

S1. Detailed systematic-review methodology

To develop a methodology applicable to the hydropower sector, with a focus on hydraulic turbines and the optimization of maintenance and operational processes, this study adopted a systematic review approach structured in two stages:

- i) critical analysis of the specialized literature;
- ii) extraction and correlation of relevant technical data from scientifically validated sources.

The review was designed to identify operational, maintenance, modernization, digitalization, life-cycle, and eco-efficiency practices that can improve turbine performance while supporting sustainable hydropower operation. Reporting follows the PRISMA 2020 statement.

The bibliographic search was carried out in the Web of Science Core Collection and Scopus, selected for their broad coverage of engineering and energy research. Peer-reviewed journal and conference papers published between 2020 and 2025 were considered in order to capture recent advances under current regulatory, climate, and sustainability constraints. Reference lists of the included studies were also screened to identify additional relevant records. The final search was performed on 15 January 2026. No automation tools, machine-learning classifiers, or screening software were used during the selection process. All eligibility decisions were made through manual reviewer assessment based on the predefined inclusion and exclusion criteria.

Eligible studies explicitly addressed hydraulic turbine operation, reliability, maintenance, refurbishment, modernization, monitoring and digitalization, life-cycle assessment or eco-efficiency, circular economy strategies for refurbishment and end-of-life, or ecologically optimized operating regimes in hydropower plants. Non-relevant studies, non-technical opinion papers, and studies lacking sufficient methodological detail were excluded. The search strategy combined controlled and free-text terms, including "energy efficiency", "hydropower plants", "hydraulic turbines", "turbine efficiency", "extended life", "predictive maintenance", "sustainable renewable energy", and "hydropower plant design methodology".

Records were exported, deduplicated, and screened in two stages, consisting of title/abstract screening followed by full-text eligibility assessment. Initially, 115 records were identified, and 37 studies were included in the qualitative synthesis. Screening and eligibility decisions were performed independently by two authors, with disagreements resolved through discussion or, when necessary, consultation with a third reviewer. Data extraction was likewise carried out independently by two reviewers using a standardized extraction form, and any discrepancies were resolved by consensus. For each included paper, all results relevant to the predefined outcome domains were considered; when multiple indicators were reported, the most directly comparable technical and sustainability-related metrics were retained for narrative synthesis. Studies with incomplete or unclear information were included only when their core methodological approach and principal findings could be identified with sufficient confidence, while variables lacking clarity were excluded from comparative interpretation.

A standardized extraction sheet was used to record turbine type, operating context (head and flow regime), the assessed intervention (e.g., predictive maintenance, refurbishment, digital monitoring, or ecological operation), reported performance indicators (efficiency, availability or downtime, and costs), sustainability indicators (LCA or eco-efficiency metrics, environmental constraints, and circular strategies), and key methodological choices.

Because the included literature is highly heterogeneous and predominantly methodological or engineering-oriented, no single clinical-style risk-of-bias tool or formal certainty-of-evidence framework was applied. Instead, a qualitative methodological appraisal

was conducted independently by two reviewers, focusing on clarity of objectives, transparency of data and methods, validation and uncertainty reporting, and relevance to turbine operation; disagreements were resolved through discussion or, when required, consultation with a third reviewer. This appraisal was designed to support transparent interpretation rather than to generate a numerical quality score. No separate assessment of reporting bias due to missing results was undertaken, given the absence of a meta-analytic synthesis.

Findings were synthesized narratively through thematic clustering and comparison of reported indicators and methodological choices. Where results were sufficiently comparable, directional effects were summarized without meta-analytic pooling because of methodological and reporting heterogeneity. No statistical data conversion or imputation procedures were required; heterogeneous findings were harmonized only at the level of terminology, study focus, and outcome direction to enable structured comparison. No formal subgroup analysis, meta-regression, or investigation of statistical heterogeneity was performed, and no sensitivity analyses were undertaken, because the evidence base was synthesized narratively rather than quantitatively.

The review addressed three main questions:

- i) which operational and maintenance strategies improve turbine efficiency and reliability;
- ii) how life-cycle, eco-efficiency, and circular-economy approaches are integrated into turbine design, refurbishment, and end-of-life;
- iii) which operational practices balance energy production with aquatic ecosystem conservation.

A review protocol was prepared before screening; however, the review was not registered in a public database, and this is stated for transparency.