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Sustainable development of inland waterways transport: a review

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Abstract

Over the years, the demand for transportation has experienced a consistent rise, which has exacerbated a multitude of issues including environmental, visual, and noise pollution, congestion, land use conflicts, and various other related challenges. In this regard, the pursuit of alternatives aimed at mitigating these adverse effects stands as a priority for governments and policymakers. Consequently, inland waterway transport (IWT) emerges as an appealing solution, due to its advantages across the social, environmental, and economic considerations. However, in relation to IWT the concept of sustainable development is insufficiently investigated. The objective of this paper is to undertake a comprehensive review of how the concept of sustainable development is addressed and applied within the framework of IWT systems. To achieve this goal, a systematic literature review was meticulously conducted, utilizing three academic databases (Scopus, Google Scholar, and EBSCO). The review process yielded a total of 51 papers that proved to be pertinent and relevant to the subject matter. The comprehensive literature review facilitated the delineation of the principal elements, factors, and characteristics of the IWT system, as well as the primary drivers for its sustainable development. However, the implications for further research were identified, such as a comprehensive examination of each case due to the distinct geographical, social, economic, and political conditions inherent to each individual basin. That is essential for understanding the unique barriers present within each context and for formulating viable solutions aimed at fostering and incentivizing the sustainable development of IWT systems.

Keywords: Sustainable development, Inland waterway transport, System, Drivers

Introduction

Transportation plays a fundamental role in the socio-economic development of countries, especially in critical activities such as commuting, energy supply, goods allocation, and tourism, among others (Rodrigue 2020a). However, some aspects such as pollution, congestion, and overdependence of road transport, pose several challenges for the industry, which must establish strategies for its sustainable development (Schiller et al. 2010). Today, the transport industry is highly dependent on fossil fuels, and various environmental and social disadvantages have been reported since the 70's road network expansion (Schiller et al. 2010). In this regard, and understanding the relevance of transportation for society, in 1987, the World Commission on Environment and Development

posed the concept of sustainable development as a development of the present without compromising the resources of future generations (Brundtland 1987). This definition has been widely applied to transportation development and sustainable transport systems, proposing a balance between environmental, social, and economic aspects (Rohács and Simongáti 2007).

Various authors argue that sustainable transport must ensure the basic needs of individuals and society efficiently and affordably, limiting the generation of emissions and waste and reducing the consumption of non-renewable resources (Rohács and Simongáti 2007; Schiller et al. 2010). Moreover, developing sustainable transportation requires innovative solutions to improve performance in the different modes as well as measures to reduce negative externalities (Rodrigue 2020b). These externalities mainly focus on air, water, land and noise pollution, greenhouse gas emission, congestion, accidents, and excessive land use (Demir et al. 2015; van Lier and Macharis 2014). Given the preceding, the use of inland waterway transport (IWT) is considered an appropriate tool for the sustainable development of transport. In that sense, various European countries, the United States, and China have developed more robust IWT systems and recognize its socio-economic and environmental benefits (Williamsson et al. 2020; Miciuła and Wojtaszek 2019; Notteboom 2012; Institute for Water Resources 2012).

Wang et al. (2020) identified the most representative inland waterways in the world according to their bearing capacity and socio-economic index, being the basins of the Rhine, Volga, Yangtze, Pearl, and Amazon, which top the list. In fact, much of the literature on sustainable development of the IWT is focused on European or Asian countries; however, other developing countries such as India, Indonesia, Nigeria, and Nepal, among others, have documented the state of their waterways, the challenges, and possible solutions for its development (Achmadi et al. 2018; Emmanuel et al. 2018; Rasul 2015; Trivedi et al. 2021). It is worth mentioning that for South America, which possesses critical hydric resources and relevant basins such as Amazon, Orinoco, Paraná, and Magdalena, not only scientific research is scarce, but also the development of IWT has been framed in the limited budgetary investment since it has not been constituted as a priority in public spending, added to weaknesses of institutional nature and regulatory frameworks (Jaimurzina and Wilmsmeier 2017).

Currently, for hinterland transportation, the road is the dominant transport means. However, numerous social, economic, and environmental drawbacks have been associated with automobile dependency, such as greenhouse gas emissions, oil dependence, traffic issues (noise, visual intrusion, and congestion), increasing social health costs due to accidents, sedentarism, pollution, isolation of neighbourhoods, social and accessibility inequality, among others (Schiller et al. 2010). Despite the above, transportation is a condition for development, and the search for alternatives to alleviate these problems is necessary. Therefore, modal shift from road to rail and IWT has gained relevance to be considered as a tool to develop sustainable transportation; in addition to that, governments and some international institutions such as the European Commission have developed policy documents to support and incentive this modal change (Jonkeren et al. 2019; Mihic et al. 2011).

This paper has been divided into five parts. Section "Methodology" describes the method applied to the paper. The results will be presented in Section "Results",

addressing the concept of sustainable development of IWT, followed by the description of the elements, factors, and characteristics that constitute IWT systems, and the drivers for sustainable development of IWT system. Finally, the discussion and conclusions are presented in Sections "Discussion" and "Conclusions".

Methodology

To conduct the systematic literature review, the authors followed the process suggested by Snyder (2019), consisting of four phases, starting with the design and conduct of the research, followed by the analysis and the report.

During the first stage, the systematic literature review was designed and is described in Table 1. Three research questions were formulated: *a. How is sustainable development addressed and applied in inland waterways transport systems? B. How can inland waterways transport system be defined, and what elements and factors constitute it? c. What are the drivers to develop inland waterway transport?* The strategy for selecting literature involving inclusion and exclusion criteria was established. To select the relevant literature, the authors established "inland waterway" and "sustainab*" as the key words. The search was limited to key words included in the title, abstract and key words using "Scopus", "Google Scholar" and "EBSCO" as the databases for the paper selection.

