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Sustainable Preservation Methods for Fresh Fish Transport: A Systematic Literature Review

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Abstract– ***This systematic review evaluated sustainable preservation methods for transporting fresh fish between 2020-2025, with a focus on efficacy, sustainability, and feasibility in tropical climates. Following PRISMA guidelines and the PICOC strategy, thirty peer-reviewed articles from Scopus and SciELO were analyzed. Findings showed that emerging technologies—including solar-powered refrigeration, edible coatings, and modified atmosphere packaging (MAP)—outperformed conventional ice-based preservation in extending shelf life and reducing environmental impact. Solar refrigeration operated at 85.6% efficiency, chitosan-based coatings preserved freshness for up to 16 days, and MAP helped slow down spoilage. In contrast, ice-based methods were energy intensive and carbon heavy. Overall, sustainable approaches improved fish quality, safety, and cost-effectiveness while mitigating CO_2 emissions. The review concludes that adapting these technologies to tropical conditions, where cold chains are insufficient, is essential to ensure reliable fish preservation, enhancing food security, and supporting climate goals.***

Keywords--.Sustainable preservation, fish transport, solar refrigeration.

I. INTRODUCTION

The preservation of fresh fish during transportation represents a persistent challenge for the global fishing industry, particularly in tropical regions where high ambient temperatures (often exceeding 30 °C) and relative humidity above 80% markedly accelerate microbial proliferation and oxidative spoilage processes [1]. These environmental conditions compromise fish quality and safety, contributing substantially to post-harvest losses. According to the Food and Agriculture Organization (FAO), nearly 35% of global fish losses after harvest are directly linked to disruptions in the cold chain and inadequate preservation practices [2].

Despite ongoing technological advancements, ice-based cooling remains the predominant preservation method during fish transportation, accounting for approximately 78% of current practices due to its low initial cost, simplicity, and widespread availability [3]. However, reliance on conventional refrigeration systems associated with ice production entails significant environmental impacts. When traditional refrigerants such as R134a are used, ice-based preservation can generate up to 2.1 kg CO_2eq per kilogram of processed fish, raising concerns regarding its long-term sustainability [4].

In response to these limitations, a range of sustainable preservation technologies has emerged, including solar-powered refrigeration systems, edible biopolymer coatings, and modified atmosphere packaging (MAP). These approaches aim to enhance preservation efficiency while simultaneously reducing environmental burdens [5]. Notably, chitosan-based edible coatings have demonstrated the ability to extend fish shelf life to 14–16 days under tropical conditions, compared to only 4–7 days with ice alone [6]. Likewise, solar-powered refrigeration systems have been shown to reduce carbon emissions to approximately 0.5 kg CO_2eq per kilogram of fish and lower energy costs to around $0.13 per kWh, compared with $0.25 per kWh for conventional electric refrigeration [7].

Despite their demonstrated benefits, the adoption of sustainable preservation technologies remains limited in tropical fisheries. Approximately 62% of fishing enterprises in these regions continue to rely exclusively on ice-based methods, primarily due to economic constraints, limited access to infrastructure, and technological barriers [8]. Furthermore, existing studies often emphasize microbiological quality indicators while overlooking critical sustainability metrics such as carbon footprint, energy efficiency, and adaptability to low-infrastructure settings [9]. This oversight is particularly concerning given that tropical regions contribute nearly 45% of global fish production yet remain underrepresented in preservation-focused research.

Another major shortcoming in the current literature is the lack of standardized, comparative assessments across preservation technologies. Few studies systematically evaluate multiple approaches using consistent quality indicators such as thiobarbituric acid reactive substances (TBARS), total volatile basic nitrogen (TVB-N), and total viable count (TVC). Instead, most investigations concentrate on single preservation techniques—such as high hydrostatic pressure—without cross-technology benchmarking, thereby limiting the practical applicability of their findings [10].

To address these research gaps, this systematic review critically examines sustainable fish preservation technologies applied during transportation in tropical climates, focusing on studies published between 2020-2025. Following the PRISMA guidelines and employing a PICOC-based search strategy, the review compares preservation effectiveness, environmental sustainability, and operational feasibility. The findings aim to inform both academic research and industry decision-making, while highlighting future innovation pathways, including the development of nanoparticle-enhanced edible coatings.

