SHP projects. By optimizing project design and selecting appropriate parameters, SHP projects can significantly reduce their acidification potential, making them a cleaner alternative for renewable energy development.

Keywords Small hydropower (SHP), Acidification, Emissions, Life Cycle Assessment (LCA), Electricity

Abbreviations

SHP	Small hydropower
LCA	Life cycle assessment
EIO	Economic input–output
GHG	Greenhouse gas
DPR	Detailed project report
GDI	Green Design Institute
SO_{2eq}	Sulfur-dioxide equivalent
PPP	Purchasing power parity

The electricity demand is continuously increasing with population growth and every nation worldwide strives to increase its generation capacity. Coal and other fossil fuels have always been used to generate electricity in thermal power plants. But over time, some issues cropped up with their excessive use. The combustion of coal and other fossil fuels causes a lot of anthropogenic emissions to the environment. These emissions have adverse effects on the environment along with human health. In these emissions, some gases, specifically Sulphur-Dioxide (SO_2), Nitrous Oxide (NO_x), and Ammonia (NH_3) mix with water vapor in the atmosphere and also, along with rain water, contribute to the acidification of water in the nearby areas. Annually 70 Tg (10^{12} g) of sulphur emission comes from fossil fuel combustion as compared to 8 Tg from volcanoes and 2–8 Tg from wildfire[1]. Thus, electricity generation from conventional sources generates a lot of pollutants that result in environmental degradation through acidification. These acidic gases that are somehow released into the air are mixed with water vapour formed into an acid. This precipitated water vapours (acid), which soil, plants, and surface waters absorb, leads to soil acidity, damage to leaves, etc. Moreover, it also leads to an increase in heavy metals take up as compared to nutrients take up, adversely affecting plants' growth[2]. The emissions of sulphur dioxide (SO_2) are converted to sulphuric acid (H_2SO_4) when combined with water vapour in the atmosphere. Thus, areas downwind of the power plant receive heavy acid rain.

One of the most suitable alternatives to mitigate the acidification issue is the generation of electricity using renewable energy sources. Renewable energy-based electricity generation is more expedient in terms of

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its renewing nature, availability, and less load on the environment. Promoting electricity generation through renewable sources is also helpful for decentralizing applications and, thus, a viable source for remote areas. Although the power generated using renewable energy sources is considered to have no environmental impacts, this is not completely true. Renewable energy-based power plants contribute to emissions during the construction phase and indirect emissions in the operation phase of their life cycle[3].

Among all renewable energy sources, hydropower is considered to be a promising electricity generation source. All hydropower plants use the energy of water to generate electricity, and it is carried out at both large and small scales. Large hydropower projects have the involvement of enormous reservoirs, rehabilitation of communities, high capital investment, and environmental issues. Small hydropower (SHP) plants are the appropriate solution to the impediments associated with large hydropower projects. They are also receiving special attention due to the rising environmental and political issues and high prices associated with fossil fuel-based power production systems[4,5]. No international consensus exists to discriminate between large and small hydropower projects. The power output generally characterizes SHP plants. Around the world, countries have fixed the maximum limit of a plant capacity to be considered as SHP, which varies from 5 to 50 MW. Initially, in India, the maximum size of a plant that comes under SHP was 15,000 kW[6], and later this upper limit was increased to 25,000 kW. Further, SHP projects can be elaborated as hydro projects that cost equal to or less than Rs—one hundred crores (1000 million) nearly to a plant capacity of around 25,000 kW. India is a significant context for this study due to its growing energy demand and large untapped potential for small hydropower (SHP). SHP is critical for remote regions, and India aims to reduce its reliance on fossil fuels. The country faces several environmental challenges and reducing greenhouse gases (GHGs) under international agreements. This study helps optimize SHP development, minimizing environmental impacts and supporting India's sustainability goals. The estimated SHP potential in India is around 21,135.37 MW (7135 identified sites), of which around 4379 MW capacity plants are operational, and many more are under construction[7], highlighting a vast opportunity for SHP development. The diverse geography and water resources of India provide an ideal landscape for SHP projects, especially in remote and hilly regions where large-scale energy infrastructure is challenging. Moreover, India's commitment to reducing carbon emissions under international agreements further necessitates exploring sustainable and low-emission energy solutions, like SHP. These factors make India a critical case study for assessing the environmental impacts, particularly the acidification potential, of SHP projects. Understanding these impacts is essential for guiding future policy and ensuring the sustainable development of this resource in India. In 1897, the first hydropower project was established at Sidrapong near Darjeeling in India capacity of 130 kW. At the same time, other hydropower projects in the year 1902, 1907, and 1930, Shivasundaram in Mysore, Galogi in Mussoorie, and Jubbal in Shimla, respectively, were commissioned and are still in operation[8]. The Sidrapong power plant has undergone renovation and modernization and has an installed capacity of 600 kW. SHP projects are considered an impressive solution to obtain cleaner power however, their environmental impacts must be addressed thoroughly. The growth of SHP projects leads to environmental issues that need extreme attention[9]. The release of gases such as SO_2, NO_x, Ammonia (NH_3), etc., is associated with the life cycle of an SHP project. Acidification potential, typically assessed through Life Cycle Assessments (LCA), refers to the capacity of certain emissions to contribute to acid rain, which can have detrimental effects on ecosystems. In recent years, LCA has emerged as a critical tool for assessing the environmental impacts of various energy systems and technologies. Zahedi et al.[10] used LCA to evaluate transparent solar cells, comparing their environmental and health impacts with traditional solar technologies. Their study highlighted the crucial role LCA plays in advancing sustainable energy solutions and underscored the need for environmental impact assessments in developing new technologies.

Building on these insights, Zahedi et al.[11] and Khalili et al.[12] broadened the use of LCA to assess more energy-intensive systems, such as cryptocurrency mining and 3D-printable buildings. Their work demonstrated the significant environmental impacts of modern industrial processes, reinforcing the importance of LCA in fostering sustainable technological developments. Aslani et al.[13] emphasized the growing need for modern LCA methods to evaluate environmental footprints across a range of industries, from emerging technologies to traditional sectors. Their research called for innovative strategies to reduce environmental impacts in diverse fields, from digital payment systems to conventional construction.

In line with these studies, the current research applies LCA to estimate the acidification potential of small hydropower (SHP) projects in India. By carefully quantifying sulphur dioxide equivalents (SO_{2eq}) released during the construction, operation, and maintenance phases, this study explores how factors such as project capacity and type affect overall emissions. The findings provide essential insights for policymakers and developers seeking to minimize the environmental impacts of SHP projects in India.

Some studies have been reported on estimating the acidification potential of various power generation systems. Keller et al.[14] have assessed the life cycle environmental effect of the alternative and conventional feedstocks for olefin production using GABI software. Results show that, for a possible solution, the integration of renewable energy is required. Valente et al.[15] studied the life cycle acidification for hydrogen energy systems and found no relation between gross carbon emissions and acidification. In the present study, the estimation of SO_{2eq} gas emissions from various SHP projects in India is carried out through LCA. In the view of above discussion, an attempt has been made to calculate the total life cycle SO_{2eq} emissions of three different SHP systems (dam-toe, canal, and run-of-river). Correlations are also established for different schemes and sizes based on the expected amount of SO_{2eq} emissions.

Novelty and significance of this research

The key contributions and significance of this study are as follows:

- Focus on Small Hydropower (SHP): This research explores the environmental impact of SHP projects, with a particular emphasis on acidification potential—an area that has received limited attention in India's renewable energy landscape.
- Application of LCA Methodology: The study distinctively employs Life Cycle Assessment (LCA) to measure SO_2 emissions from SHP projects in India is a novel work that needs to be addressed.
- Development of Predictive Models: It establishes correlations using regression analysis to forecast SO_2 emissions across various SHP project types, considering factors such as capacity and head.
- Comprehensive Data Analysis: Drawing on data from 123 SHP projects across India, the research provides robust and generalizable results that can inform future efforts to mitigate environmental impacts.
- Practical and Policy Relevance: The derived correlations serve as valuable tools for policymakers and developers to effectively reduce the acidification potential of SHP projects.
- India-Specific Environmental Framework: By creating a framework tailored to Indian SHP projects, this study addresses a critical gap in the assessment of environmental impacts in the country.

The study's significance lies in its integration of environmental science and renewable energy policy, providing critical insights for promoting sustainable SHP development.

Methodology

This section outlines the methodology used to estimate the acidification potential of Small Hydropower (SHP) projects in India. The study applies the Life Cycle Assessment (LCA) methodology, specifically focusing on the calculation of sulfur dioxide equivalents (SO_{2eq}) to assess acidification potential. The LCA methodology followed a cradle-to-gate approach, covering the construction, operation, and maintenance phases of SHP projects. The demolition phase was excluded due to its insignificance in the life cycle of SHP projects.