Table 1 Stages followed in the systematic literature review

Research questions	
a. How is sustainable development addressed and applied in inland waterways transport systems? b. How can inland waterways transport system be defined and what elements and factors constitute it? c. What are the drivers to sustainable development of inland waterway transport?	
Identification of key words	
"inland waterway" AND sustainab* (The use of asterisk will allow the selection of publications that contain the words "sustainable""sustainability")	
Inclusion criteria	Exclusion criteria
Academic Journals—Reports—Book chapters Full access to text Research covering sustainable development of IWT	Articles that are not directly focused on inland waterway transport Repetitive studies found in the different databases
Stages for filtering data Stage one: Eliminating duplicates Stage two: Application of inclusion and exclusion criteria on title, abstract, and key words Stage three: Application of inclusion and exclusion criteria on full text Stage four: If necessary, the inclusion of articles using a snowballing technique	
Papers identification	Papers selection
Scopus: 424 Google Scholar: 354 EBSCO: 221 Total: 999	After the title, abstract, and keywords review Excluded papers after applying inclusion and exclusion criteria: 923 Selected papers: 76
Papers selection After full-text review Excluded papers after applying inclusion and exclusion criteria: 33 Selected papers using snowballing: 8	
Selected literature: 51 papers	

Source Compiled by the authors

In the following phase, a pilot test was applied to revise the quantity of information; the three stages for data selection were conducted, starting with duplicate elimination, inclusion and exclusion criteria application, and the use of the snowballing technique. Finally, after applying the stages for filtering data, 44 papers were identified. The research resulted in 424 from Scopus, 354 from Google Scholar, and 221 from EBSCO. Finally, following the stages for filtering and selection, 51 papers were used to conduct the systematic literature review.

Results

Bibliographic analysis

VOSviewer software was utilized to develop the bibliographic analysis (van Eck and Waltman 2010). Figure 1 shows the distribution of the papers published by year starting from 1994 to middle 2022.The research into the sustainable development of IWT dated back to 1994; however, a notable surge in publications was observed in 2016. A country-wise citation analysis reveals that Begum, the Netherlands, and China account for the majority of publications, indicating a predominant focus on the development of studies in European countries.

Figure 2 illustrates a bibliographic analysis employing high co-occurrence of key words. Three primary clusters are discernible: the blue cluster pertains to topics related to freight transportation, ships, and inland navigation; the red cluster encompasses subjects associated with sustainable transport, development, and waterway transport; and the green cluster focuses on inland waterway transport. Notably, the prevalence of studies conducted within the European Union is evident in the green cluster.

Finally, Figs. 3 and 4 shows the bibliographic coupling using the citation analysis of the papers and the bibliographic coupling networks of the authors. The last highlights just one cluster with three authors, reflecting the extent to which these authors share citations with each other. The strength of their relationship is directly proportional to the number of publications cited in common, a higher count indicating a stronger connection between them (Perianes-Rodriguez et al. 2016).

Reviewing the concept of "Sustainable Development of IWT"

Although most of the literature on IWT deals with the concept of sustainable development, few papers present a definition in this regard. In most cases, reference is

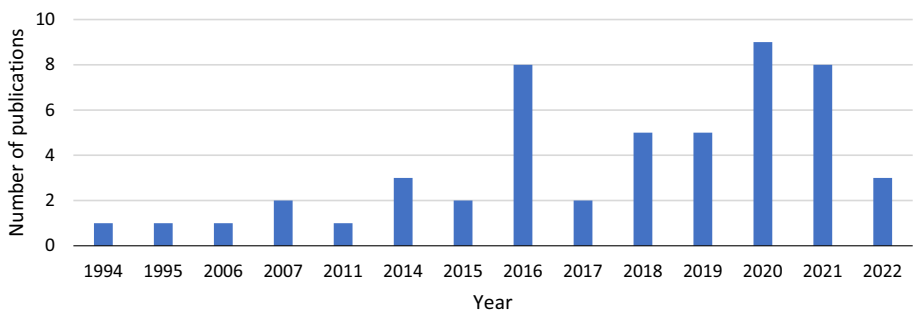

Fig. 1 Number of papers published annually. Source: Drawn by the authors

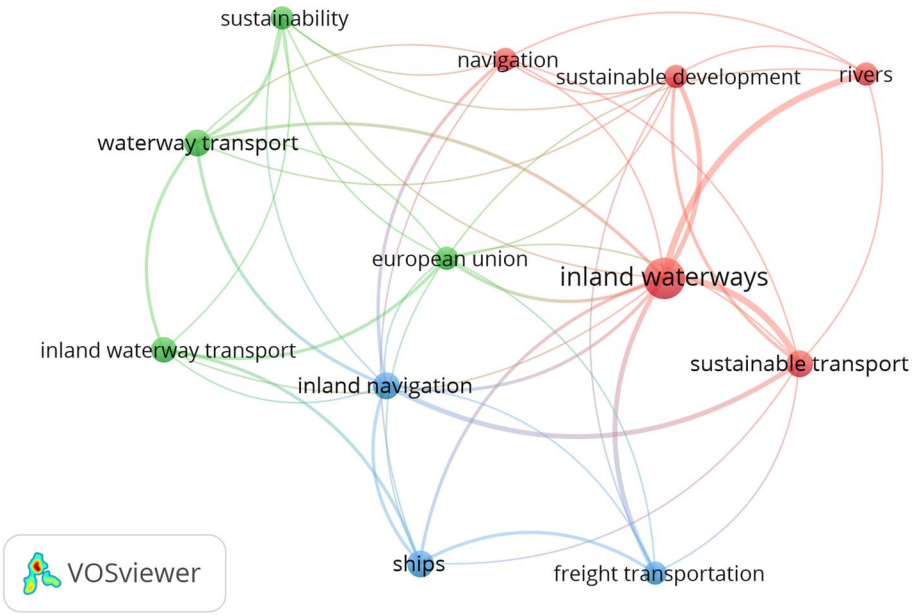

Fig. 2 Co-occurrence analysis of the key words. Source: Map obtained using VOS viewer