II. MATERIALS AND METHODS

A. Type of Study

This research employed a numerical and systematic approach to conduct a comprehensive literature evaluation in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework [10]. Originally introduced in 2009, PRISMA provides a transparent structure for reporting the objectives, methods, and findings of systematic reviews, and was updated in 2020 to reflect methodological and terminological advances [11]. Systematic reviews constitute a specific research design in which original primary studies serve as the unit of analysis; therefore, methodological rigor is essential to ensure reliability and transparency [12].

Previous studies have reported suboptimal compliance with PRISMA reporting guidelines, particularly in rapid reviews, underscoring the need for well-defined protocols and standardized reporting practices [13]. In this study, data were organized using a structured, spreadsheet-based system to ensure consistency throughout the screening, selection, and synthesis processes. Together, these methodological elements highlight the importance of transparent, reproducible, and comprehensive reporting to enhance the scientific value and practical applicability of systematic reviews.

To guide the literature search quality and shelf life, and the context as supply chains operating in tropical climates. Based on these components, relevant keywords were identified and combined using Boolean operators to construct precise search equations in the Scopus database, enabling the systematic identification of peer-reviewed studies published between 2020 -2025 on sustainable technologies for fresh fish preservation during transportation.

The fig. 1 illustrates the components of the PICOC research question. The PICOC question formulated for this study was: What sustainable preservation methods are most effective in ensuring the quality of fresh fish during transportation, compared with traditional methods in tropical climates?

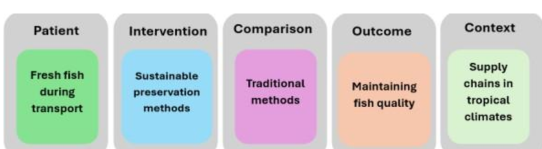

Fig. 1 Questions PICOC

Subsequently, Fig. 2 presents the PICOC sub-questions.

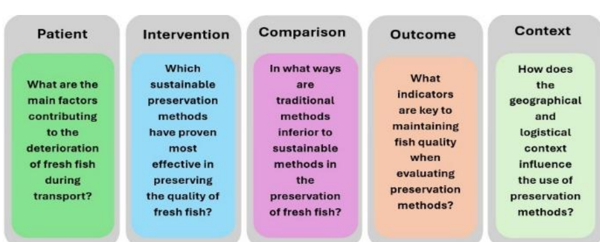

Fig. 2 Subquestions PICOC

B. Data Collection

The sources of information consulted for this study were obtained exclusively from the Scopus database. The search process was conducted using the fields Article, Title, Abstract, and Keywords to ensure comprehensive coverage of relevant publications. Boolean operators (AND, OR) were applied to construct precise and reproducible search strategies.
The literature search was structured using the PICOC framework to clearly define the scope of the review.

TABLE I
DECRYPTORS

N°	PICOC	Key words	Ecuation
1	Patient	Fresh fish during transport	("fresh fish" OR "seafood spoilage") AND ("transport challenges" OR "post-harvest losses")
2	Intervention	Sustainable preservation methods	("sustainable fish preservation" OR "biodegradable packaging") AND ("efficacy" OR "quality maintenance")
3	Comparison	Traditional methods	("traditional fish preservation" OR "ice preservation") AND ("limitations" OR "environmental impact")
4	Outcome	Maintaining fish quality	("shelf life extension" OR "microbial quality") AND ("fresh fish" OR "seafood")
5	Context	Supply chains in tropical climates	("tropical climate" OR "developing countries") AND ("fish preservation methods" OR "cold chain logistics")

C. Study Selection and Eligibility Criteria

Subsequently, inclusion and exclusion criteria were implemented, as illustrated in Table II.

TABLE II
INCLUSION AND EXCLUSION CRITERIA

N°	CRITERIA
CR1	Scientific articles published between 2020-2025, in English or Spanish, in areas such as agricultural and biological sciences, environmental sciences, engineering, energy, and chemistry.
CR2	Articles addressing sustainable preservation methods applied to the transport of fresh fish.
CR3	El estudio fue publicado dentro del período establecido (2021–2025).
CR4	Articles analyzing the logistical or environmental impact of methods in tropical climate supply chains

D. PRISMA Flow Diagram

Subsequently, Fig. 3 presents the PRISMA flow diagram of the study selection process.

