A Comprehensive Systematic Overview of Canadian Hydrogen Supply Chains Downstream

Farzam Farahmand¹, James King¹, Davoud Ghaheeranlou¹, Priya Sakthi² & Mohammad Reza Moghadas Jafari³

¹ Faculty of Business Administration, Memorial University of Newfoundland, Canada
² Faculty of Engineering and Applied Science, Memorial University of Newfoundland, Canada
³ Faculty of Science, Memorial University of Newfoundland, Canada

Correspondence: Farzam Farahmand, Faculty of Business Administration, Memorial University of Newfoundland, Canada. Tel: 1-709-864-2615. E-mail: farzamf@mun.ca

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Abstract
This paper investigates Canada's endeavor for carbon neutrality by 2050 and its strategic response to the European energy crisis resulting from the Russia-Ukraine war. With a significant potential for hydrogen production, Canada's hydrogen exports to Europe are poised to reshape its hydrogen supply chains downstream (HSCD). Through a systematic review of 39 papers published before October 2023, our examination explores HSCD components, decision levels, and sustainability perspectives. Consequently, we offer recommendations for scientific, legislative, and industrial sectors for forward horizons. Additionally, this study proposes future research avenues for similar systematic review papers.

Keywords: hydrogen supply chain, downstream, decision levels, sustainability, systematic review, Canada.

1. Introduction
Supply chain management has taken center stage in this era where businesses must integrate all operations from raw materials to end user to take advantage of every opportunity for staying competitive. Among the supply chains it is vital to study energy supply chains, the backbone of contemporary civilization, as it supports economic activity, technical developments, as well as the general well-being of civilizations. Hydrogen as an ecofriendly renewable energy carrier is gaining increasing attention, as nations, including Canada, are working to meet environmental targets, leading to the formation of Hydrogen Supply Chains (HSCs). Additionally, efforts for development of HSCs have drastically escalated since the initiation of the Russia-Ukraine war (Steffen and Patt, 2022). Canada has been recognized as a reliable source of supplying hydrogen to Europe due to its natural resources, while satisfying its global environmental commitments, please see Dolata (2022). Europe as a new customer will radically change the downstream of the Canadian HSCs. Furthermore, Gordon et al. (2023b) emphasize the significance of addressing HSC downstream challenges, e.g., pipeline repurposing, for expansion of HSCs. Thus, investigation into Canada’s HSC downstream forms the essence of this paper.

To satisfy the goal of this research, and maintaining the consistency in our systematic analysis, we introduce the framework of this study through which we examine the former review papers regarding the downstream HSCs in Section 2. Then, Section 3 presents the methodology for compiling relevant literature. In Section 4 the same framework is utilized again to synthesize the selected body of knowledge and discuss the existing gaps. Accordingly, we offer recommendations for scholars, regulators, and corporations in Section 5. Finally, we conclude the paper in Section 6.

2. Framework and Prior Review Studies
To highlight the significance of this paper, we comprehensively examine previous systematic review works relevant to the Hydrogen Supply Chain Downstream (HSCD). To that end, we first establish a framework to minimize bias in our analysis, i.e., HSCD components, HSCD decision levels and research characteristics, sustainability and geographical domain in the following three Subsections 2.1, 2.2, and 2.3, respectively; this framework is a customization of the one used by Sahebi et al. (2014) for oil supply chains, due to the similarity of both oil and hydrogen supply chain downstreams. Furthermore, providing the framework first improves the paper’s streamlining. Each of the subsections offers their contents in two sequences: (i) developing a solid ground for evaluation, and (ii)
studying the relevant review papers, published from the onset of the Russia-Ukraine conflict, February 2022 to October 2023, changing the global energy supply chain (International Energy Agency, 2023). This section will be devoted to our investigation of the 43 pertinent review papers that we found.

2.1 Hydrogen Supply Chain Downstream (HSCD) Components

Figure 1 shows the structure for the HSCD components. In this figure, there are letters written in bold, mainly in parentheses, representing the code we considered for the corresponding term, e.g., (TP) stands for Transportation. The reason for coding the terms is keeping the analysis manageable considering number of aspects we investigate. We employ the same convention throughout of this study, e.g., Table 1, to enhance readability.