Goal and scope

The primary goal of this Life Cycle Assessment (LCA) is to assess the acidification potential linked to small hydropower (SHP) projects in India. By quantifying SO_2-equivalent (SO_{2eq}) emissions across the entire life cycle of different SHP configurations—such as run-of-river, canal-based, and dam-toe systems. The study aims to provide a thorough evaluation of their environmental impacts. The overarching aim is to create predictive models that correlate SO_2 emissions with critical project factors like installed capacity and head height. These models are intended to act as practical tools, aiding in the design and execution of future SHP projects, helping to minimize acidification potential, and promoting sustainable hydropower development.

Scope

- System Boundaries: The LCA follows a cradle-to-gate approach, covering emissions during construction, operation, and maintenance, while excluding the demolition phase, which is generally insignificant for SHP projects. The analysis covers:
  - Civil works (e.g., dams, canals, penstocks)
  - Electro-mechanical equipment (e.g., turbines, generators, transformers)
  - Operational emissions over a 30-year lifespan
- Functional Unit: Environmental impacts are calculated per 1 kWh of net electricity generated, allowing for comparisons across different SHP configurations.
- Impact Category: The study focuses on acidification potential, quantified in terms of kg SO_{2eq} per kWh, based on life cycle emissions.
- Geographical and Temporal Scope: The research uses data from 123 SHP projects across India, standardized to the base year 2010 for economic inputs as most of them were installed before 2010.
- Data Sources: Information is obtained from Detailed Project Reports (DPRs), site inspections, and economic input–output (EIO) tables, leveraging the Carnegie Mellon University Green Design Institute model for emissions estimation.

Life cycle assessment

Life cycle studies can be classified as process chain, input–output, and hybrid LCA. The process chain approach is used to estimate various toxic releases and energy usage from manufacturing construction materials and electro-mechanical equipment used in these schemes. The input–output-based LCA uses economic data of different countries to assess the environmental impacts. Hybrid LCA integrates input–output and process chain analysis. In the present study, economic input–output (EIO) based LCA has been carried out to evaluate life cycle GHG emissions for various SHP schemes[16–18]. The EIO-LCA approach was chosen because it allows for a broad assessment of environmental impacts by utilizing readily available economic data across sectors. This method is particularly suitable for national-level studies to cover a diverse range of small hydropower projects. Process-based LCA would require detailed, site-specific data, which is often unavailable for large-scale analyses. The hybrid LCA, though comprehensive, combines both methods but demands more extensive data, which wasn't feasible for this study. The limitations of EIO-LCA, such as its reliance on aggregated data and its assumption of linear relationships between economic output and environmental impacts, might reduce precision compared to process-based or hybrid approaches. In this approach, the real economic data of a country/region is segregated into different sectors, which are represented in the form of EIO tables. This table is used to estimate the interdependence of each sector on one another. In evaluating the indicators such as carbon footprint, acidification potential, land use etc., a coefficient is required that is used with a matrix of sector-level environmental coefficients. The model developed by GDI at Carnegie Mellon University is used to evaluate acidification potential[19]. The calculation of the acidification in terms of kg-SO_{2eq} corresponding to m_j kg of a significant component (*j*) is analogous to the computation of the pollutant potential. Table 1 shows the general acidification potential of selected gases[20,21].

$$Acidification\,(kg - SO_{2eq}) = AP_j\left(\frac{kg - SO_2}{kg}\right) \times m_j(kg) \quad (1)$$

To estimate the acidification potential, the price of significant components is initially required, and a list of materials is prepared. In this study, the complete list of materials was first investigated (PCA) and then the cost of each member was estimated and its emissions were evaluated (EIO). Based on the price of the materials, their associated emissions are quantified. Here 123 SHP schemes are studied, and these schemes are commissioned in different years. The cost estimates of SHP schemes pertain to several years. To make this analysis on a common year, all the prices are inflated against the price for 2010 in the Indian rupee. To estimate its associated impact, the material/components' price is required in US dollars. Thus, the prices are converted into their equivalent dollars by using Purchasing Power Parity (PPP) through the given formula[22,23].

$$EquivalentCostinUS2002(\$) = \frac{\text{Price in INR}}{\text{PPP in 2004}} \times \frac{Index(\text{inflation})\text{foryear2002}}{Index(\text{inflation})\text{foryear2004}}$$

To perform an LCA study, a functional unit is to be assigned which relates environmental impact to a product. The present study takes 1 kWh of net electricity produced as a functional unit. The choice of 1 kWh of net electricity produced as the functional unit in this study is appropriate for several reasons:

- Standardized Comparison: 1 kWh of net electricity enables direct comparison across different SHP projects, regardless of variations in size, capacity, or geographical location.
- Alignment with LCA Standards: It aligns with LCA practices for energy projects, ensuring consistency and allowing benchmarking against similar renewable energy studies.
- Relevance to Acidification Potential: The choice directly links acidification potential to the actual electricity output, showing the environmental impact per unit of energy produced.
- Scalability: It allows easy extrapolation of environmental impacts for larger systems or multiple projects, supporting broader assessments at regional or national levels.

Acidification potential is estimated regarding SO_{2eq} emissions per unit of net electricity generation based on general acidification equivalents expressed relative to SO_2[20,21].

$$SO_2\,emissions\left(\frac{g.SO_{2eq.}}{kWh_e}\right) = \frac{Total\,SO_2\,emissions\,throughout\,its\,life - cycle\,(g - SO_2)}{Annual\,Power\,Generation\,\left(\frac{kWh_e}{year}\right) \times lifetime\,\,(year)}$$

To perform LCA, an SHP scheme is divided into four stages: (i) electro-mechanical (E&M) equipment (ii) civil works (iii) operation & maintenance and; (iv) decommissioning. In the present study, demolition of the plant is not considered in the life cycle as it is pretty uncommon to demolish SHP plants. Three types of SHP projects are analyzed, viz. run-of-river, canal-based, and dam-toe SHP. Further economic data for around 123 SHP projects (including run-of-river, canal-based, and dam-toe type SHP projects) have been obtained. The data have been collected by visiting some project sites and detailed project reports (DPRs). The lifetime of SHP projects is taken as 30 years, and the SHP projects' details are provided in Table 2.

Data sources

The data for this study were sourced from Detailed Project Reports (DPRs), site visits, and economic input–output (EIO) tables. While DPRs are reliable industry-standard documents, there is the potential for variations due to differences in site-specific conditions, geographic factors, and economic assumptions. To mitigate such biases, standardized the economic data to the base year 2010 and conducted sensitivity analyses to assess the impact of variations in material costs and site conditions on the overall results. Site visits also provided an

S. No	Substance	Acidification potential (AP_i in kg SO_2-eq./kg)
1	SO_2	1.00
2	NO	1.07
3	N_2O	0.70
4	NO_x	0.70
5	NH_3	1.88
6	HCl	0.88
7	HF	1.60

Table 1. Acidification potential of different gases.