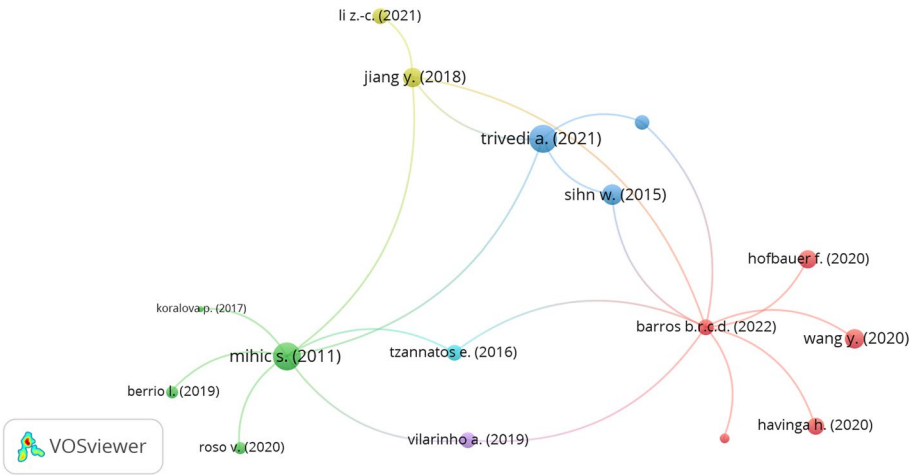

Fig. 3 Citation analysis using the identified papers. Source: Map obtained using VOS viewer

made to the definition proposed by the World Commission on Environment and Development in 1987, which reads Sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland 1987).

On the other hand, Rohács and Simongáti (2007) embrace the definition of sustainable transport following the guidelines of the European Union, which contains three main points, basic access and development needs of individuals, affordable and efficient transportation, and limit emissions and use renewable resources. Recently, Wang et al. (2020) suggested that "Sustainable inland waterways should meet the needs of navigation without compromising the health of riverine ecosystems". Finally,

Fig. 4 Citation analysis using bibliographic coupling networks focused on authors. Source: Map obtained using VOS viewer

Barros et al. (2022) defined sustainable IWT as "the one in which freight increase meets lower environmental and economic costs in waterway developing works and operations, while being resilient to climate change and promoting social equity."

Table 2 Characteristics of sustainable development of IWT

Characteristics of sustainable development of IWT	Literature
Environmental	
Maintenance of river health and protect ecosystems	Sommerauerová et al. (2018), Wang et al. (2020)
Protect ecological functions of watercourses	Havinga et al. (2006), Mihic et al. (2011), Wang et al. (2020)
Preserve biodiversity	Wang et al. (2020)
Riverine nature rehabilitation	Havinga (2020)
Ensure flow regime	Wang et al. (2020)
Design river training works to prevent erosion and avoid dredging operations (if required)	Havinga et al. (2006)
Ecological conservation and restoration	Wang et al. (2020)
Low energy consumption energy efficiency	Mihic et al. (2011), Sommerauerová et al. (2018)
Climate change resilience (flood protection)	Barros et al. (2022), Havinga (2020), Havinga et al. (2006)
Socio-economic	
Encourage education and research	Rohács and Simongáti (2007)
No represent threat to the public health	Sommerauerová et al. (2018)
Guaranty riparian connectivity	Wang et al. (2020)
Clear legislation and policies for the promotion of IWT	Mihic et al. (2011), Rohács and Simongáti (2007)
Appropriate infrastructure and maintenance	Wang et al. (2020)
Poses the ability to move people and goods in an affordable, fairly, and efficient way	Rohács and Simongáti (2007), Wang et al. (2020)
Investment projects to buy or improve fleet for cargo and passenger transport	Mihic et al. (2011), Barros et al. (2022), Mihic et al. (2011)
Preparedness to modal shift from road to IWT	Mihic et al. (2011)
Develop stronger information systems for safety and operations	Barros et al. (2022), Mihic et al. (2011)
Efficient and effective operations on terminals	Wiercx et al. (2019)
Optimization of pre/end haulage activities of IWT	Wiercx et al. (2019)

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Nevertheless, diverse authors have discussed various characteristics to explain the concept of sustainable development of IWT. For the present research, the sustainable development of IWT can be understood as the development of the IWT, which promotes better environmental practices and considers socio-economic aspects, such as those listed in Table 2.

IWT as a transport system

The definitions of systems have been approached from multiple disciplines, and systems have been classified in several ways (by discipline, size, location, and functions, among others); however, the choice is made depending on the purpose of use (Ackoff and Gharajedaghi 1996). Jackson and Keys (1984) defines a system as a group of at least two interrelated elements connected to each other directly or indirectly. From the author's perspective, this definition can be complemented by Ackoff and Gharajedaghi (1996), who defined a system as a "functioning whole that cannot be divided into independent parts." Moreover, systems are characterized according to the way they interact with their surroundings; these can be open, closed, or isolated. In that regard, most human systems are open, given that societies are based on trade and the exchange of goods. Besides, every system possesses a boundary with which it interacts with the environment (Fieguth 2021).

Another important notion proposed by Fieguth (2021) is the concept of *systems of systems*, referring to an interacting collection of systems that are not just a more extensive system. On the other hand, the performance of the systems not only depends on the performance of the parts, but it also falls on the relationships between the elements of the system and its interactions; therefore, the best way to interpret the problems and propose solutions to them is to obtain an interdisciplinary and inclusive perspective using different perspectives and points of view (Ackoff 1994).

Considering the points mentioned above, the authors define IWT as a transportation system that possesses three main elements: first, waterways as the means to develop inland waterway transportation; second, inland fleet or inland waterway vessels; and the third element, which is divided into two categories inland river ports and seaports, as the nodes or links to develop IWT operations (Fig. 5). To that effect,

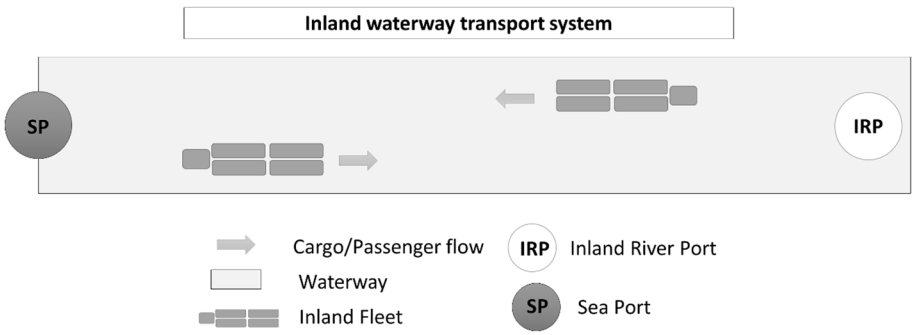

Fig. 5 Physical elements of Inland waterway transport system. Source: Drawn by the authors

IWT can be considered more as a social system as the system and its essential parts possess purposes. Furthermore, IWT acts as a system of systems since it belongs to the transportation system. Moreover, IWT is considered an open system due to its interaction and exchange with the environment and the other transportation systems, mainly road, maritime, and rail transport.