The HSCD, colored in dark pink, consists of four main components shown in blue, from left to right: transportation, storage, distribution, and end user, which follows Riera et al. (2023). Each component has different subcomponents, represented in green color. Transportation can take place through pipeline (PL), truck (TRK), vessel (VSL), and rail (RL), reflecting the categorization of Oh et al. (2023). The next component from left is storage (ST), which includes physical (PS), chemical (CH), and techniques (T), mirroring Zhang et al. (2023). Descending through the breakdown, physical encompasses gaseous hydrogen ($GH_2$), liquid hydrogen ($LH_2$), and a combination of both ($GH_2 + LH_2$), replicating Noh et al. (2023). Likewise, chemical has two subcategories: liquid (LI) and solid (SO), colored in yellow, where liquid includes $NH_3$ (ammonia), $CHO$ (methanol), $MCH$ (methylcyclohexane), and $HDBT$ (perhydro-dibenzyltoluene) which are colored light pink, and solid includes $MgH_2$ and Others (OTH), i.e., dodecahydro-N-ethylcarbazole and dibenzylmethane, which are colored in light pink as well, echoing Hampp et al. (2023). In a similar vein, storage techniques (T) are tank (TA), cylinder (CY), and salt caverns (SC) based on Vishal et al. (2023). These products are distribution (DIS) by pipeline (PL) and truck (TRK) (Vijayakumar et al., 2023). Yue et al. (2021) conclude transportation (TP), industries (ID), and residential (RE) as end user (EU) for hydrogen.

Figure 1. Structure and codes for the HSCD components
Table 1 demonstrates how the 43 former systematic review papers, rows #1 to 43, address various components of the HSCD, explained in Figure 1. According to the table, none of the papers has investigated all the components of HSCD (no row has × sign under all the columns). Furthermore, none of the criteria has been studied by over 75% of the review papers, please see the row before the last, including the percentages. However, this paper addresses all existing research gaps regarding HSCD components, please see the last row of the table.

To use hydrogen fuel in a wide range of industrial applications, it is imperative to discover an appropriate method of transportation for hydrogen. To that end, understanding the chemical properties of hydrogen is crucial to prevent explosions and leaks. Furthermore, hydrogen exists in many states based on temperature and pressure, which adds additional constraint for selecting the transportation means (Faye et al., 2022). Table 1 illustrates pipeline, trucks, and vessels have been studied by 53%, 56%, and 51% of the papers, while the study of rail transportation has been incorporated in only 29% of the papers. All of these options should be well studied since Canada is second largest country in the world and has 840,000 kilometers of pipelines Natural Resources Canada (2023), over 30 million kilometers of heavy truck roads (Transport Canada, 2021b), over 550 ports (Chircop, 2023), and over 46,000 kilometers of railway tracks (Streiner, 2019). Similar rationale holds for distribution within a short distance, for which pipeline and trucks are used and these have been studied by 66% and 56% of the papers.

Transportation of gaseous hydrogen over a long distance is challenging due to its chemical properties, e.g., high reactivity (Hampp et al., 2023). Therefore, other forms of hydrogen (e.g., the liquid and solid forms in Table 1) like ammonia (NH₃) are recognized as more promising options for transportation (Cui and Aziz, 2023), which explains why LH₂, NH₃, and CH₃OH, with higher energy density, have been studied by 54%, 60%, and 54% of the review papers, respectively. On the other hand, GH₂, GH₂ + LH₂, MCH, H₁₈DBT, and MgH₂ have been considered in a minimum number of studies; however, GH₂ has quick charge and discharge rates, making it simpler to industrialize. Stable liquids with significant storage capacities, i.e., MCH and H₁₈DBT, are appropriate for long range transportation. MgH₂ is often employed in lab research because of its great volumetric storage capacity and safety (Chu et al., 2023).