S. no	Name of project	State	Type of scheme	Installation (kW)	Installed capacity (kW)	Head (m)	Year	SO_{2eq} (g/kWh$_e$)
1	Rina Mini Hydel project	Arunachal Pradesh	Run-of river	4 × 500	2000	110.00	1995	0.1537
2	Payu Mini Hydel Project	Arunachal Pradesh	Run-of river	2 × 500	1000	118.00	1993	0.1651
3	Subbung Mini Hydel Project	Arunachal Pradesh	Run-of river	3 × 1000	3000	93.35	1995	0.1006
4	Dehar SHP	Himachal Pradesh	Run-of river	2 × 1500	3000	300.00	2004	0.1260
5	Chandini SHP	Himachal Pradesh	Run-of river	2 × 1500	3000	350.80	2003	0.1054
6	Brahmagana SHP	Himachal Pradesh	Run-of river	2 × 2500	5000	229.36	2004	0.0738
7	Baragran SHP	Himachal Pradesh	Run-of river	2 × 1500	3000	168.92	2003	0.0850
8	Jiwa MHS	Himachal Pradesh	Run-of river	2 × 500	1000	102.07	2004	0.1522
9	Manjhal SHP	Himachal Pradesh	Run-of river	2 × 500	1000	117.00	2006	0.1418
10	Ching SHP	Himachal Pradesh	Run-of river	2 × 500	1000	145.00	2005	0.1391
11	Ringali Mini Hydel Project	Uttarakhand	Run-of river	2 × 500	1000	427.50	1996	0.1715
12	Hanumanganga MHS	Uttarakhand	Run-of river	2 × 1500	3000	152.00	2005	0.1336
13	Manihamsa Power Project Ltd	Andhra Pradesh	Run-of river	2 × 1500	3000	34.00	2001	0.1001
14	Liromoba Mini Hydro Electric Project	Arunachal Pradesh	Run-of river	2 × 1000	2000	73.00	1993	0.1800
15	Kambang Mini Hydro Electric Project	Arunachal Pradesh	Run-of river	2 × 1500	3000	75.00	1994	0.3067
16	Ganga Mini Hydel Scheme	Arunachal Pradesh	Run-of river	3 × 250	750	47.86	1998	0.3242
17	Solang SHP	Himachal Pradesh	Run-of river	2 × 500	1000	81.96	2002	0.1700
18	Timbi SHP	Himachal Pradesh	Run-of river	2 × 1500	3000	88.37	2004	0.1300
19	Palor SHP	Himachal Pradesh	Run-of river	2 × 1500	3000	74.30	2004	0.1189
20	Bogdong Mini Hydro Electric Project	Jammu and Kashmir	Run-of river	3 × 300	900	90.00	1996	0.1100
21	Tangtse Mini Hydel Project	Jammu and Kashmir	Run-of river	3 × 100	300	18.00	1995	0.3136
22	Rayat Mini Hydel Project	Uttar Pradesh	Run-of river	3 × 1000	3000	88.00	1996	0.1185
23	Moti Ghat SHP	Uttarakhand	Run-of river	2 × 1500	3000	49.70	2003	0.1018
24	Tanga SHP	Uttarakhand	Run-of river	2 × 1500	3000	49.20	2003	0.1137
25	Kail Ganga SHP	Uttarakhand	Run-of river	2 × 1500	3000	48.00	2002	0.0695
26	T.B Dam R.B.L.C Small Hydro Electric Project	Andhra Pradesh	Canal based	3 × 2750	8250	10.00	2004	0.0646
27	Vemuleruvagu SHP	Andhra Pradesh	Canal based	3 × 1335	4005	11.60	2003	0.0735
28	Addauki BC MHS	Andhra Pradesh	Canal based	2 × 1500	3000	9.60	2003	0.0995
29	Guntur BC-II	Andhra Pradesh	Canal based	2 × 2150	4300	8.85	1997	0.1017
30	Lock-in Sula	Andhra Pradesh	Canal based	2 × 2000	4000	12.00	1998	0.0929
31	Ongole BC MHS	Andhra Pradesh	Canal based	2 × 750	1500	7.80	1999	0.0951
32	Saurashtra Branch Canal Fall CH. 32940 m SHP	Gujarat	Canal based	2 × 8000	1600	11.17	1999	0.1000
33	Shahapur Distributory-9	Karnataka	Canal based	1 × 1000	1000	17.00	2003	0.0901
34	Dandeli Ferro Pvt. Ltd	Karnataka	Canal based	2 × 750	1500	21.00	1997	0.1147
35	Hebbakavadi-3 MHS	Karnataka	Canal based	1 × 850	850	11.24	2003	0.1018
36	D9 MHS (Shahpur)	Karnataka	Canal based	1 × 1000	1000	17.00	2003	0.0925
37	Hebbakavadi-2 MHS	Karnataka	Canal based	1 × 850	850	9.00	2001	0.1090
38	SBC-SHP-3	Karnataka	Canal based	1 × 1300	1300	9.80	1997	0.0951
39	Killara MHS	Karnataka	Canal based	2 × 1000	2000	10.50	1999	0.0969
40	Chargaon Jatlapur	Madhya Pradesh	Canal based	1 × 800	800	12.00	1997	0.1127
41	Dhom	Maharashtra	Canal based	2 × 1000	2000	18.00	1992	0.0960
42	Potteru Small Hydro Electric Project	Orissa	Canal based	2 × 3000	6000	11.58	1998	0.0865
43	Micro Hydel Scheme at GGSSTP,Ropar	Punjab	Canal based	2 × 850	1700	9.57	2005	0.0893
44	Pugal-I	Rajasthan	Canal based	1 × 1500	1500	9.73	1995	0.1042
45	Anoopgarh-II	Rajasthan	Canal based	3 × 1500	4500	8.24	1988	0.0866
46	Suratgarh	Rajasthan	Canal based	2 × 2000	4000	8.48	1992	0.0657
47	Singrauli Small Hydro Power Project	Uttar Pradesh	Canal based	1 × 1500	1500	8.00	1993	0.0820
48	Thirumala Hydel Power	Andhra Pradesh	Canal based	2 × 400	800	2.63	2000	0.1221
49	Thirumala Hydel Power	Andhra Pradesh	Canal based	1 × 800	800	3.60	2000	0.1122
50	Thirumala Hydel Power	Andhra Pradesh	Canal based	1 × 800	800	4.87	2000	0.1018
51	Mini Hydel Power Project at Karumanchi, Guntur Dt	Andhra Pradesh	Canal based	2 × 1000	2000	6.37	2000	0.1098
52	Mini Hydel Power Project at Karumanchi, Guntur Dt	Andhra Pradesh	Canal based	2 × 1000	2000	6.71	2000	0.1013
53	Mini Hydel Power Project at Muppalla, Guntur Dt	Andhra Pradesh	Canal based	1 × 650	650	5.30	2001	0.1145
54	Kallam Spg. Mills Ltd	Andhra Pradesh	Canal based	1 × 800	800	4.32	2002	0.1021
55	Saraswati Power & Ltd	Andhra Pradesh	Canal based	2 × 1000	2000	6.50	2001	0.0882

Continued

S. no	Name of project	State	Type of scheme	Installation (kW)	Installed capacity (kW)	Head (m)	Year	SO_{2eq} (g/ kWh_e)
56	Akshay Profiles Pvt. Ltd.(Ph I)	Andhra Pradesh	Canal based	1 × 500	500	5.60	2000	0.1337
57	Akshay Profiles Pvt. Ltd.(Ph II)	Andhra Pradesh	Canal based	1 × 500	500	6.28	2000	0.1372
58	Srinivasa Power Private Ltd	Andhra Pradesh	Canal based	1 × 550	550	3.66	2001	0.1338
59	Bellamkonda BC MHS	Andhra Pradesh	Canal based	1 × 550	550	3.98	2004	0.1121
60	Nippulavagu SHP (G)	Andhra Pradesh	Canal based	2 × 1650	3300	5.70	2003	0.0832
61	Chilaklurpet Major M#1MHS	Andhra Pradesh	Canal based	1 × 500	500	5.48	2002	0.1199
62	Nippulavagu SHP (V)	Andhra Pradesh	Canal based	2 × 1650	3300	5.70	2002	0.0834
63	Janapadu MHS	Andhra Pradesh	Canal based	1 × 1000	1000	6.50	2000	0.1064
64	Pedanandi SHP	Andhra Pradesh	Canal based	1 × 650	650	5.30	2001	0.1138
65	GBC Mile # 21 MHS	Andhra Pradesh	Canal based	2 × 400	800	4.87	2000	0.1509
66	Addanki # 440	Andhra Pradesh	Canal based	2 × 1000	2000	6.71	2000	0.1086
67	Addanki # 550	Andhra Pradesh	Canal based	2 × 1000	2000	6.37	2000	0.1121
68	Bellamkonda BC MHS	Andhra Pradesh	Canal based	2 × 925	1850	4.50	2000	0.0908
69	OBC#080 MHS	Andhra Pradesh	Canal based	2 × 850	1700	5.10	2000	0.0977
70	OBC#580 MHS	Andhra Pradesh	Canal based	2 × 850	1700	5.50	2000	0.0989
71	Guntoor 0-0-550	Andhra Pradesh	Canal based	3 × 1250	3750	7.00	1996	0.1062
72	Sebari SHP	Bihar	Canal based	2 × 500	1000	4.70	2000	0.1188
73	Shirkhinda SHP	Bihar	Canal based	2 × 350	700	3.50	1999	0.1486
74	Sipaha SHP	Bihar	Canal based	2 × 500	1000	3.20	1999	0.1210
75	Arwal SHP	Bihar	Canal based	1 × 500	500	3.20	2000	0.1288
76	Rampur Small Hydel Project	Bihar	Canal based	1 × 250	250	3.00	1999	0.1642
77	Belsar SHP	Bihar	Canal based	2 × 500	1000	3.25	1999	0.1218
78	Laxmipur Mini Hydro Electric Project	Bihar	Canal based	2 × 250	500	2.00	2003	0.1271
79	Dhelabagh SHP	Bihar	Canal based	2 × 750	1500	3.20	1999	0.1032
80	Jainagara SHP	Bihar	Canal based	2 × 500	1000	4.45	1999	0.1153
81	Kunnu-Charang MHP	Himachal	Canal based	2 × 100	200	3.12	2003	0.1632
82	Dhupdal SHP	Karnataka	Canal based	2 × 1400	2800	4.80	1997	0.1179
83	Shahpur BC SHP-1	Karnataka	Canal based	1 × 1300	1300	6.20	1997	0.0995
84	SBC-SHP-2	Karnataka	Canal based	1 × 1300	1300	6.20	1997	0.1033
85	SBC-SHP-4	Karnataka	Canal based	1 × 1300	1300	6.20	1997	0.1094
86	SBC-SHP-5	Karnataka	Canal based	1 × 1400	1400	6.20	1998	0.0956
87	Tilwada SHP	Madhya Pradesh	Canal based	1 × 250	250	5.00	1997	0.1730
88	Marand	Madhya Pradesh	Canal based	3 × 335	1005	3.65	1992	0.1294
89	Satpura	Madhya Pradesh	Canal based	2 × 500	1000	1.97	1997	0.1552
90	Bhanubhura MHS	Punjab	Canal based	2 × 650	1300	2.56	2002	0.1169
91	Babanapur SHP	Punjab	Canal based	2 × 500	1000	2.40	2005	0.1220
92	Killa MHP	Punjab	Canal based	2 × 875	1750	4.45	2005	0.1005
93	Chupki	Punjab	Canal based	2 × 750	1500	2.92	1999	0.1311
94	Narangal	Punjab	Canal based	2 × 750	1500	2.77	1999	0.1311
95	Tugal	Punjab	Canal based	2 × 750	1500	3.00	1999	0.1287
96	Kanganwal	Punjab	Canal based	2 × 650	1300	2.90	1999	0.1478
97	Birshalpur	Rajashthan	Canal based	1 × 535	535	6.34	1998	0.1263
98	Charanwala	Rajashthan	Canal based	1 × 1200	1200	5.28	1993	0.1439
99	Birupa	Tamil Nadu	Canal based	3 × 750	2250	4.50	2000	0.0997
100	Betwa-II Mini Hydro Power Project	Uttar Pradesh	Canal based	3 × 500	1500	1.50	2004	0.1453
101	Dhoba Mini Hydel Power Plant	NA	Canal based	2 × 600	1200	2.30	1994	0.1497
102	Yeleru Reser SHP	Andhra Pradesh	Dam-toe	2 × 1500	3000	34	2002	0.0771
103	Mid Pennar MHS	Andhra Pradesh	Dam-toe	2 × 1000	2000	12.50	1999	0.0954
104	Singoor	Andhra Pradesh	Dam-toe	2 × 7500	15,000	20.00	1999	0.0742
105	Somasila SHP	Andhra Pradesh	Dam-toe	2 × 5000	10,000	17.00	2005	0.0749
106	Nugu MHS (I & II)	Karnataka	Dam-toe	2 × 750 2 × 750	3000	28.00	2000	0.1046
107	TB Dam SHP	Karnataka	Dam-toe	2 × 4000	8000	10.00	2004	0.0611
108	Madhanmantri SHP	Karnataka	Dam-toe	3 × 1000	3000	4.70	2001	0.1128
109	Deverebelekara	Karnataka	Dam-toe	2 × 1000	2000	10.90	1993	0.1192