Previous research findings argue that the key elements of the management of IWT are the fleet, inland ports, waterways, and locks (Koralova 2017). Moreover, (Barros et al. 2022) grouped IWT activities into five clusters: development works; operation and maintenance; inland ports, and governance issues. Nevertheless, after analysing and classifying the selected articles, the most relevant topics addressed in the literature are focused on the assessment and understanding of the fleet, ports, and waterways to support the sustainable development of IWT, highlighting the benefits or drivers and the challenges for its development (Table 3). Having as a reference the identified elements of the IWT system, some factors and their characteristics were identified and classified in categories as shown below.

Ports (Inland River ports—Seaports)

Even though the term "Inland Port" has been widely discussed in the literature, Rožić et al. (2016) argue that it refers to those facilities that prolong the activities of seaports. Nevertheless, for this research, the authors will adopt the definition of inland river port proposed by Wiegmans et al. (2015) as "transportation infrastructures along waterways with facilities and equipment for loading and unloading ships." Although there are some differences between the two types of ports, the elements and characteristics described in Table 4 are applicable to both cases, so they will not be presented independently.

First of all, the governance scheme of ports and how policies are implemented are essential factors for the sustainable development of the IWT. Coordinated and independent regimes are part of the differences in governance and administration of each waterway and require in-depth analysis to establish the best practices in each case (Li et al. 2021). In this respect, the selected governance mode has to generate financial frameworks that directly impact the construction or improvement of port infrastructures and docks (Nguyen and Nguyen 2020), as well as the management strategies in terms of planning, construction, maintenance, and disposal of ports (Rožić et al. 2016; van Lier and Macharis 2014).

Table 3 Classification of the approaches found in the literature review

Topic	Articles
Sustainable development of IWT	7
Fleet	6
Ports	5
Waterway	4
Fleet/Port—Fleet/Waterway—Waterway/Fleet/Port	3
Specific case study	7
Others	19
Total	51

Source Compiled by the authors

Table 4 Factors and features of ports

Element	Factors	Features	References
Ports	Governance and Policies	Regulatory frameworks	Li et al. (2021)
		Investments schemes (public and private)	Li et al. (2021)
		Financial frameworks	Nguyen and Nguyen (2020)
	Management	Planning	Rožić et al. (2016)
		Construction, maintenance, and disposal	van Lier and Macharis (2014)
	Operational	Barge handling at ports	Oganesian et al. (2021)
		Port equipment and yard configuration	Wiercx et al. (2019)
	Technology and Innovation	Implementation and optimization of digital applications	Oganesian et al. (2021), Rožić et al. (2016)
	Infrastructure	Improvement of port infrastructure to support IWT	Bu and Nachtmann (2021)
		Facilities and equipment	Rožić et al. (2016)
		Private investment to boost IWT	Bu and Nachtmann (2021)
		Capacity of cargo collection and distribution	Rožić et al. (2016)
		Construction or expansion of inland river ports	Vilarinho et al. (2019)
	Human resources	Skilled labor force	Koralova (2017), Pfoser et al. (2018), Vilarinho et al. (2019)

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On the other hand, optimization of handling activities in IWT terminals and seaports, including the analysis of yard configuration, is necessary to perform optimal operations (e.g., analysis of reach stackers and terminal yard cranes) (Oganesian et al. 2021). Moreover, the uncertainty of barge handling and loss of time in seaports decrease the reliability of IWT (Wiercx et al. 2019). Apart from that, the optimization and implementation of digital applications for data exchange and cargo operations will impact the capacity to plan, direct, and monitors vessel traffic, optimizing cargo reception and storage, especially for container transshipments and transport (Oganesian et al. 2021; Rožić et al. 2016).

For sustainable development of IWT, the assessment of ports infrastructure and equipment to support IWT operations is a priority; this can lead to the construction of intermodal terminals to improve logistics performance or the expansion of main ports in some strategic geographical location, to improve the capacity of cargo collection, distribution, and performance in general (Bu and Nachtmann 2021; Rožić et al. 2016; Vilarinho et al. 2019). Finally, from a human resources perspective, currently, the is a staff shortage in ports and the requirement for a skilled labour force to support IWT operations (Koralova 2017; Pfoser et al. 2018; Vilarinho et al. 2019).

Fleet

IWT fleet is mainly dominated by self-propeller vessels and convoys of barges. The characteristics of the fleet used for IWT vary according to the characteristics of the waterways (Table 5). For example, not all ships that sail on the Rhine can sail on the Danube despite their close geographical location (Mako and Galieriková, 2021). Koralova (2017)

Table 5 Factors and features of Inland Fleet

Element	Factors	Features	References
Fleet	Governance and Policies	Promotion of green technologies	Mako and Galieriková (2021), Perčić et al. (2021)
		Fleet characterization	
	Management	Enforcement of policies and regulations	Awal (2007)
		Harmonization of regulations for vessels between sheered basins	Mako and Galieriková (2021)
		Assessment of external costs (for construction, maintenance, and disposal of the fleet)	van Lier and Macharis (2014)
		Safety (design and regular check)	Maternová et al. (2022)
	Operational	Regular line services	Koralova (2017)
		Optimization of transport routes Improvement of fleet scheduling	Zhu et al. (2021)
	Technology and Innovation	Alternative power systems and alternative fuels	El Gohary et al. (2014), Perčić et al. (2021)
		Vessel design optimization to improve efficiency	Bernardini et al. (2018), Koralova (2017), Sihn et al. (2015)
		Inclusion of autonomous shipping for IWT	Chen et al. (2016)
		Modernization of the fleet	Mihic et al. (2011), Vu (2011)
		Information and communication applications (RIS)	Niedzielski et al. (2021)
	Human resources	Qualified vessels crews Training and certification Working conditions	Koralova (2017), Maternová et al. (2022), Pfoser et al. (2018)

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describes the fleet as an indicator of performance and competitiveness and argues that technical specifications, carry capacity, equipment, safety, and security, are the competitive advantages compared to other transport modes. For that reason, the understanding of the characteristics of the fleet is an essential input for policymakers not only for the development of IWT regulations but to promote green technologies for the IWT fleet.