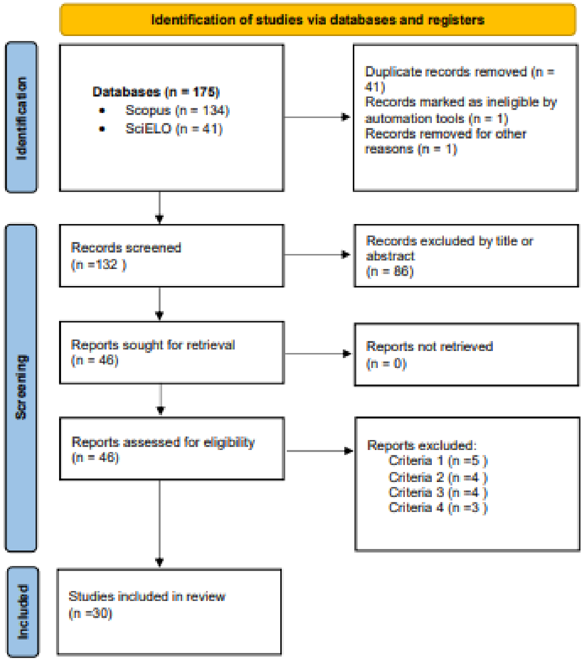

Fig. 3 Prsima Flow

E. Data Extraction Process

In this regard, Table III presents the advanced search string used in the reviewed database. This not only demonstrates the work carried out in the present study but also allows the search strategy to be replicated.

TABLE III
GENERAL SEARCH EQUATION

Database	EQUATION
Scopus	("fresh fish" OR "fish") AND ("preserv*" OR "conserv*" OR "storage" OR "transport*" OR "supply chain" OR "logistic*") AND ("sustainab*" OR "eco-friendly" OR "environment* friendly" OR "renewable" OR "low carbon" OR "low energy") AND ("cold chain" OR "refrigerat*" OR "cooling" OR "freezing" OR "temperature control" OR "thermal" OR "ice" OR "chilling")

III. RESULTS AND DISCUSSION

A. Bibliometric

Fig. 4 shows the bibliometric distribution of publications from 2021 to 2025. A gradual increase is observed from 2021 to 2023, with a peak in 2024 (12 studies), reflecting growing interest in sustainable fish preservation driven by concerns over post-harvest losses and the environmental impact of traditional methods. The lower number in 2025 (2 studies) is due to the ongoing year. This trend is associated with a shift toward technologies such as solar refrigeration, edible coatings, and modified atmosphere packaging, which significantly extend shelf life compared to conventional methods.

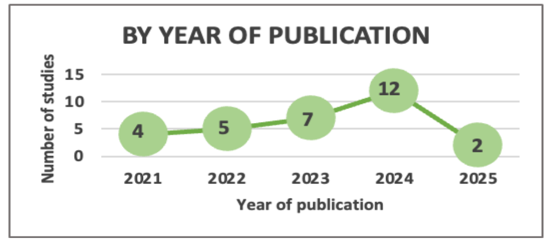

Fig. 4. Studies included according to the year of publication

Fig. 5 highlights keywords such as supply chain, solar energy, edible coatings, and shelf life, highlighting the relevance of sustainable methods for preserving fresh fish during transport.

Fig. 5. Fish of key words present in the selected studies

Fig. 6 shows a clear predominance of English-language publications, facilitating global knowledge dissemination andmethodological standardization. However, it may limit the visibility of locally developed solutions in non-English-speaking regions.

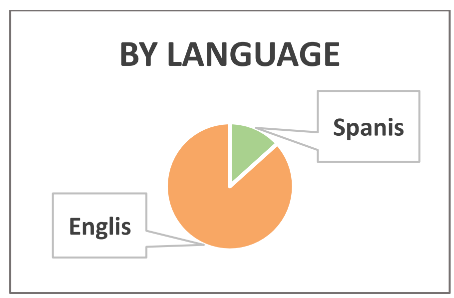

Fig. 6. Studies included according to the language in which they were written

According to Fig. 7, the studies come mostly from Italy, Spain, India, Brazil, Peru, and Indonesia, countries with strong fishing activity and, in many cases, tropical or subtropical climates. This reinforces the practical relevance of the research, as these regions face critical challenges related to temperature and humidity that accelerate spoilage.