Likewise, chemical properties of hydrogen impacts its storage. Tanks are studied by 73% of the reviewed papers; however, this number is due to tanks being an umbrella term for various types of tanks used for hydrogen transportation; for example, compressed H storage systems use pressurized cylinders to store GH₂. In contrast, cryogenic tanks are used in liquid hydrogen storage systems to hold hydrogen in a liquid form. Lastly, solid materials that can absorb and release hydrogen reversibly are used in metal hybrid storage systems, making them ideal for solid hydrogen storage (Qureshi et al., 2023). Cylinders and salt caverns have been investigated by 53% and 47% of the papers; however, a proven method for storing compressed hydrogen gas is cylinders. With entirely composite containers, they may attain high gravimetric density and handle a range of pressure. They may be used in fixed, on-board, and ground transportation applications because of their versatility (Yang et al., 2023). Furthermore, because salt caves have self-healing capabilities and little permeability they are advantageous for storing hydrogen. They are easy to mine and monitor, sustain high flow rates, and need less cushion gas. They are an easily accessible resource due to their abundance in nature (Abreu et al., 2023). According to Hui et al. (2023), Ontario’s geological features make it a province with substantial potential for salt cavern storage.

Hydrogen can be used as energy for transportation, industries, and in residential use. 73% of the review papers have studied the application of hydrogen in industries, e.g., oil and gas. However, transportation and residential use have been studied by 67% and 33% of the review papers. Between 2005 and 2018, greenhouse gas emissions from road transportation have grown 19% in Canada (Transport Canada, 2021a). Furthermore, Canada is one of the coldest countries in the world (Health Canada, 2019). Therefore, it is crucial to utilize hydrogen as a renewable source of energy for transportation and residential use, considering Canada’s global environmental commitments to net zero emissions by 2050 (Government of Canada, 2020).

2.2 HSCD Decision Levels and Research Characteristics

Figure 2 illustrates the HSCD decision levels with same coloring convention we used in the former section. The HSCD decision levels, colored in dark pink, is divided into three components: strategic, tactical, and operational, shown in blue (Azadnia et al., 2023). To highlight the significance of strategic decisions in supply chains, we placed it in the center of figure. To develop the branches in the figure, we have projected the frameworks of Alizadeh and Karimi (2023) and Sahebi et al. (2014) regarding oil supply chain on the framework in Li et al. (2019) focused to HSCs.
Table 1. Analysis of relevant systematic review papers (published from February 2022 to October 2023) from HSC components dimension

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<td>At the Tactical level (TCL) of the HSCD decisions regarding project planning (PJP), production planning (POP), inventory management (INM), and distribution (DIS) are considered. More longer term, and often financially</td>
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heavier decisions focus on investment (INV), facility location (FLC), capacity selection (CSC), facility allocation (FAL), capacity expansion (CAE), capacity reduction (CAR), technology selection (TES), technology upgrading (TEU), technology downgrading (TED), and outsourcing (OUT). The INV decisions affect storage (ST), transportation (TP), distribution (DIS), and end user (EU), which here means building/purchasing refueling stations. The FLC decisions address the location for refueling stations (EU), transportation (TP), and storage (ST). The best places for facilities are chosen to provide a smooth flow of hydrogen by minimizing transportation costs, streamlining distribution networks, and increasing end-user accessibility (Kumar et al., 2023). The next are CSC decisions, which involves choosing the best capacities for ST, TP, DIS, and EU. The FAL is the next group of decisions. The allocation of resources to ST, TP, and EU is managed under the FAL. Strategies for capacity expansion, or CAE, entails the deliberate addition of capacity in the ST, TP, DIS, and EU segments. These choices involve making capital-intensive strategic decisions that will affect the supply chain’s performance over the long run (Oliveira et al., 2013). The subcategory of capacity reduction (CAR) involves the strategic determination of capacity reductions in the following areas: DIS, ST, TP, and EU. Demand variations, operational effectiveness, and cost optimization are factors that impact these choices, making it possible to distribute resources wisely and minimize unnecessary capabilities sensibly, thereby eliminating surplus capacity. Strategic decisions about the use of technologies for ST, TP, DIS, and EU are made under TES. These decisions, which are influenced by market preferences, environmental concerns, and technology breakthroughs, keep the supply chain at the forefront of innovation and sustainability. Strategic choices are made regarding TEU to improve the technologies that are currently being used in ST, TP, DIS, and EU. Strategic choices to downgrade technologies in the ST, TP, DIS, and EU sectors may need to be made in order to preserve operational efficiency for a variety of reasons, including cost-effectiveness, market demands, or the need to switch to more sustainable alternatives. Finally, the strategic level of outsourcing decisions (OUT) includes the thoughtful choice of outside partners and service providers for specific aspects of the operation.