Although IWT stands out for its low rates of incidents and accidents (Gołębiowski 2016), various authors have conducted analyses focusing on the underlying causes of such incidents and proposed strategies for their mitigation. These analyses have emphasized the importance of rigorous enforcement of policies and regulations governing the inland fleet, alongside the adoption and integration of advanced technologies associated with river information systems as a robust communication network aimed at proactively preventing such occurrences (Awal 2007; Koralova 2017; Niedzielski et al. 2021). Moreover, from a managerial perspective, harmonizing regulations is indispensable in shared basins to ensure the cargo flow and reliability of IWT (Mako and Galieriková 2021; van Lier and Macharis 2014). In addition to the foregoing, other characteristics in terms of establishment of regular line services, optimization of transport routes, and improvement of fleet scheduling are required to improve and strengthen not only the operational performance but the emissions reduction and energy saving (Koralova 2017; Zhu et al. 2021).

Technology and innovation in the inland fleet constitute one of the most important factors for the sustainable development of IWT. These relate mainly to the modernization

of the fleet (Mihic et al. 2011; Vu 2011), the use of alternative fuel and power systems (El Gohary et al. 2014; Perčić et al. 2021), the optimization of vessel design to improve the efficiency (e.g., hull improvement, adaptable draft using ballast tanks, adaptation to serve other industries as car transport) (Bernardini et al. 2018; Koralova 2017; Sihn et al. 2015); the inclusion of autonomous shipping (Chen et al. 2016); and the implementation or improvement of information and communication applications to support crew members choosing adequate speed for fuel optimization and knowledge about waterway meteorological conditions (Niedzielski et al. 2021). Finally, the most important feature when talking about the IWT fleet is the crew members that operate it; this personnel requires appropriate working conditions and the formulation of solid training and certification programs to provide qualified vessel crews, as well as the adaptation or implementation of training directed to the use of new technologies (Koralova 2017; Pfoser et al. 2018).

Waterway

Van Dorsser (2016) defines inland waters as waters not categorized as 'sea'; this definition includes canals, rivers, lakes, and some estuarial waters. Inland waterways systems provide several socio-economic and environmental functions, being the most important: fresh water supply, safety against flooding, and inland waterway transport (van Dorsser 2016; van Vuren et al. 2015). Moreover, other important economic features rely on waterways, such as tourism, agriculture, and industry (Konings and Weigmans 2016). For the purposes of this study, Table 6 shows four waterway factors and the main characteristics identified during the literature review.

Diverse governance models for IWT have been established worldwide. First, a centralized governance model with special administrations for each basin that manages the operational activities and has the responsibility for the infrastructure and the development of IWT. In other cases, local governments are responsible for those activities on behalf of the central government (Jiang et al. 2018). Regardless of the governance models, several regulations and long-term master plans are required to support IWT's sustainable development; moreover, the participation of public and private sectors is indispensable to stimulate a modal shift from road and rail to IWT (Bu and Nachtmann 2021; Chen et al. 2016; Havinga 2020; Malkus et al. 2020; Nguyen and Nguyen 2020; Roso et al. 2020). Other necessary environmental regulations that include integrated ecological strategies, such as emission reduction and implementing subsidies related to environmental sustainability, are a priority (Barros Cavalcante et al. 2020; Mihic et al. 2011; Vilarinho et al. 2019). On the other hand, policies that promote economic incentives and regulate the operational and economic activities of IWT should be addressed, especially in shared basins (Barros Cavalcante et al. 2020; Malkus et al. 2020; Nguyen and Nguyen 2020; Niedzielski et al. 2021; Rohács and Simongáti 2007; Tzannatos et al. 2016).

From a managerial view and due to the multiple functions of waterways, Havinga et al. (2006) argue that "river measures should be designed in such a way that they cause only local effects and do not affect the entire system" This statement is supported by Maksin et al. (2017) since the consequences of these interventions are of great relevance in rivers that share their basin. For this reason, the design of dynamic River management

Table 6 Factors and features of Inland Waterways

Elements	Factors	Features	References
Waterways	Governance and Regulations	Diverse governance models	Jiang et al. (2018)
		Coordinated legislative bodies	Sommerauerová et al. (2018)
		Road maps and long-term master plans with well-defined priorities	Havinga (2020), Havinga et al. (2006), Rohács and Simongáti (2007)
		Policies to promote and support IWT	Roso et al. (2020)
		Public and private sector participation in decision-making	Chen et al. (2016), Nguyen and Nguyen (2020)
		Local and regional policies that stimulate modal shift from road to IWT	Bu and Nachtmann (2021), Malkus et al. (2020)
		Long-term strategies to develop IWT passenger transport	Vu (2011)
		Prioritize or increase the investment in IWT infrastructure	Oulfarsi (2016)
		Integrated ecological strategies	Mihic et al. (2011)
		Environmental policies and legislation emission reduction	Barros Cavalcante et al. (2020), Vilarinho et al. (2019)
		Subsidies related to environmental sustainability efforts	Barros Cavalcante et al. (2020)
		Legislation that guarantees freedom of navigation (e.g., European Union)	Niedzielski et al. (2021)
		Clear taxation systems and procedures (particularly in shared basins)	Malkus et al. (2020), Rohács and Simongáti (2007)
		Compensations for stoppage	Niedzielski et al. (2021)
		Regulations for the operational management	Nguyen and Nguyen (2020)
		Economic incentives to support technical and operational investments	Tzannatos et al. (2016)
	Management	Dynamic river management	Havinga (2020)
		Adaptative management-based strategies	Barros Cavalcante et al. (2020)
		Strategical transnational planning for sustainable development of shared basins	Maksin et al. (2017)
		Stakeholder identification and participation in preparation and implementation programs	Havinga (2020), Roso et al. (2020)
		Mental shift to support modal shift	Roso et al. (2020)
		Administrative and institutional systems to support IWT	Mihic et al. (2011)
		Standardized management for shared basins	Mako and Galieriková (2021)
		Transnational cooperation for shared basins	Pfoser et al. (2018)
		Clear of institutional structure	Nguyen and Nguyen (2020)
		Clear border controls requirements	Pfoser et al. (2018)
		Established charges and fees	Pfoser et al. (2018)
	Operational	Connectivity and interoperability among various waterways, industrial centers connected with other transport means	Koralova (2017), Mako and Galieriková (2021), Sidaway et al. (1995), Vilarinho et al. (2019)
		Environmental factors (wind, current, waves, ice formation)	Chen et al. (2016), Koralova (2017)
		River Information Services (RIS) to harmonize information	Koralova (2017), Mihic et al. (2011)