Fig. 7. Countries of origin of the chosen studies

To ensure quality and comparability in SLR, it is key to identify the type of study. Fig. 8 shows a majority of experimental studies and theoretical reviews, thereby enriches the analysis by combining empirical evidence with conceptual foundations.

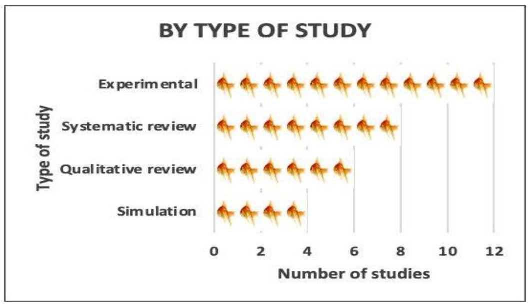

Fig.8. Records chosen according to the type of study

The studies consulted come from the SciELO and Scopus databases, both recognized for their access to high-quality and relevant scientific literature in the academic and regional fields. As shown in Fig. 9, Scopus is the most popular, accounting for 77% of the sources, compared to 23% for SciELO.

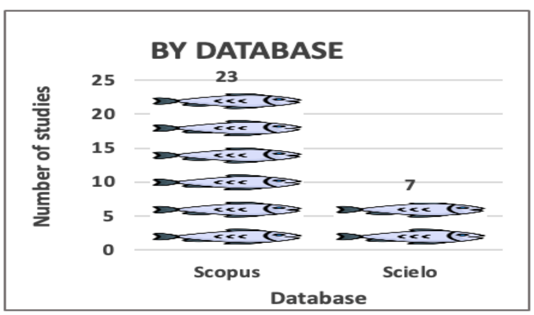

Fig.9. Databases of the studies consulted

B. Content analysis

In this section, the PICOC sub-questions are addressed in order to answer the main research question.

Patient question: What factors cause deterioration in fresh fish during transport?

Based on the qualitative and quantitative analysis of the 30 selected studies, key patterns related to sustainable preservation methods for transporting fresh fish were identified. This systematic review addressed a series of relevant questions formulated within the PICO framework, which facilitated the organization and analysis of the extracted data.

Fresh fish deterioration during transport is driven by multiple interacting factors, including microbial activity, lipid oxidation, endogenous enzymatic reactions, and environmental conditions. Microbial spoilage is primarily associated with bacteria such as *Pseudomonas* spp. and *Shewanella putrefaciens*, which degrade fish nutrients and produce odorous compounds such as total volatile basic nitrogen (TVB-N) and trimethylamine (TMA), leading to significant losses in sensory quality and consumer acceptance [14].

Lipid oxidation represents another major deterioration mechanism and is commonly assessed using the thiobarbituric acid reactive substances (TBARS) index. This process results in the formation of malonaldehyde and other secondary oxidation products that adversely affect color, texture, and nutritional stability, particularly in fish species rich in polyunsaturated fatty acids [15].

In addition, endogenous enzymes naturally present in fish muscle accelerate protein and lipid hydrolysis after harvest, causing softening of the flesh and the release of compounds that further promote microbial growth. These effects are exacerbated in tropical regions, where high temperatures and humidity prevail during transportation without adequate refrigeration [16].

Temperature fluctuations above 5 °C during transport significantly disrupt the cold chain, favoring microbial proliferation and oxidative reactions. Studies conducted in tropical countries such as Indonesia and Brazil have shown that even short-term temperature deviations can sharply reduce shelf life and compromise microbiological and sensory quality within hours [17].

Finally, inadequate packaging systems and direct exposure to oxygen intensify all deterioration processes. The lack of protective packaging not only accelerates oxidation and microbial growth but also compromises food safety and reduces the commercial value of fresh fish during distribution [18].

As illustrated in Table IV:

TABLE IV
FACTORS CONTRIBUTING TO FISH DETERIORATION DURING TRANSPORT

DETERIORATION FACTOR	EXPLANATION
Microbial activity	Pseudomonas spp. and Shewanella putrefaciens produce TVB-N and TMA, affecting smell and taste.
Lipid oxidation	Generates malonaldehyde (TBARS), affecting color and nutrients, especially in fish with polyunsaturated fats.
Endogenous enzymes	They break down proteins and lipids, reducing muscle firmness, especially without a cold chain.
High temperatures	>5°C reduces shelf life; In tropical climates, deterioration occurs within a few hours.
Exposure to oxygen	Promotes oxidation and microbial growth.