Continued

S. no	Name of project	State	Type of scheme	Installation (kW)	Installed capacity (kW)	Head (m)	Year	SO_{2eq} (g/kWh$_e$)
110	Aanveri Mini Hydel	Karnataka	Dam-toe		1500	21.70	1998	0.0956
111	Harangi	Karnataka	Dam-toe	2 × 4500	9000	24.00	1997	0.0882
112	Hemawathi	Karnataka	Dam-toe	4 × 4000	16,000	16.00	1999	0.0722
113	Bhimgarh SHP	Madhya Pradesh	Dam-toe	2 × 1200	2400	10.00	1998	0.0793
114	Majalgaon	Maharashtra	Dam-toe	3 × 750	2250	5.25	2000	0.1235
115	Warna	Maharashtra	Dam-toe	2 × 8000	16,000	29.50	1999	0.0555
116	Vaitarna	Maharashtra	Dam-toe	1 × 1500	1500	17.50	1987	0.0791
117	Mukurthy	Tamil Nadu	Dam-toe	2 × 350	700	21.30	2000	0.1461
118	Aliyar	Tamil Nadu	Dam-toe	2 × 1250	2500	30.00	2000	0.0704
119	Perunchani	Tamil Nadu	Dam-toe	2 × 650	1300	15.00	2000	0.1256
120	Pykara	Tamil Nadu	Dam-toe	1 × 2000	2000	27.31	1989	0.2046
121	Bhatsa	Maharashtra	Dam-toe	1 × 15,000	15,000	70.00	1991	0.1370
122	Lower Ghagri Mini Hydro Electric Project	Bihar	Dam-toe	2 × 200	400	258.00	1993	0.2369
123	Sadani Mini Hydro Electric Project	Bihar	Dam-toe	2 × 500	1000	101.00	1993	0.2001

Table 2. Acidification data of SHP projects.

additional layer of validation. However, minor regional differences and other external factors may introduce slight variability, which we acknowledge as a limitation of the study. This discussion clarifies the reliability of the data used for our life cycle acidification potential estimations.

Life cycle interpretation

In Life Cycle Assessment (LCA), Life Cycle Interpretation is pivotal for understanding the environmental impacts of the small hydropower (SHP) projects analyzed in this study. During this phase, the results from the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) are evaluated to derive meaningful conclusions regarding the acidification potential of SHP projects.

In this study, the interpretation phase involved a comprehensive analysis of the sulfur dioxide equivalent (SO_{2eq}) emissions data obtained during the construction, operation, and maintenance phases of SHP projects. The analysis was conducted across three types of SHP configurations: run-of-river, canal-based, and dam-toe systems. Key parameters such as project capacity, head height, and scheme type were considered to develop correlations that predict SO_{2eq} emissions.

Limitations and assumptions

The EIO-based LCA method follows a linear model, and it signifies that the variation of $1000 in demand of any economic activity in results will give ten times the consequences of $100 variation in the demand. The outcomes will further show the impacts of the sector over its output/production along with augmented demand. In most sections, no direct relationship of results is associated with the operation and end-of-life phase. The EIO models present a single nation's economies; imports and exports are the primary elements of their transactions. Similar production attributes in imports are assumed owing to the comparable products manufactured in the nation's interest[19].

Small hydropower

In India, hydropower projects with a capacity less than or equal to 25 MW are considered SHP projects. The SHP projects can be further classified as Run-of-River type, Canal based, and; Dam toe schemes.

Run-of river SHP schemes

The process of power generation in a run-of-river scheme is simple. The hydraulic energy extracted from the water stream drives a turbine and generator. The volume and net difference in the height of the source and water outlet are the main factors that determine the energy extracted from water. The run-of-river SHP schemes are established for SHP generation and don't involve the construction of big reservoirs as required in other large hydropower plants. Run-of-river projects utilize persistent and continuous natural water flow and are thus established on a river. In fact, as per the definition, a run-of-river plant should have water storage that can provide a continuous water supply of 48 h. The stream is diverted from the river through a weir and then Forebay (a small head tank) towards the penstock, delivering water downhill to the powerhouse. Thus, the energy of water generated through gravity is utilized to run the turbines in the powerhouse, which convert this energy into electricity using a generator. The water is further redirected back to the flow of the river.

Correlation development for run-of river SHP schemes

The data obtained from EIO-LCA method is used for the regression analysis and development of statistical correlations. A curve of SO_2 emissions in g-SO_{2eq}/kWh$_e$ versus installation capacity (C) kW, is shown in Fig. 1. SO_{2eq} emissions tend to decrease with increasing capacity for run-of-river SHP schemes. This relationship

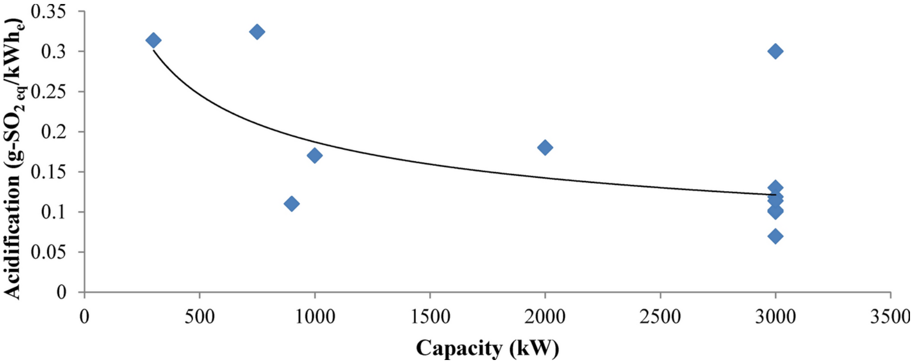

Fig. 1. Variation of SO_{2eq} emissions with capacity for head range 10–90 m for run-of river schemes.