Table 6 (continued)

Elements	Factors	Features	References
		RIS for traffic and transport services	Koralova (2017), Maternová et al. (2022), Mihic et al. (2011), Niedzielski et al. (2021)
	Infrastructure	Infrastructure development and improvement (Navigable waterways with sufficient depth, locks, and bridges)	Bu and Nachtmann (2021), Chen et al. (2016)
		Investment and improvement (traffic channels, signal buoys, bridges, and well-connected ports)	Nguyen and Nguyen (2020)
		Optimal maintenance programs	Havinga (2020), Havinga et al. (2006)
		Sustainable river training	Havinga (2020), Havinga et al. (2006)
		Quality infrastructure	Sommerauerová et al. (2018)
		Maintenance of waterways	Mihic et al. (2011)
		Strategies for investment and financing infrastructure (e.g., implementation of PPP)	Miloslavskaya and Plotnikova (2018)
		Develop waterway infrastructure to improve connectivity between strategic regions (e.g., Czech Republic and Germany)	Cempírek and Čejka (2017)
		Improve waterway network and connectivity with other transport modes	Mako and Galieriková (2021), Nguyen and Nguyen (2020), Sidaway et al. (1995)
		Integration between transport modes	Vilarinho et al. (2019)
		Financial frameworks	Nguyen and Nguyen (2020)

Source Compiled by the authors

and adaptative management-based strategies will protect the ecological functions of the waterway and promote transnational cooperation for shared basins (Barros Cavalcante et al. 2020; Havinga 2020; Mako and Galieriková, 2021; Pfoser et al. 2018).

On the other hand, infrastructure is essential for developing any means of transport. For IWT is critical the improvement of navigable waterways with sufficient depth, traffic channels, signal buoys, bridges, locks, bridges and well-connected ports (Bu and Nachtmann 2021; Chen et al. 2016; Nguyen and Nguyen 2020). Moreover, implementing optimal maintenance programs that possess integrated solutions and creating long-term master plans to ensure navigation and other functions of the systems, such as fresh water supply, flood protection, and agriculture, among others (Havinga 2020; Havinga et al. 2006). Additionally, improvement and maintenance of IWT infrastructure to meet the current transport requirements entail programs that consider sustainable river training, which should include sediment management to avoid degradation of the bed of the basin and the water levels, and structural measures such as fixed layers, groyne adaptations, bendway weirs, bottom vanes, since dredging is not a sustainable solution over time (Chen et al. 2016; Havinga 2020; Havinga et al. 2006).

Finance challenges for IWT infrastructure have been reported since the mid-eighteenth century (Sidaway et al. 1995). Since then, there is necessary to create financial frameworks and identify strategies for investment, such as public private parentships (PPP) with the participation of private and public stakeholders (Jiang et al. 2018; Miloslavskaya and Plotnikova 2018; Nguyen and Nguyen 2020). These strategies

should include waterways maintenance funds and capital investment for infrastructure construction (Nguyen and Nguyen 2020). Considering that the development of waterway infrastructure will improve connectivity between urban areas and strategic regions that can serve as logistics centres and help maintain connections with other transportation modes (Cempírek and Čejka 2017; Sidaway et al. 1995; Vilarinho et al. 2019).

Drivers for sustainable development of inland waterway transport system

IWT represents one of the most important strategies to achieve sustainable development in hinterland transportation for its ability to meet massive demand and improve economic and environmental performance (Oulfarsi 2016). In fact, the European Union has recognized the importance of waterborne transport as a critical factor for developing sustainable transportation (Rodseth et al. 2020). Moreover, IWT provides solutions for economic development, population growth, and climate change (Wang et al. 2020). Added to this, modal shift and intramodality are one of the four targets identified by seaports to improve their environmental performance; although this goal has been set mainly in Europe, North America, and Asia, for Middle East, African, and South American ports, it has been less prioritized (Gonzalez Aregall et al. 2018).

Benefits of IWT act as drivers for IWT development (Roso et al. 2020). For the purpose of this research, drivers are defined as the characteristics or activities that incentive or generate some benefit in one or more of the three pillars of sustainable development (social, economic, and environmental).

Environmental drivers

Currently, the hinterland transport sector consumes a large amount of energy; however, when comparing the different modes, IWT is the one that performs the best (Rohács and Simongáti 2007). The oldest paper that described IWT as a sustainable transportation system was published by Blonk (1994), and described IWT as an energy and environmentally-friendly transport mode due to its low levels of pollution and noise and highlights its exemplary record in terms of safety.

Emissions have a relevant impact on global warming, climate change, acidification, human and ecosystem toxicity, and eutrophication (Tzannatos et al. 2016). Among all modes of internal transport, IWT is considered the most environmentally friendly due to its performance in terms of CO_2 release (Jonkeren et al. 2019). In fact, measurements of greenhouse gas emissions for IWT are approximately 40% lower than road transport (Hofbauer and Putz 2020). Moreover, a river convoy generates four times less CO_2 and emits 2.6 times fewer greenhouse emissions than road transport (Oulfarsi 2016).

Another essential matter is that IWT consumes less fuel per ton-kilometre than trucks (Rohács and Simongáti 2007); indeed, diesel consumption of IWT is lower than road and rail transportation (Gołębiowski 2016). In that sense, energy consumption is about 75% less than road; besides, noise pollution and land use are lower compared with other hinterland transportation modes (Gołębiowski 2016; Mihic et al. 2011). Tzannatos et al. (2016) calculated the number of vehicles required to transport 2000 tons in all available means of transport; the results showed that the use of 77 trucks, 16 train wagons, and

only two ships or barges would be required. For that matter, Roso et al. (2020) argue that a barge can replace between 70 and 80 trucks that travel to the same place. Demonstrating the advantages of IWT in terms of energy efficiency that is not only reflected in the reduction of fuel costs but also in the environmental performance.