Intervention question: What sustainable methods best preserve fresh fish during transport?

Among the most effective sustainable preservation methods are

those that combine technological innovation with reduced environmental impact and improved operational performance. Solar-powered refrigeration systems have shown strong potential in tropical regions, maintaining temperatures between 0 and 5 °C and extending fish shelf life to 9–14 days, compared with approximately 4–7 days using conventional ice-based methods. In addition, these systems can reduce carbon emissions from around 2.1 kg CO_2eq/kg (using synthetic refrigerants such as R134a) to approximately
0.5 kg CO_2eq/kg when solar energy or natural CO_2 is used. Energy consumption is also reduced by up to 40–60%, making these systems particularly suitable for regions with limited or unstable electricity supply [19].

Edible coatings incorporating natural antioxidants also represent an effective approach. Chitosan-based coatings enriched with essential oils have been shown to reduce lipid oxidation (TBARS) by up to 50–70% and extend the refrigerated shelf life of fish products up to 16 days, compared with about 7 days in untreated samples. Similarly, biopolymer films enhanced with nanoparticles have demonstrated reductions of up to 30–45% in total volatile basic nitrogen (TVB-N), indicating delayed spoilage and improved biochemical stability. These coatings can also reduce microbial growth by approximately 1–2 log CFU/g, contributing to improved safety and quality preservation [20].

High hydrostatic pressure (HPP), particularly when combined with biodegradable coatings, has demonstrated remarkable preservation efficiency. Pressures between 400 and 600 MPa can extend salmon shelf life under refrigerated transport to over 30 days, while achieving microbial reductions of 3–5 log CFU/g. Compared with traditional freezing, HPP can reduce energy consumption by approximately 20–30% in optimized systems, while better preserving texture and sensory attributes. Modified atmosphere packaging (MAP) and vacuum systems have also proven effective, extending shelf life by 30–60% compared to conventional storage, maintaining oxygen levels below 5%, and stabilizing microbial loads below critical limits. However, slight increases in lipid oxidation (around 10–15%) have been
reported under certain gas compositions [21].

Finally, emerging technologies such as cold plasma treatments and microencapsulated essential oils are gaining increasing attention. Cold plasma has demonstrated microbial reductions of up to 2–4 log CFU/g within short treatment times (5–15 minutes), while microencapsulated essential oils allow controlled release of antimicrobial compounds, extending shelf life by an additional 20–40% compared to conventional coatings. These methods are particularly effective under elevated temperatures (above 25 °C), typical of tropical supply chains, where spoilage rates are significantly higher. Additionally, these technologies reduce reliance on non-biodegradable inputs such as polystyrene packaging and synthetic preservatives, supporting more sustainable production systems [22].

Comparison question: In what ways are traditional methods inferior to sustainable methods? Traditional preservation methods such as ice, conventional electric refrigeration, and synthetic antioxidants are generally less efficient, more polluting, and less sustainable than modern alternatives. A major limitation is their higher carbon footprint: refrigeration systems using synthetic refrigerants such as R134a can emit up to 2.1 kg CO_2eq per kilogram of fish, whereas sustainable options such as solar-powered refrigeration or systems using natural refrigerants (R744) reduce emissions to approximately 0.5 kg CO_2eq/kg [23]. In tropical regions, ice-based transport is particularly inefficient, requiring substantially higher energy inputs due to rapid melting under high temperatures.

In terms of preservation performance, traditional methods offer limited shelf-life extension. Ice typically preserves fish for only 4–7 days, while sustainable approaches such as chitosan-based edible coatings with natural antioxidants can extend shelf life to 14–16 days at 4 °C without compromising quality. Similarly, conventional packaging materials perform comparably to eco-friendly alternatives in terms of shelf life, but with a significantly greater environmental impact [24].