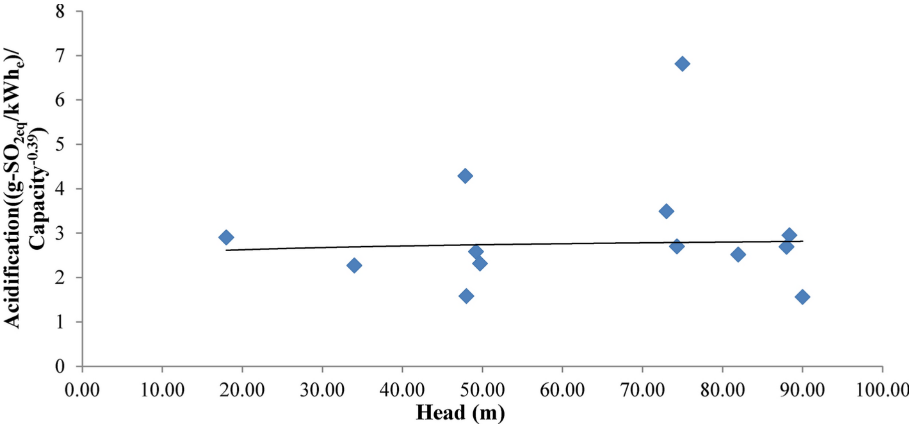

Fig. 2. Variation of SO_{2eq} emissions/capacity$^{-0.39}$ with head for run-of river SHP schemes.

demonstrates that larger capacity installations benefit from economies of scale, leading to lower emissions per unit of electricity generation. This is significant for optimizing project size to minimize environmental impact. The data considered in the curve is for the projects having head (H) ranging from 10 to 90 m. The relation for SO_2 emission in terms of capacity is expressed as:

$$SO_2emission = A_0 \times C^{-0.39} \tag{4}$$

The coefficient A_0 will depend on other parameters. The other parameter considered in the study is the head. Figure 2 shows curve between the values of SO_2 emissions/Capacity$^{-0.39}$ against the head. Figure 2 indicates that emissions per unit of capacity are influenced by head height in run-of-river projects. With higher heads, additional civil infrastructure is required, which contributes to higher emissions. This highlights the trade-off between energy extraction efficiency and environmental impact in high-head schemes. The final correlation for estimation of SO_2 emissions can be expressed as:

$$SO_2emission/C^{-0.39} = 2.286 \times H^{0.046} \tag{5}$$

$$SO_2emission = 2.286 \times H^{0.046} \times C^{-0.39} \tag{6}$$

Similarly, the expression of SO_2 emissions for the projects having head varying from 90 to 430 m can be obtained. The curve of SO_2 emissions in g-SO_{2eq}/kWh$_e$ versus capacity in kW is shown in Fig. 3. As shown in Fig. 3 higher head ranges in run-of-river schemes (90–430 m) lead to a consistent decrease in emissions with increasing capacity. However, the infrastructure required for high-head schemes moderates this reduction slightly, underscoring the need for optimized designs to balance emissions and efficiency and the obtained power law relation can be expressed as:

$$SO_2emission = B_0 \times C^{-0.36} \tag{7}$$

The coefficient B_0 will depend on other parameters i.e. head of the system. Figure 4 shows the curve plotted between the values of SO_2 emissions/Capacity$^{-0.36}$ and head. Figure 4 illustrates how higher heads in run-of-river projects allow for more efficient energy extraction, reducing emissions per unit of capacity. This correlation

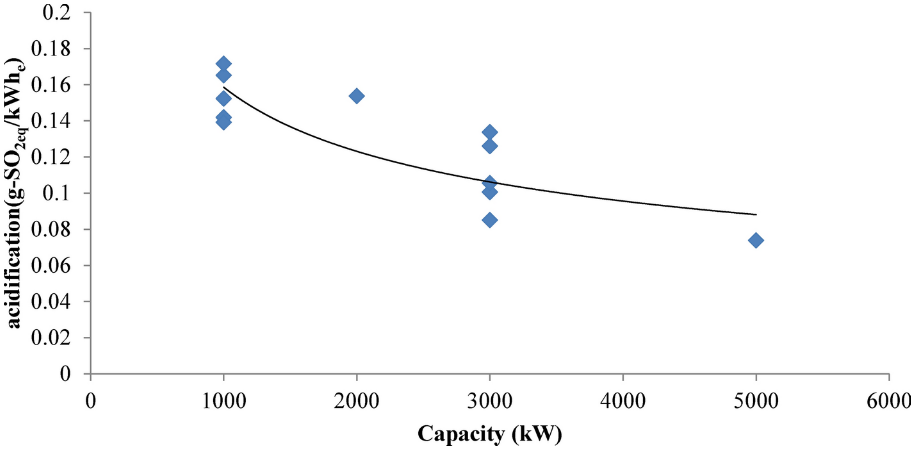

Fig. 3. Variation of SO_{2eq} emissions with capacity for head range 90–430 m for run-of river schemes.

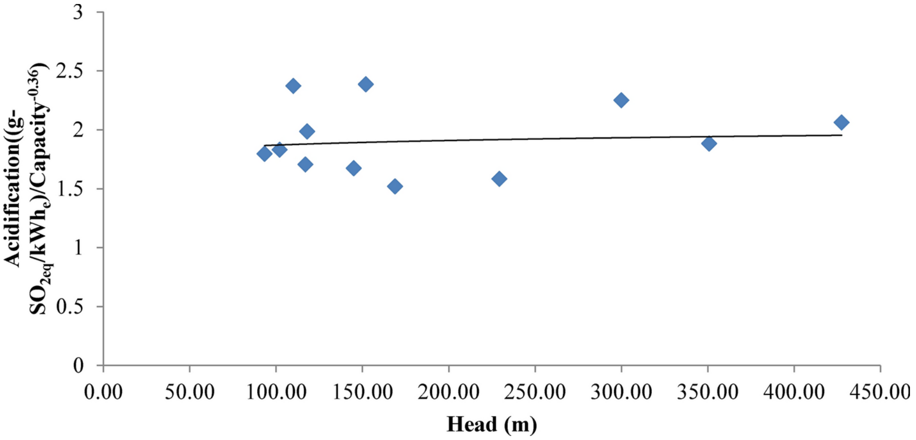

Fig. 4. Variation of SO_{2eq} emissions/capacity$^{-0.36}$ with head for run-of river schemes.

emphasizes the need to carefully select head height during the design phase to minimize environmental impact. The correlation can be expressed as:

$$SO_2emission/C^{-0.36} = 1.628 \times H^{0.03} \tag{8}$$

$$SO_2emission = 1.628 \times H^{0.03} \times C^{-0.36} \tag{9}$$

Canal based SHP schemes

The civil works involved in canal-based SHP schemes greatly depend on site characteristics. The design considerations of SHP projects differ from large hydro projects owing to financial constraints. The civil works associated with canal-based schemes include the construction of a diversion channel, spillway, and powerhouse. In low-head hydropower schemes, equipment size is relatively more extensive, and associated costs are considerably high due to handling large amounts of water. Turbines, along with governing systems, generators, switch gears, control & protection systems, auxiliary systems, transformers etc. are the main electro-mechanical equipment.

Correlation development for canal-based SHP schemes

The development of statistical correlations of the data obtained through EIO-LCA method is carried out by regression analysis. The variation of SO_2 emissions in g-SO_{2eq}/kWh$_e$ with capacity (kW) is shown in Fig. 5. This reveals that in low-head canal-based schemes, smaller capacity installations result in higher emissions per unit of electricity generated. This finding suggests that optimizing capacity is crucial for reducing emissions in low-head environments, where energy extraction is less efficient. The data used here is for the SHP projects having head varying from 1 to 7 m and the power law relation for SO_2 emissions in terms of capacity can be expressed as:

$$SO_2emissions = A_0 \times C^{-0.17} \tag{10}$$

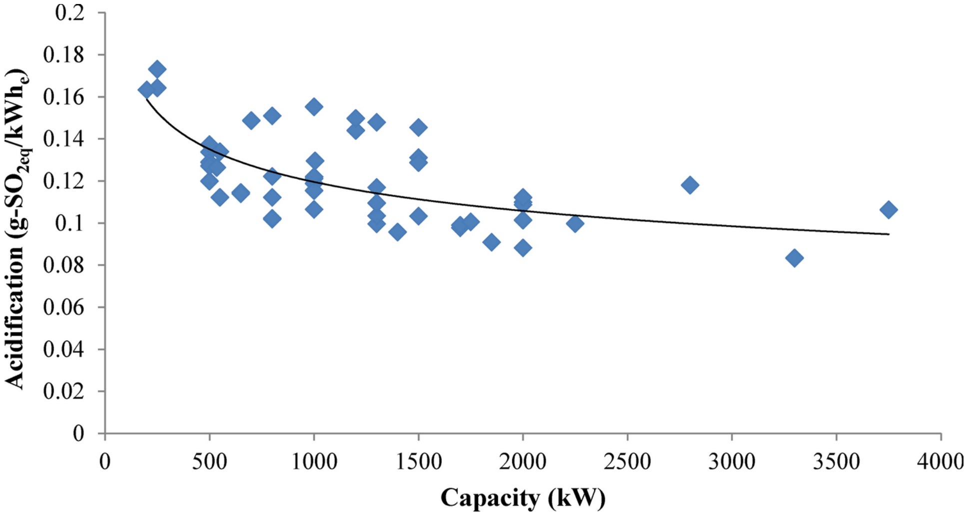

Fig. 5. Variation of SO_{2eq} emissions with capacity for head range 1–7 m for canal-based SHP schemes.