Several authors emphasize the potential of waterborne to reduce pollution and road congestion due to its high carry capacity per vessel unit and the availability to transport oversize and large volumes of cargo rod (Koralova 2017; Rodseth et al. 2020). However, when comparing transportation speed, IWT is the slowest hinterland transport mode; therefore, it is mainly attractive for the transport of non-perishable products (Barros et al. 2022), including construction materials, agricultural raw materials, petroleum products, coal, and in some cases, such as in northern Europe (the Netherlands, Belgium, and Germany) container cargo (Gołębiowski 2016; Rogerson et al. 2019; Sidaway et al. 1995). Furthermore, the improvement and optimization of inland vessels could improve efficiency and provide several environmental and economic benefits (Bernardini et al. 2018).

Finally, the adoption of greener solutions, such as promoting the use of renewable energies instead of fossil fuels (for cranes, fleets, and other port requirements), added to water management plans that take into consideration ecological conditions should be a priority among policymakers worldwide (Woś et al. 2022).

Economic drivers

Countries near the Flow of the rivers have demonstrated economic growth over time (Mihic et al. 2011). Commercial benefits of IWT have been reported since 1995, Sidaway et al. (1995) underline the advantages related to low-cost transportation of heavy and bulk goods, when speed is less relevant than materials flow, exist appropriate loading and unloading facilities, and there are safety procedures to handle of large volumes. Moreover, according to Gołębiowski (2016), external costs related to IWT are 19 euros less per 1000 ton-km compared to road. In fact, in Poland, Woś et al. (2022) assessed different means of transportation, and the cost–benefit analysis concluded that waterways base model investment is profitable using the Vistula River and stands out savings in costs related to cargo, accidents, congestion, pollution, emissions, among others.

Several economic activities could be improved or implemented along with IWT development as tourism, hydroelectric production, or the inclusion of new trades (Woś et al. 2022). For instance, Sihn et al. (2015) assess the automotive industry in order to distribute cars via IWT from the production plants to the distribution centres due to the facilities and easy access to inland waterways and the increasing industry of car manufacturing. On the other hand, Mommens et al. (2014) argue that using intermodal transport for palletized goods in Brussels-Capital Region has economic potential and can be successfully transported by barges.

There are multiple benefits in terms of increased capacity and productivity of ports, road congestion reduction, rural and regional development, and improved environment (Roso et al. 2020). Furthermore, from the cost reduction perspective, IWT is the cheapest transport mode and generates less external costs in comparison with the road (Cempírek and Čejka 2017; Gołębiowski 2016; Maternová et al. 2022; Mihic et al. 2011). Moreover, saving costs related to flood losses (agriculture), accidents, pollution, climate

change, noise, congestion, and transport costs, represent an economic advantage of IWT development (Woś et al. 2022).

Projections about infrastructure investments predict that the return on investment takes a little longer until the threshold is reached due to the geographical, economic, and political conditions of each basin that require different levels of capital spending (Rohács and Simongáti 2007). In that sense, establishing strategies to attract new freight flows, key stakeholders' participation, and subsidy implementation are required to promote and incentivize modal shifts. In that regard, trust and confidence in local authorities are required, and companies appreciate the support and the strategies to reduce the tensions when there is an intention to invest in IWT (Roso et al. 2020).

Social drivers

IWT supports rural development and is relevant to passenger transport, especially in regions where road access is almost nil (Awal 2007; Berrio et al. 2019; Vu 2011). In addition to that, IWT impacts the well-being of the citizens due to the increase in goods transportation and the positive effects of flood stabilization (Woś et al. 2022). Indeed, improving IWT could be a solution for isolating remote rural areas due to the support in access to basic needs such as education, health care, and governmental services (Vu 2011).

In some countries in Asia (China, Cambodia, India, Indonesia, Thailand, and Vietnam), IWT plays an essential role in the economic development and welfare of people in rural areas; moreover, it can alleviate costs related to congestion, reduce accidents and noise and increase accessibility to global markets (Knapčíková and Kaščák, 2019; Vu 2011). Some authors, based on literature and statistics, recognize IWT as one of the safest means of transport due to its low number of fatalities or injuries (Koralova 2017; Rohács and Simongáti 2007). Besides, IWT can contribute to diminishing road congestion which is one of the major issues related to hinterland transportation, constituting one of the predetermining aspects for modal shift since congestion generates inconveniences that impact on the reliability of land transport modes (Roso et al. 2020).

Discussion

Although all the literature reviewed in this research contains information related to sustainability or sustainable development of the IWT, of the 51 reviewed papers, only three propose a definition as shown in Section 3.1. However, these three definitions are broad and do not describe the specific features that should be developed or carried out when it comes to the sustainable development of the IWT. In this sense, this paper presents a list of characteristics that serve as a guide for the implementation of sustainable IWT systems. Nevertheless, given the varying characteristics or geographic, social and political diversity of each region, it is necessary to analyse the specific conditions of each basin in order to adapt the definition to each circumstance, understanding that sustainability or sustainable development are not static elements with an immovable specific purpose, but rather it requires flexible plans that adapt not only to the needs of each region, but to the new technologies and social requirements that they entail.

On the other hand, when referring to the sustainable development of IWT, it is imperative to consider the vital roles that waterways play within society. These roles

encompass not only the provision of water for human consumption but also encompass activities such as fishing and agriculture. Furthermore, waterways serve as a source for hydroelectric power generation in certain regions across the globe. In this context, the sustainable advancement of IWT must align harmoniously with strategies that aim to preserve the multifaceted functions of rivers, thus striving for equilibrium between economic and social development and the conservation of natural resources. It is at this juncture where the comprehension of the elements and attributes inherent to IWT systems becomes pivotal. Such comprehension forms the foundation for comprehending a system that demands adapted strategies and solutions for its development.