Traditional methods also rely heavily on non-renewable resources and potentially harmful substances. Practices such as wood smoking generate toxic emissions, and synthetic antioxidants (e.g., BHA and BHT) are non-biodegradable. In contrast, sustainable technologies—including essential oils, cold plasma treatments, and solar refrigeration systems with thermal storage—provide safer, low-impact solutions while maintaining fish quality and microbial safety. Moreover, sustainable systems often present lower operational costs, with cooling costs around \$0.13/kWh compared with approximately \$0.25/kWh for conventional electric refrigeration, and reduced logistical expenses due to decreased dependence on ice replacement in tropical supply chains [25].

As illustrated in Table V:

TABLE V.
TRADITIONAL VS. SUSTAINABLE METHODS

CRITERIA	TRADITIONAL METHODS	SUSTAINABLE METHODS
Environmental impact	The product has a high carbon footprint (2.1 kg CO_2eq/kg with R134a), as reported in [4]	Low footprint: 0.5 kg CO_2eq/kg with solar or natural CO_2 [4].
Energy efficiency	Ice requires 3–4 times more energy in warm climates [16].	Solar cooling with 85.6% efficiency [2].
Fish shelf life	4–7 days with ice [16].	Up to 16 days with chitosan and essential oils [21].
Packaging	Polystyrene: high environmental impact.	$CaCO_3$ and PE packaging: lower impact without affecting preservation [29].
Type of inputs	Firewood and synthetic antioxidants are non-biodegradable [22].	The use of essential oils and cold plasma (biodegradable) is recommended [22].

Beyond performance advantages, a more critical comparison reveals important economic and operational limitations associated with sustainable preservation technologies. Although these methods demonstrate superior effectiveness, quantitative evidence highlights significant constraints that may limit their large-scale implementation.

For instance, high hydrostatic pressure (HPP) systems operate at 400–600 MPa and require capital investments ranging from USD 400,000 to 800,000, with annual maintenance costs estimated at 10–15% of the initial investment. In addition, their energy consumption can reach 150–250 kWh per ton of processed fish, and their technological maturity is typically classified between TRL 6–7, indicating pilot-to-industrial transition stages [21].

Solar-powered refrigeration systems, while capable of reducing emissions to approximately 0.5 kg CO_2eq/kg of fish and lowering energy costs to around \$0.13/kWh, require solar irradiance levels above 4–5 kWh/m^2/day and initial installation costs 30–50% higher than conventional systems (USD 2,000–5,000 for small-scale units). Their technological maturity is estimated at TRL 7–8; however, their performance depends heavily on climatic conditions and energy storage capacity, which can limit reliability in certain tropical regions [16].

Edible coatings, particularly chitosan-based formulations, extend shelf life to 14–16 days but increase processing time by approximately 20–30% due to additional coating and drying stages. Their implementation cost ranges between USD 0.05–
0.15 per kg of fish, and they are generally classified at TRL 5–6, reflecting limited industrial standardization and challenges in achieving uniform application at scale [22].

Modified atmosphere packaging (MAP) requires gas mixtures typically composed of 40–60% CO_2 and 20–40% O_2, along with specialized sealing and monitoring systems. This increases packaging costs by 15–25% and requires continuous quality control. MAP systems are considered more mature (TRL 8–9), but their adoption is constrained by infrastructure requirements, including gas supply systems and trained personnel [25].

Cold plasma treatments and emerging technologies, although effective in reducing microbial loads by up to 2–3 log CFU/g, remain at TRL 4–6 and require controlled environments, high initial equipment costs (USD 50,000–150,000), and further validation for industrial-scale applications [22].

As illustrated in Table VI:

TABLE VI.
COMPARATIVE LIMITATIONS OF SUSTAINABLE VS. TRADITIONAL METHODS

Technology	Cost (USD)	Energy Consumption	Infrastructure Requirements	Scalability Level
High Hydrostatic Pressure (HPP)	400,000 – 800,000 (equipment) [21]	150–250 kWh/ton [21]	High (specialized equipment, high-pressure systems)	Low–Medium
Solar Refrigeration	2,000 – 5,000 (small-scale units) [16]	~0.13 \$/kWh [2]	Medium (solar panels, batteries, thermal storage)	Medium
Edible Coatings (Chitosan)	0.05 – 0.15 per kg of fish [22]	Low [22]	Low–Medium (controlled application and drying)	Medium
Modified Atmosphere Packaging (MAP)	+15–25% vs traditional packaging [25]	Moderate [25]	Medium–High (gas systems, sealing, monitoring)	High
Cold Plasma	50,000 – 150,000 (equipment) [22]	Moderate [22]	High (controlled chambers, technical expertise)	Low

Outcome question: What indicators allow us to evaluate whether a preservation method maintains fish quality?