Figure 2. HSCD decision levels and codes
Figure 3 outlines a range of research characteristics used in the HSCD: research approach (RAP) and uncertain features (UCF), shown in blue. The foundation of the RAP includes mathematical modelling (MMM), optimization (OPT), and others (OTH), i.e., qualitative and quantitative approaches. The UCF is further detailed into deterministic (DET) and non-deterministic (NDT) elements to cover all the factors in HSCD. The NDT breaks down into four sections, ST, TP, DIS, and EU. This classification is based on Li et al. (2019).

Table 2 compares this work to pertinent systematic review studies published since February 2022 from the viewpoints of research characteristics and decision levels. None of the decision levels are studied by more than 70% of the papers. Investment decisions are pivotal to HSCD, however, Table 2 displays disparities in this category: ST (49%), TP (38%), DIS (33%), and EU (31%) considerations. The feasibility of HSCD depends on investments made across these components. A strong infrastructure, a smooth supply chain, and the broad adoption of hydrogen technologies all depend on adequate finance and the planned deployment of resources. One major obstacle to making well-informed decisions and accelerating the shift to hydrogen-based energy is the paucity of thorough research in these areas (Gordon et al., 2023a).

There has not been considerable study completed about location of facilities, only 33% in storage, 20% in transportation, and 24% end user. Determining the best sites for facilities is essential for cutting costs, minimizing transit distances, and guaranteeing prompt access to hydrogen; nevertheless, these fac- tors are notably absent from the literature assessment (Sgarbossa et al., 2023). Furthermore, decisions regarding capacity show inequalities in the following areas: end user capabilities (16%), distribution (13%), transportation (24%), and storage (53%). One reason for disregarding end user capacity and distribution might be the difficulty in forecasting future needs. However, ignoring these factors might lead to less-than-ideal capacity planning, which would impede the smooth integration of hydrogen. Additionally, optimizing the HSCD requires making judgements on FAL, including storage, transportation, and refueling station facilities. Nonetheless, there are gaps in the study of this field particularly when it comes to refueling stations (13%). The effective integration of hydrogen into diverse applications is impeded by appropriate localized facility allocation.

Making decisions on capacity expansion (CAE) for ST, TP, DIS, EU is essential to meet rising demand. However, there are still research shortages, particularly in the areas of distribution (13%) and end user capacity (11%). On the other hand, although it is sometimes ignored, capacity reduction is essential for guaranteeing economic sustainability. However, this feature receives little, if any, attention in the literature that is currently available. Furthermore, although there is a significant focus on initial technology selection, particularly in the areas of storage (56%) and transportation (51%), refueling station technology exploration results reflect a 20% research focus. This basic lack of knowledge regarding refueling station technology choices is impeding the smooth integration of hydrogen applications across many sectors. Moreover, there is a clear lack of study on technology upgrading, especially with regard to refueling station technologies (4%). This disparity is a result of the industry’s inability to keep up with the quick speed of innovations, which hinders the adoption of creative solutions and reduces the efficiency benefits that may be attained through technological improvements. Conversely, decisions on technology downgrade, which are essential for retiring obsolete technologies, are remarkably understudied, as seen by the scant attention they receive in all industries. Comprehending the technology downgrade process is essential for facilitating a seamless shift to more effective substitutes. Finally, outsourcing received just 2% of the attention in the current literature. Making judgements on outsourcing is essential for assuring specialized knowledge, cutting expenses, and simplifying processes (Lahiri, 2016).
Table 2. Analysis of relevant systematic review papers (published from February 2022 to October 2023) from decision level and research characteristics dimension

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Notes: X indicates presence; O indicates absence.
Differences may be seen in the tactical choices that are crucial to HSCD operations, PJP (18%), POP (27%), INM (18%), and DIS (31%). Project planning and inventory management may be neglected because of their alleged subordinate status. These elements, however, are essential for efficient HSCD operation. While ineffective inventory management upsets supply networks, inadequate project planning causes delays. Furthermore, about 47% of the papers reviewed detail operational choices, which highlight the industry’s emphasis on daily productivity. Still, it is necessary to further investigate these points to guarantee efficient execution of daily activities.