Few authors have addressed the measurement of sustainability or sustainable development of IWT. In some cases, reference is made to recommendations proposed by international institutions or organizations. For example, the European Union recommended measuring external costs to measure the environmental sustainability of transportation (Bu and Nachtmann 2021). Furthermore, Sommerauerová et al. (2018) argue that EUROSTAT possesses two indicators to measure sustainable development in the transport sector; the first one, and not applicable for the purposes of this research, is the share of collective transport modes, and the second measurement the share of rail and IWT in total inland freight. On the other hand, Rohács and Simongáti (2007) proposed a list of indicators to measure sustainable transport and grouped it among economic, environmental, and social indicators; these indicators are very general but could be adapted particularly for IWT. Particularly for IWT, Maksin et al. (2017) suggest the assessment of planning solutions for IWT and propose some activities and measures. Moreover, Wang et al. (2020) assessed the performance of the longest basins in the world using some indexes related to consistency, exploitation ratio, ecological pressure, and eco-efficiency, suggesting a balance between the economic growth and the ecological health of the basins.

Congestion problems and environmental damage caused by transport have been reported since 1994 and continue increasing (Blonk 1994). In the same vein, the demand for transportation has increased and is expected to continue with this trend. Therefore, the implementation of sustainable practices for transportation development has increased, and IWT is seen as an alternative to meet the demand for transportation and its sustainable development (Chen et al. 2016). Notwithstanding the numerous advantages and drivers mentioned in the literature regarding the use of IWT worldwide. These advantages refer mainly to the reduction of emissions and pollution, either thanks to the optimization of the use of fuels, the implementation of new technologies on board ships, or the development of alternatives to replace fossil fuels. Although one of the most significant disadvantages of the IWT is its slow speed, which would denote an inability to operate in short distances, Gołębiowski (2016) states that due to the high congestion in the areas near the ports, the profitability of the IWT in terms of distance has decreased from 350 to 400 to 60 km. This shows that although the development of the IWT has been slower compared to other means of transport, every day, it gains relevance among policymakers and stakeholders involved in the IWT system.

Even though there are several alternatives proposed in the literature to optimize and promote the use of the IWT to achieve a modal shift from road and rail in specific cargo categories, today, some issues need to be solved or improved. For instance, alternative

power systems for inland waterway vessels are scarce, and shipping emission decarbonization has been focused on seagoing vessels (Perčić et al. 2021). In fact, in Croatia, the inclusion of electric road transport has been encouraged, but shipowners have not received this kind of incentive (Perčić et al. 2021). While El Gohary et al. (2014) propose using hydrogen for IWT vessels; however, several economic considerations must be considered given the high investment costs required for its use. Additionally, other measures, such as the imposition of strict regulations around meeting sustainable environmental goals and the remotion of fossil fuel subsidies in the European Union with the aim of incentivizing energy-efficient technologies, could incentivize the modal shift to IWT (Perčić et al. 2021; Roso et al. 2020).

Currently, IWT infrastructure is aging since it has not been prioritized as a strategic matter, while the road transport infrastructure has been strengthened (Vilarinho et al. 2019). In general, the distribution of public spending between different transport means is usually unequal; Oulfarsi (2016) argues that French infrastructure investment was 66% to road transportation while 1% to IWT. One of the most relevant problems to developing IWT is the lack of financing for infrastructure, Miloslavskaya and Plotnikova (2018) suggest the implementation of public private partnerships and user fees to meet the requirements of the state, industry, and society.

On the other hand, Trivedi et al. (2021) argue that IWT poses numerous challenges to its implementation, being the lack of governance and policy the most critical barrier to developing IWT in India due to its inhibiting impact on other factors such as infrastructure improvements and the participation of the private sector because of the high costs associated with this type of transport. Finally, there is a need for available information and research to understand not only the unique hydrological characteristics of each basin but its commercial and infrastructure, and managerial requirements to support modal shift and policymakers' decisions to develop sustainable IWT systems (Berrio et al. 2019; Vilarinho et al. 2019).

Conclusion

Although some authors have addressed the definition of sustainability or sustainable development of the IWT, this study presents a more comprehensive perspective that encompasses the essential characteristics necessary for the for sustainable development of IWT systems. Additionally, it has enabled us to delineate IWT as a system comprising three fundamental components: waterways, inland fleets, and ports (comprising inland river ports and seaports). These components interact cohesively, facilitating the continuous flow of cargo and passengers. Moreover, this research has identified five factors relevant to each of these elements, all possessing distinct characteristics that, in accordance with their performance, foster the optimal development of IWT within a specific region. Furthermore, this study contributed by pinpointing the primary drivers for the sustainable development of IWT, highlighting the key environmental, social, and economic benefits linked to its potential to mitigate air and noise pollution, alleviate congestion, reduce costs, and promote rural development and well-being.

The predominant geographic focus of the studies incorporated within this review are centered on Europe and Asia. Only two articles within the study touched upon certain facets of Latin America, notwithstanding the extensive presence of waterways in the

region. Considering this geographic bias, prudence is warranted when contemplating the generalizability of the findings derived from this review. In view of the above, while numerous characteristics and drivers for the sustainable development of the IWT sector can be broadly conceptualized, it is imperative to conduct a comprehensive analysis specific to each basin. Such an analysis must consider various factors, including but not limited to geographical, environmental, social, economic, and infrastructural considerations. This multifaceted examination will facilitate the understanding of the primary challenges and barriers within each unique context, as well as the identification of viable solutions and alternatives. These insights are crucial for the formulation and implementation of policies aimed at fostering, promoting, and allocating resources towards the sustainable development of the IWT.

Future studies should consider the involvement of stakeholders and the benefits arising from their active engagement in the decision-making process. These studies should also examine investment strategies and incentives geared towards sustainable development, with a primary focus on both social and environmental impacts. Additionally, there is a need to explore business strategies to ensure that projects remain economically viable and do not incur financial insolvency. Furthermore, it is relevant to conduct a thorough evaluation of the primary barriers and potential solutions in the context of sustainable IWT development, tailored to the unique characteristics of each waterway. This approach enables the formulation of strategies that take into consideration geographical disparities, environmental considerations, cultural diversity, and the safeguarding of water resources, which serve a multitude of vital functions for ecosystems and society. Finally, it is imperative to comprehend IWT systems in regions beyond Europe and China, as these regions possess significant potential that is presently undervalued.

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NC IB FB designed the methodological approach. NC conducted research collecting and analysing data. All authors read and approved the final manuscript.

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