The effectiveness of fish preservation methods is commonly evaluated using microbiological, physicochemical, and sensory indicators, which together determine product safety, quality, and commercial acceptability while enabling comparisons between traditional and sustainable techniques. From a microbiological perspective, total viable count (TVC) values above 6–7 log CFU/g indicate loss of safety; however, sustainable technologies such as cold plasma treatments and edible coatings with natural antimicrobials have demonstrated significant reductions in spoilage microorganisms, thereby extending shelf life [26].

Physicochemical indicators are equally critical, particularly lipid oxidation and protein degradation. Thiobarbituric acid reactive substances (TBARS) values exceeding 1–2 mg MDA/kg reflect oxidative rancidity, whereas chitosan-based coatings have been shown to maintain TBARS levels below 1 mg/kg during refrigerated storage. Similarly, total volatile basic nitrogen (TVB-N) values above
35 mg/100 g signal spoilage, while modified atmosphere packaging (MAP) systems with elevated CO_2 concentrations can effectively delay this increase. Additional parameters such as pH stability and textural firmness are also preserved through technologies like high hydrostatic pressure (HPP) and high-voltage electric fields (HVEF) [27].

Sensory indicators, including color, odor, and overall organoleptic quality, remain essential for consumer acceptance. Sustainable preservation approaches, such as biopolymer-based coatings and optimized smoking processes, have been shown to maintain visual stability and sensory attributes for extended storage periods, outperforming conventional treatments [28].

Context question: How does the tropical climate affect the effectiveness of sustainable methods?

Tropical climates, characterized by temperatures between 25 and 35 °C and relative humidity above 80%, significantly accelerate fish spoilage, posing major challenges for preservation while highlighting the need for adaptive sustainable technologies. Under these conditions, deterioration indicators such as TVB-N can exceed acceptable limits within
48 hours at ambient temperature. However, sustainable approaches

such as solar-powered refrigeration systems have demonstrated effectiveness in maintaining storage temperatures between 0 and 5 °C even under high thermal stress, supporting their applicability in regions with weak or unstable cold chains [29].

High temperatures also intensify microbial growth and lipid oxidation. Spoilage bacteria proliferate more rapidly at tropical temperatures, and TBARS values increase sharply within short storage periods. Nevertheless, innovative solutions such as edible coatings with natural antimicrobials, cold plasma treatments, and functional biopolymer films have proven capable of slowing microbial activity and oxidative processes, thereby extending shelf life without continuous refrigeration [29].

In addition, tropical regions often face infrastructural limitations, including unreliable electricity supply. Autonomous solar-powered cold storage systems and other low-energy technologies address these constraints by maintaining low temperatures for extended periods without external power. Emerging methods such as high hydrostatic pressure (HPP) further enhance preservation performance by inactivating heat-resistant enzymes and significantly prolonging shelf life under refrigerated conditions, outperforming traditional methods even in challenging tropical environments [30].

C. Discussion

The results of this systematic review address the central research question concerning the effectiveness of sustainable preservation methods for maintaining fresh fish quality during transport in tropical climates. Based on the analysis of 30 scientific articles selected using the PICOC strategy and the PRISMA protocol, the findings indicate that sustainable technologies consistently outperform traditional methods in both preservation efficiency and environmental impact, particularly under conditions exceeding 25 °C and 80% relative humidity [13], [18], [21].

Fish spoilage during transport is mainly driven by microbial activity (*Pseudomonas* spp., *Shewanella putrefaciens*), lipid oxidation, endogenous enzymatic reactions, and temperature fluctuations. In tropical environments lacking proper thermal control, spoilage indicators such as TVB-N can exceed acceptable limits within 48 hours, while ice-based preservation typically limits shelf life to 4–7 days and is associated with high energy consumption and carbon emissions [16], [19], [24]. In contrast, sustainable approaches—including solar-powered refrigeration, edible biopolymer coatings, modified atmosphere packaging (MAP), and high hydrostatic pressure (HPP)—significantly extend shelf life while reducing energy use and greenhouse gas emissions [21], [22], [25].