Finally, in the Research Characteristic, using mathematical models is the most common study strategy for HSCD, covering a significant 69% of the examined publications. Through mathematical modeling decision-making procedures can be optimized, as a variety of scenarios may be analyzed (Lingefjärd, 2006). Furthermore, 64% of the studies make use of optimization methods, e.g., stochastic optimization. Two thirds of the studies use both qualitative and quantitative approaches. In-depth investigation of phenomena, frequently via case studies or interviews, qualitative approaches offer important insights into environmental variables and human behavior. The use of numerical data analysis, quantitative approaches provide study conclusions and statistical validity. The knowledge of the HSCD dynamics is enhanced by the distinct views offered by both qualitative and quantitative methodologies (Riera et al., 2023). Moreover, 24% of the studies are devoted to deterministic models, representing situations with well-specified parameters and no uncertainty. Deterministic models are useful for comprehending baseline circumstances and for forecasting future events. Diverse phases of the HSCD exhibit variable amounts, falling into the non-deterministic category, e.g., demand. Uncertainties related to ST, TP, DIS, and EU are investigated by 18%, 20%, 11%, and 13% of studies, respectively. These differences underscore the necessity for robust models that can account for these uncertainties.

Figure 4. Structure and codes for hydrogen supply chain downstream sustainability
2.3 HSCD Sustainability

Figure 4 shows sustainability includes environmental, social, and economic aspects (Ghahremanlou and Kubiak, 2020). Subsequently, the environmental aspect encompasses both emission harmful to the climate (EHC) and process harmful to the environment (PHE) (Wang et al., 2022). The EHC entails criteria (CRI), i.e., carbon monoxide (CO), oxides of nitrogen (NOx), particulate matter (PM), ozone (O3), oxides of sulfur (SOx), and Lead (Pb) and non-criteria (NCR), i.e., total organic gases (TOG), volatile organic compounds (VOC), total hydrocarbons (THC), methane (CH4), air toxics (AT), and greenhouse gases (GHG); the rest of the EHC is considered under others (OTH), i.e., fuel consumption, (U.S. Department of Energy, 2023a). Wang et al. (2022) categorize PHE into resource depletion (RD) and destruction of habitats (DH).

Blohm and Dettner (2023) divide social aspect into three factors, employment (EMP), safety (SAF), and energy equity (EE). On the other hand, the economic element is analyzed from cost, revenue (REV), and others (OTH), i.e., profit and net present value (Ogumerem et al., 2018). The sources of revenue in the HSCD are selling metals: hydrolysis (MeH2), methylycyclohexane (MCH), methanol (CH3OH), gaseous hydrogen (GH2), ammonia (NH3), and perhydro-dibenzyltoluene (H20DBT). Moreover, the costs involved are transportation (TP), storage (ST), distribution (DIS), and end user (EU) (Le Dui gou et al., 2017). Lahnaoui et al. (2018) further detail TP into pipelines (PL), trucks (TK), rails (RL), and vessels (VL). Likewise, for storage (STO) they consider tanks (TA), cylinders (CY), and salt caverns (SC), and for distribution (DIS) just pipelines (PL) and trucks (TK).

Table 3 provides a comparative analysis of this paper with relevant systematic reviews from the sustainability point of view. With 27% and 29%, respectively, CO and NOx make considerable contributions among CRI subcategories. However, CH4 and GHGs, in particular, are the NCR that accounts for 38% and 56% review papers, respectively. Nevertheless, there is still a significant knowledge gap regarding the effects of process related emissions considering none of the CRI and NCR have been studied in more than 60% of the review papers. Furthermore, RD and DH being incorporated in 7% and 4% respectively, indicates a significant research gap in the current body of the PHE.