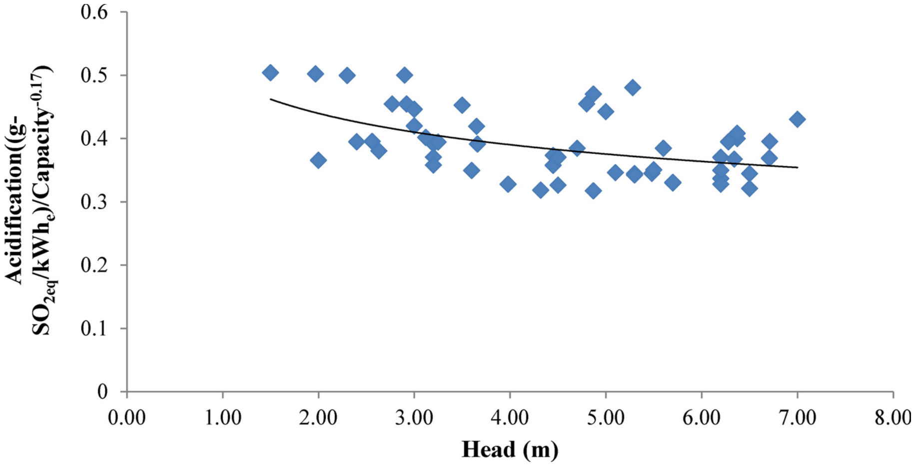

Fig. 6. Variation of SO_{2eq} emissions/capacity$^{-0.17}$ with head for canal-based SHP schemes.

The coefficient A_0 will depend on any other parameters and the parameter considered here is head. Figure 6 shows the curve showing the variation of SO_2 emissions/capacity$^{-0.17}$ with head. In Fig. 6, higher heads in canal-based schemes correlate with lower emissions per unit capacity, emphasizing the benefit of using higher head designs to enhance efficiency and reduce environmental impact and gives the following expression:

$$SO_2 emissions/C^{-0.17} = 0.495 \times H^{-0.17} \tag{11}$$

Thus, the correlation for estimation of SO_2 emissions associated with canal-based projects with head varying from 1 to 7 m is obtained as;

$$SO_2 emissions = 0.495 \times H^{-0.17} \times C^{-0.17} \tag{12}$$

Similarly, the correlation for estimation of SO_2 emissions associated with SHP projects with head varying from 7 to 25 m can be obtained. The variation of SO_2 emissions in g-SO_{2eq}/kWh_e with capacity in kW is shown in Fig. 7. As demonstrated in Fig. 7, emissions decrease as capacity increases in canal-based schemes with higher heads (7–25 m), reinforcing the importance of optimizing project capacity to reduce environmental impact. and the power law relation between them can be expressed as:

$$SO_2 emissions = B_0 \times C^{-0.14} \tag{13}$$

The coefficient B_0 will depend on some other parameter and can be considered as head. Figure 8 shows the variation of SO_2 emissions/capacity$^{-0.14}$ with head. This indicates that canal-based schemes benefit from higher

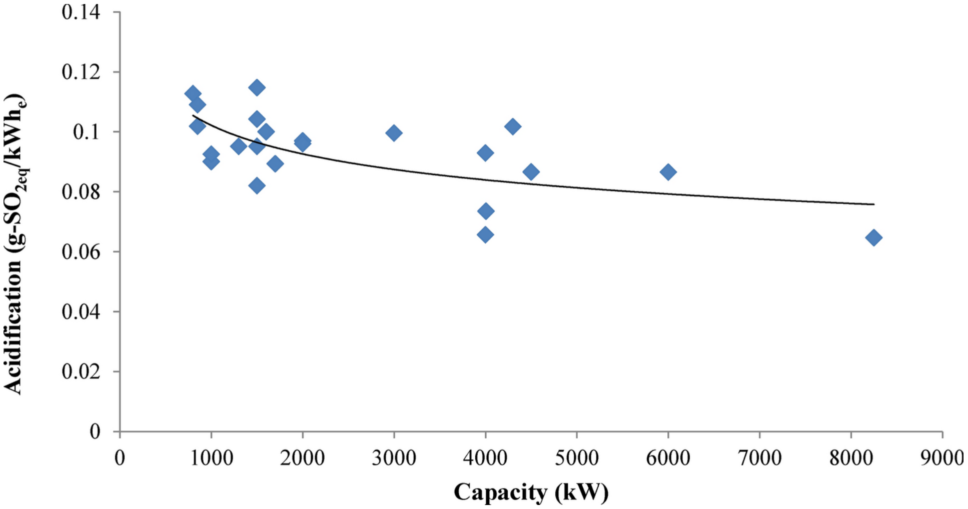

Fig. 7. Variation of SO_{2eq} emissions with capacity for head range 7–25 m for canal-based SHP schemes.

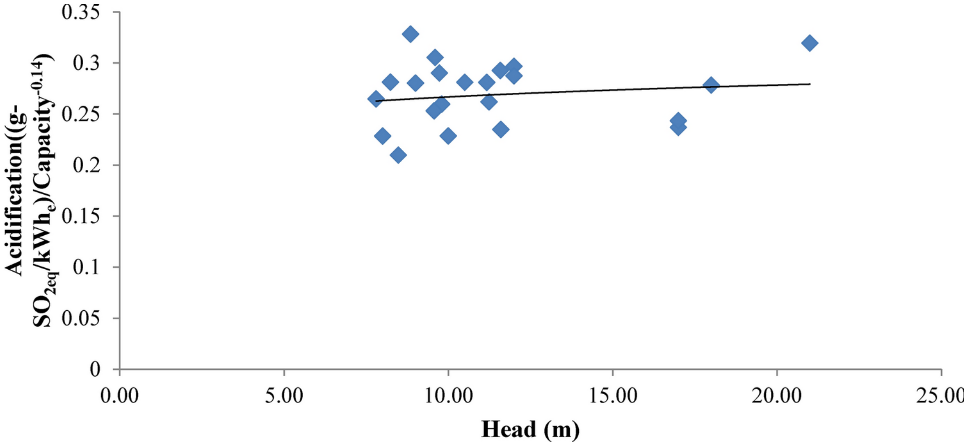

Fig. 8. Variation of SO_{2eq} emissions/capacity$^{-0.14}$ with head for canal-based SHP schemes.

heads in terms of lower emissions per unit capacity, due to improved hydraulic energy extraction at greater heads. and gives the following relation:

$$SO_2emissions/C^{-0.14} = 0.231 \times H^{0.061} \tag{14}$$

Thus, the correlation for estimation of SO_2 emissions associated with canal-based projects with head varying from 7 to 25 m is obtained as;

$$SO_2emissions = 0.231 \times H^{0.061} \times C^{-0.14} \tag{15}$$

Dam–toe SHP schemes

In dam-toe schemes, water is accumulated in a dam constructed across the river for other purposes like water supply, irrigation, etc., and power is produced using a controlled flow of water from the dam to the powerhouse, which is constructed at the toe of the dam. Water is carried out to the turbines using penstock directly from the dam. The dam-toe schemes are pretty popular in the southern part of India. Kaplan, propeller, tubular, and bulb turbines are quite appropriate for low-head projects and are commonly used in dam-toe schemes.