Solar refrigeration systems maintain temperatures between 0 and 5 °C and extend freshness up to 14 days while lowering cooling costs and CO_2 emissions. Chitosan-based coatings with natural antioxidants effectively reduce lipid oxidation and microbial growth, preserving fish quality for up to 16 days. MAP systems control bacterial proliferation, and HPP treatments extend refrigerated shelf life beyond 30 days with substantially lower energy requirements than conventional freezing [21], [24], [30].

Emerging technologies such as cold plasma treatments and coatings incorporating natural nanoparticles or microcapsules further enhance preservation by reducing pathogenic and spoilage microorganisms and slowing chemical degradation processes. These methods are particularly relevant for regions with limited or unstable electricity, offering viable alternatives for small-scale fisheries and rural communities [22], [27].

Across the reviewed studies, quality indicators—including TBARS, TVB-N, total viable count (TVC), texture, and color difference (ΔE)—showed consistently better outcomes with sustainable methods compared to traditional practices. TBARS values remained below rancidity thresholds, and ΔE values below 3 units indicated preserved visual quality and consumer acceptability [18], [26].

Despite their advantages, the adoption of sustainable technologies remains constrained by limited infrastructure, resistance to technological change, and insufficient technical training. Addressing these challenges will require supportive public policies, financial incentives, and strengthened capacity-building initiatives in tropical regions [28], [29].

This review contributes to existing knowledge by providing a comparative synthesis of sustainable fish preservation technologies under tropical conditions. Nevertheless, limitations include variability in quantitative indicators, differences among fish species, and geographic concentration of the available studies. Furthermore, some emerging technologies remain at the experimental stage and require validation at an industrial scale. Future research should prioritize standardized comparative studies across species, climatic conditions, and operational contexts to improve the scalability and real-world applicability of sustainable preservation methods [30].

IV. CONCLUSION

This systematic review answers the PICOC research question by demonstrating that sustainable preservation methods are markedly more effective than traditional techniques in maintaining the quality of fresh fish during transportation in tropical climates. Based on the analysis of 30 peer-reviewed studies selected through a structured PICOC strategy and the PRISMA protocol, the findings confirm that innovative, low-impact technologies outperform conventional methods in terms of preservation efficiency, environmental sustainability, and operational feasibility.

From a population perspective, fresh fish transported under tropical conditions is particularly vulnerable to rapid spoilage due to high temperatures and humidity. Regarding intervention, sustainable methods such as solar-powered refrigeration, edible biopolymer coatings, modified atmosphere packaging, cold plasma treatments, and high hydrostatic pressure significantly reduced microbial growth, lipid oxidation, and enzymatic degradation. In contrast, the comparison with traditional methods—mainly ice-based cooling and conventional electric refrigeration—revealed shorter shelf life, higher energy consumption, and greater carbon emissions.

In terms of outcomes, sustainable technologies consistently improved key quality indicators, including total viable count (TVC), thiobarbituric acid reactive substances (TBARS), total volatile basic nitrogen (TVB-N), texture, and sensory attributes, thereby extending shelf life while maintaining safety and consumer acceptability. Concerning the context, these benefits were especially evident in tropical supply chains, where limited infrastructure and unstable electricity make traditional preservation methods less effective and more costly.

However, it is important to acknowledge that this review is based predominantly on studies indexed in Scopus, with partial inclusion of SciELO. This selection criterion was adopted to ensure the inclusion of high-quality, peer-reviewed, and internationally recognized scientific literature. Nevertheless, this approach may introduce a potential selection bias by excluding relevant studies published in other databases or regional sources not indexed in these platforms. Consequently, some local innovations or context-specific practices, particularly from developing regions, may be underrepresented. This limitation should be considered when interpreting the findings, as it may affect the generalizability of the results across all tropical contexts. Future research should aim to incorporate a broader range of databases to achieve a more comprehensive and inclusive evidence base.

Overall, the review concludes that sustainable preservation technologies represent a viable and necessary alternative for fresh fish transportation in tropical regions. Their adoption has the potential to reduce post-harvest losses, lower environmental impact, and enhance food security. Future efforts should focus on scaling these technologies through standardized evaluations, policy support, and targeted training programs to facilitate their implementation in real-world tropical fisheries.

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