Remarkably, studying revenue generation from hydrogen and its various forms, e.g., LH2 is not being addressed by any of the papers. However, this is the primary motive for for-profit companies to invest in HSCD. None of the storage, transportation, distribution, end user, and other costs are studied by more that 40% of the papers, while their analysis provides insights towards competitiveness of hydrogen in comparison to other energies. Additionally, 27% of the conversations that center on employment opportunities and energy equity, the major social benefits, suggests the hydrogen industry has a significant ability to support job and energy access development. One of the main concerns is safety, which has received 60% of the researchers’ attention. In order to ensure the hydrogen sector creates job opportunities as well as supports safe working conditions, and promotes fair access to clean energy supplies, it is imperative that these social factors be addressed as they have a direct impact on communities (Almaraz et al., 2023).

To accomplish what we aimed in the last row of Tables 1, 2, and 3 accumulatively, and add to the body of knowledge related to systematic review, we: (i) consolidate the entire body of research focusing on the HSCD in Canada, (ii) carry out bibliometric analysis to evaluate the performance of papers and their hosting journals, (iii) conduct a systematic examination of the selected papers from: (a) the HSCD components and geographical focus, (b) decision levels and research characteristics, and (c) sustainability dimensions, (iv) conclude our findings by providing forward horizons and recommendations for further investigations from academic, policymaking, and practitioner standpoints.

3. Methodology

To gather the body of literature for this review, we focus on peer-reviewed journals in the domains of supply chain, energy, sustainability, and engineering through searching publication portals, i.e., ScienceDirect, Elsevier, Scopus, IEEE Xplore, and SpringerLink. The wide reach of these platforms serve as a justification for this approach. We applied “Hydrogen Supply Chain”, “Hydrogen Distribution”, “Hydrogen Supply Chain Transportation”, “Hydrogen Supply Chain Storage”, “Hydrogen Supply Chain Network Design”, “Refueling Station”, “Hydrogen Supply Chain Sustainability”, as well as “Decision Level” as keywords to perform our systematic searches. To direct our search to Canada, geographical names e.g., Ontario, Alberta, British Columbia, that denote Canadian provinces and territories were paired with the keywords through using the Boolean operator AND. To further enhance our search, we looked through the references of papers we found in our primary search where we used keywords and locations. Then, documents like theses, conference papers, reports, were excluded to maintain the concentration on English peer-reviewed journals. Our search resulted in a total of 39 original papers, which will be analyzed using the
framework we employed in Section 2 for evaluating the review papers. However, we provide some insights about the trends in the Canadian HSCD by conducting a brief bibliometric analysis on the 39 papers in this section.

Table 3. Analysis of relevant systematic review papers (published from February 2022 to October 2023) from sustainability dimension
Figure 5 illustrates patterns in the temporal order of the 39 selected papers, utilizing four blocks, each representing a distinct time period. The green block, showing the years 2006-2008, is the least published period for the Canadian HSCD researchers with 8% of the total papers. During 2009-2013 and 2014-2018 there are same amount of publications, 28% of the papers, which is over three times more than publications from 2006 to 2008. There is another growth in the quantity of papers between the years 2019-2023, making up 36% of all publications. Overall, as demonstrated, over the past 18 years there has been a discernible increase in academic publishing regarding the Canadian HSCD. This is a sign of the intensive efforts towards further understanding the HSCD in Canada.

Figure 6 demonstrates which journals have published the 39 selected papers by exhibiting the information as cylinders, with each cylinder denoting a distinct journal. The *International Journal of Hydrogen Energy*, symbolized by an orange cylinder, accounts for a sizable 64% of the selected papers. Then, under the heading *Others*, a number of journals are gathered, *Mining, Journal of Power Sources, Energies, Energy Policy, Renewable and Sustainable Energy Reviews*, and *Renewable Energy Focus*, each of which just published one of the papers. This group, which is represented in yellow, makes up about 17% of the papers. The *Journal of Cleaner Production* makes up 13% of the total publications. Finally, *Energy Conversion Management* with just 6% of the papers, represents the smallest amount of publications.
4. Results and Discussion