Correlation development for dam–toe SHP schemes

In dam-toe schemes also, regression analysis is used to develop correlations for predicting life cycle SO_2 emissions from dam-toe schemes based on EIO-LCA method. The variation of SO_2 emissions in g-SO_{2eq}/kWh$_e$ with capacity in kW is presented in Fig. 9. This illustrates that dam-toe schemes with higher capacities tend to exhibit lower emissions per unit of electricity generation. This suggests that increasing the capacity of dam-toe projects can significantly reduce emissions, contributing to more sustainable energy production. The data used

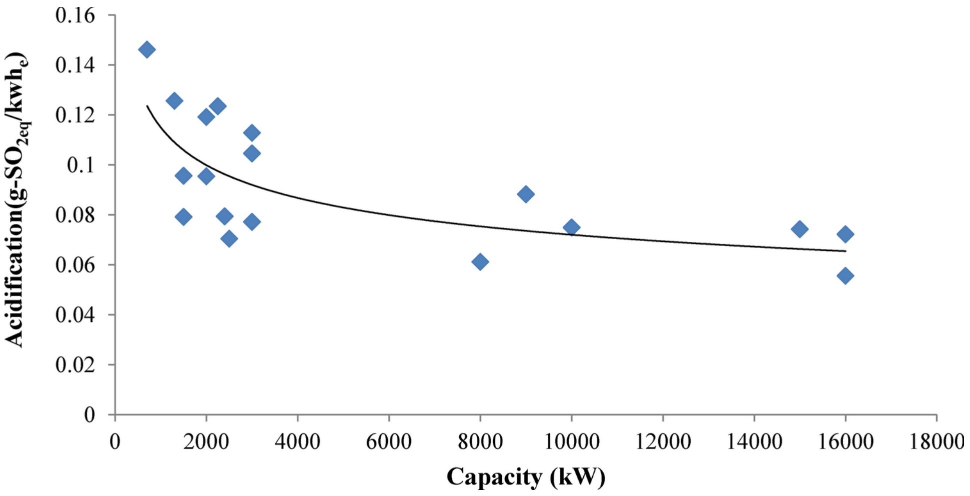

Fig. 9. Variation of SO_{2eq} emissions with capacity for head range 10–40 m for dam-toe SHP schemes.

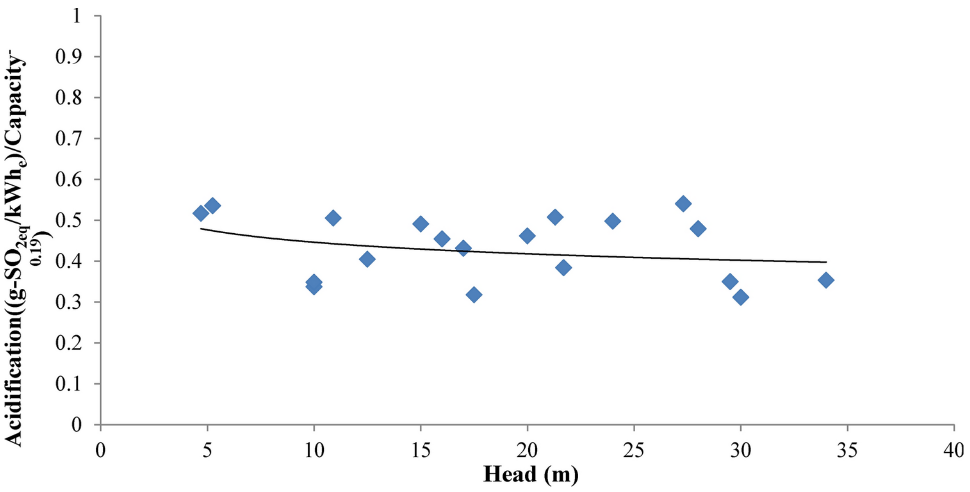

Fig. 10. Variation of SO_{2eq} emissions/capacity$^{-0.19}$ with head for dam-toe SHP schemes.

here is associated with the dam-toe schemes having head varying from 10 to 40 m and the following power law relationship is obtained:

$$SO_2 emissions = A_0 \times C^{-0.19} \tag{16}$$

The coefficient A_0 will depend on any other parameter i.e., head. Further, Fig. 10 presents the variation of SO_2 emissions/capacity$^{-0.19}$ with head. As seen in Fig. 10, increasing the head height in dam-toe schemes leads to reduced emissions per unit capacity, due to the greater energy extraction efficiency at higher heads. This supports the use of higher-head designs for minimizing environmental impacts in dam-toe projects and gives the following relationship.

$$SO_2 emissions/C^{-0.19} = 0.554 \times H^{-0.09} \tag{17}$$

The observed correlation, where SO_{2eq} emissions per unit capacity raised to the power of – 0.19 decrease with increasing head, suggests that higher heads are associated with reduced emissions. This reduction can be attributed to the greater energy generation efficiency at higher heads, which allows for more hydraulic energy to be harnessed from each unit of water. Consequently, this improved efficiency reduces the reliance on extensive infrastructure and civil works, which are typically significant contributors to emissions during the construction and operational phases. Therefore, dam-toe SHP schemes not only enhance energy output but also minimize environmental impacts as head height increases.

The final correlation for estimation of SO_2 emissions for dam-toe schemes with head varying from 10 to 40 m is expressed as:

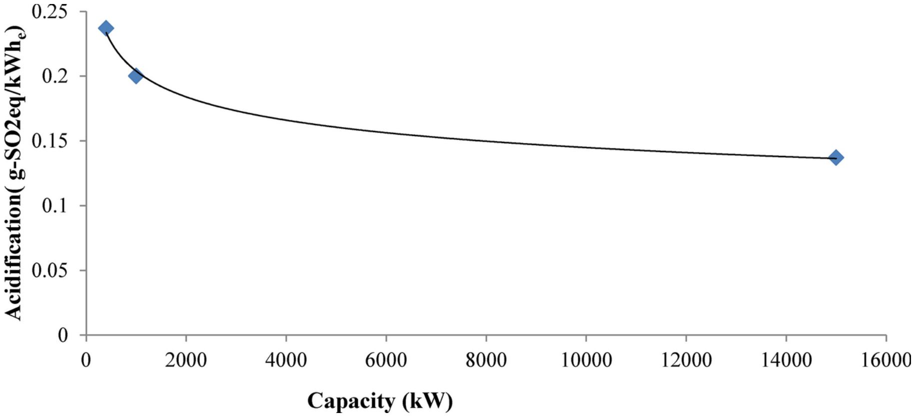

Fig. 11. Variation of SO_{2eq} emissions with capacity for head range 40–300 m for dam-toe schemes.

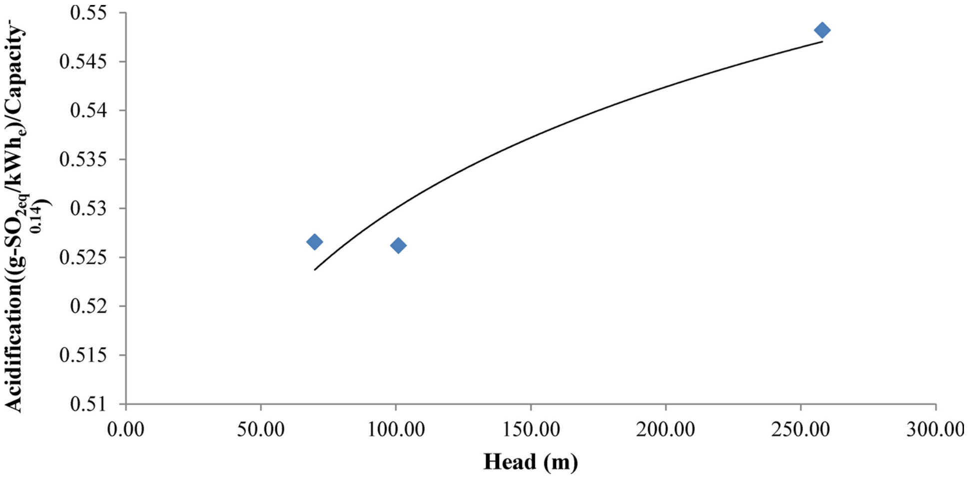

Fig. 12. Variation of SO_{2eq} emissions/capacity$^{-0.14}$ with head for dam-toe schemes.

$$SO_2 emissions = 0.554 \times H^{-0.09} \times C^{-0.19} \tag{18}$$

Similarly, the same method is used to develop correlations for dam-toe schemes with head varying from 40 to 258 m. The variation of SO_2 emissions in g-SO_{2eq}/kWh$_e$ with capacity in kW is shown in Fig. 11 which also gives the following power law relationship. Figure 11 demonstrates that emissions decrease with higher capacity installations in dam-toe schemes, especially in higher head ranges (40–258 m), highlighting the importance of maximizing capacity to achieve lower emissions per unit of electricity generated.

$$SO_2 emissions = B_0 \times C^{-0.14} \tag{19}$$

Again, the coefficient B_0 will depend on any other parameter i.e. head. Figure 12 shows the variation of SO_2 emissions/capacity$^{-0.14}$ with head. Figure 12 emphasizes that higher head dam-toe schemes result in lower emissions per unit capacity, making them an efficient option for minimizing environmental impact in small hydropower projects. The final correlation for estimation of SO_2 emissions for dam-toe schemes with head varying from 40 to 258 m is expressed as:

$$SO_2 emissions/C^{-0.14} = 0.454 \times H^{0.033} \tag{20}$$

$$SO_2 emissions = 0.454 \times H^{0.033} \times C^{-0.14} \tag{21}$$

Results and discussion

The results of this study indicate a clear trend in the emissions of sulphur dioxide equivalents (SO_{2eq}) across various types of SHP projects. A notable finding is that larger projects generally have lower emissions per unit of electricity generated (g-SO_{2eq}/kWh), owing to the economy of scale. Additionally, the head of the SHP projects was found to significantly affect emissions. While run-of-river projects displayed increased emissions with

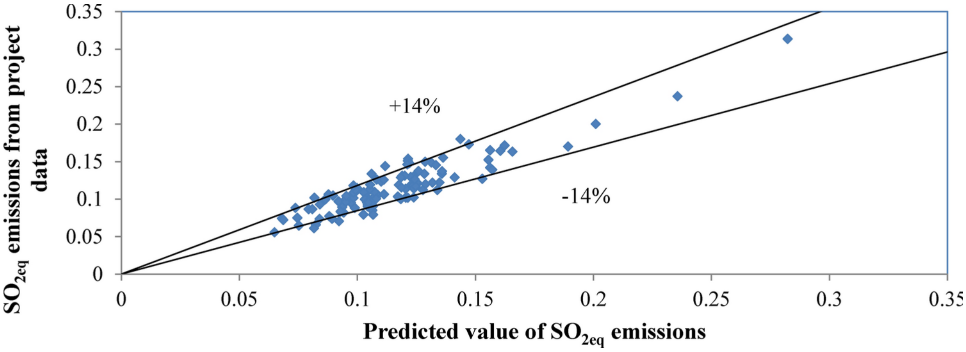

Fig. 13. Comparison graph between the actual and predicted value of SO_{2eq} emissions for different small hydropower (run-of river, canal based, dam-toe) schemes.

higher heads, canal-based and dam-toe projects experienced the opposite, with higher heads leading to lower emissions.

The findings of this study align with previous research on the environmental impacts of hydropower. Keller et al.[14] found that integrating renewable energy sources reduces environmental degradation, supporting our conclusion that SHP projects contribute to lower acidification potential compared to conventional systems. Similarly, Hondo[9] emphasized the lower greenhouse gas emissions from hydropower, which complements our results showing that SHP projects, while not emission-free, produce significantly fewer acidifying pollutants. Additionally, Yang et al.[2] highlighted how site-specific factors influence acidification potential, a key aspect also observed in our study where head height and project type significantly affect SO_2 emissions. By correlating emissions with project parameters, this study contributes to the broader understanding of reducing the environmental impact of hydropower projects.

To validate the developed correlations, a comparison between the actual and predicted SO_{2eq} emissions was made. As shown in Fig. 13, the actual SO_{2eq} emissions from run-of-river, canal-based, and dam-toe SHP schemes closely align with the values predicted by the statistical models. The deviations between the predicted and actual values are within an acceptable range of 14%. These deviations are likely due to site-specific factors such as local geography, civil works, and the type of electro-mechanical equipment used. This validation supports the reliability of the developed models and demonstrates their applicability in accurately predicting emissions for future SHP projects. The findings of this study provide valuable insights into the acidification potential of SHP projects in India, which has been a relatively unexplored area. The study highlights the importance of optimizing project design to reduce environmental impacts, particularly in regions where SHP projects are expected to grow. The study also finds that higher head heights in canal-based and dam-toe schemes further improve efficiency and reduce emissions. The implications for SHP development in India suggest prioritizing larger, high-head projects to minimize environmental impact. Additionally, optimizing design and using the study's predictive models can guide sustainable SHP development and help meet India's energy and environmental goals.

The study's findings provide key insights for policymakers involved in SHP project development. Based on the correlations between project parameters and SO_2 emissions, the following recommendations can help guide the selection of environmentally sustainable SHP projects.

Policies should prioritize larger SHP projects, within the 25 MW threshold, as they generally have lower SO_2 emissions per unit of electricity. For run-of-river schemes, it is important to optimize head height, as higher heads may lead to increased emissions, whereas canal-based and dam-toe projects should aim for higher heads to reduce emissions. Additionally, environmental assessments should integrate predictive models from this study to guide project approvals based on minimizing acidification potential.

Conclusions

This study successfully quantifies the life cycle acidification potential (SO_{2eq} emissions) of various Small Hydropower (SHP) projects in India using an economic input–output life cycle assessment (EIO-LCA) methodology. A key contribution of this research is the development of predictive models that estimate SO_{2eq} emissions based on specific project parameters such as capacity, head, and scheme type. These models fill a significant gap in the existing literature by providing a nuanced understanding of SHP environmental impacts in India.

Key findings

- Capacity and Emissions: The analysis demonstrates that larger SHP projects typically exhibit lower emissions per unit of electricity generated, benefiting from economies of scale.
- Head Height and Emissions: The emissions are influenced by the head height, with canal-based and dam-toe projects showing reduced emissions at higher heads, highlighting the efficiency gains from better hydraulic designs.

Future directions

- Technological Innovations: Further research is suggested to incorporate emerging technologies like artificial intelligence and machine learning, which could refine SHP design and operational strategies to minimize environmental impacts.
- Materials and Construction: Investigating the use of sustainable, low-emission construction materials could help decrease the overall environmental footprint of SHP projects.
- Climate Change Impact: Future studies should consider the potential impact of climate change on hydrological conditions, which could affect both the feasibility and the environmental performance of SHP projects.
- Policy Integration: It's recommended that the models developed through this study be integrated into national and regional policy frameworks to support the sustainable expansion of SHP projects.

These findings and recommendations are aimed at guiding future SHP developments in a manner that aligns with India's sustainability goals, ensuring that the environmental impacts are adequately managed while continuing to meet the growing demand for renewable energy.

The life cycle inventory analysis for the Rayat Mini Hydel Project (3000 kW, Run-of-River) and the Sadani Mini Hydroelectric Project (2 × 500 kW, Dam-Toe) is based on the economic input–output life cycle assessment (EIO-LCA) method.

For the *Rayat Mini Hydel Project,* main civil works accounted for ₹65.845 million, with significant emissions primarily from construction. Electro-mechanical equipment mainly including turbines and generators, ₹60.98 million further contributing to emissions.

In the *Sadani Mini Hydroelectric Project,* the main civil works cost was ₹17.922 million, and the electro-mechanical equipment cost mainly was ₹20.852 million. Due to its smaller capacity, this project had lower emissions compared to Rayat, especially in the operation and maintenance phase.

Overall, the civil works and electro-mechanical equipment phases contribute the most to life cycle emissions, with the larger Rayat project exhibiting higher emissions.

S.No	Component	Cost in Rs 2004-05 (10^6)		Cost in US $ (2002) (10^6)	
		1 (Rayat)	2 (Sadani)	1 (Rayat)	2 (Sadani)
	Civil works				
1	Construction	65.845	17.922	5.82	1.58
2	Erection	10.59	1.92	0.94	0.16
3	Penstock	4.971	4.47	0.44	0.39
4	Coffer dam	–	0.590	–	0.053
	Electro-mechanical equipment				
1	Turbine and generator	60.98	20.852	5.39	1.84
2	Control panel	18.79	–	1.66	–
3	Station auxiliary	13.58	0.836	1.21	0.073
4	Transformer and switchyard	10.50	2.164	0.93	0.19
	Operation and maintenance per year				
1	Civil works	2.4422	0.747	0.22	0.06
2	Electro-mechanical equipment	3.1157	0.716	0.27	0.063
3	Others	1.710	0.492	0.15	0.043

This study uses economic data from 2004-05 (INR) and 2002 (USD) because more recent, comprehensive data was not readily available for the small hydropower projects studied. Updating to current data would require adjustments for inflation, exchange rates, and material costs, which were beyond the scope of this work. While this limits the precision of the analysis for today's context, it ensures consistency with past assessments. Future studies could address this by incorporating updated cost data.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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V.G.: Conceptualization; data curation; formal analysis; investigation; methodology; writing original draft. H.N.: Resources; software; validation; visualization. J.K.: Conceptualization; investigation; formal analysis; methodology; writing review and editing. M.S.: Supervision; writing review and editing. T.A.: Supervision; validation. T.S.: Writing review and editing. R.K.: writing-review and editing; methodology.

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