4.1 Hydrogen Supply Chain Downstream (HSCD) Dimension

Table 4 presents the results of an analysis of 39 selected papers that focus on the HSCD in Canada. 74% of the publications examined pipeline transportation, making it the most studied mode. The reason for the lack of research may be due to the high initial construction costs of pipelines (Kim et al., 2022). However, due to the importance of pipelines as the most secure and ecologically friendly with a delivery efficiency of more than 99%, this makes them an excellent choice for transporting substantial amounts of hydrogen over long distances (Kim et al., 2022). The majority of large Canadian cities are served by significant crude oil and natural gas pipelines, which are typically subterranean and operate in both inhabited and isolated locations (Natural Resources Canada, 2023). For example, British Columbia include major pipelines, e.g., Trans Mountain Pipeline, Coastal GasLink Pipeline, Pembina's NEBC/Western Pipeline system, Enbridge’s Westcoast Pipeline; please see Canada Energy Regulator (2021) for a complete list of pipelines in Canada. Therefore, more research needs to be conducted on pipelines, especially to enable evaluation of available pipelines in the country for hydrogen transportation.

According to Table 4, only 49%, just under half of the examined papers, have reviewed trucking as one of the methods for hydrogen transportation. This lack of study might be due to its limited capacity for energy transmission that prevents scalability, being more sensitive to distance travelled, which raises costs (Cui and Aziz, 2023). However, trucking is a particularly advantageous mode of transportation for hydrogen because it can reach remote areas with limited transportation access, lowering storage costs (Oh et al., 2023). Transport Canada (2021b) announces the primary means of transporting both freight and people throughout Canada is by roads, which links every region from coast to coast. British Columbia, Alberta, Ontario, and Quebec are the primary hubs for this industry Statistics Canada (2021). Therefore, further research, with focus on employing existing roads, e.g., Alberta 1 and 2, is required.

Only 18% of the analyzed papers, focused on railway as the transportation mode for hydrogen. The lack of research may be due to the fact that transporting hydrogen via a railway tube trailer results in higher carbon emissions than those of tanker trucks, and has restricted availability between certain grids (Seo et al., 2020; Erdoğan et al., 2023). However, Seo et al. (2020) claims that railway transportation of hydrogen has a lower cost than road transportation. The two major freight rail companies in Canada, Canadian National Railway Company and Canadian Pacific Railway, own the majority of the country’s 46,000 miles of rails, e.g., Algoma Central Railway in Ontario. Therefore, it is essential for researchers to evaluate the potential of rail infrastructure in various provinces, regions, and territories in Canada.

Vessels are considered solely in 26% of papers. Navigating environmental effects of burning marine diesel oil and energy-intensive procedures for preserving carrier conditions may be the reason behind this lack of research (Noh et al., 2023). However, large cargo capacities and transport of significant volumes of hydrogen can be considered as advantages of vessels. They are, therefore, a cost-effective option for bulk transportation. Transporting hydrogen can be realized through a variety of forms, including liquid or compressed gas, depending on the infrastructure and particular needs (Aglen and Hofstad, 2022). According to Transport Canada (2019), over 550 port facilities exist in Canada, with 17 of them being Canada Port Authorities, which manage over 60% of the country’s tonnage of commercial cargo. Furthermore, in terms of performance, nearly $200 billion of Canada’s imports and exports were processed by ports in 2017, and during the previous ten years, container throughput has increased by 35%. Thus, future research endeavors could focus more closely on advancing vessel technologies to utilize various ports across Canada, e.g., in Nova Scotia, the port of Halifax, and in Newfoundland and Labrador, the port of Argentia.

Table 4 shows that of 39 papers, only 5% of the papers delved into the gaseous form of hydrogen, while 3% of papers focused on liquid hydrogen storage. A notable research gap in this field is highlighted by the surprising lack of studies that have examined the combination of gaseous and liquid storage (0%). This gap in research may be due to the low density of gaseous hydrogen, even when compressed to high pressures of up to 700 bar (Seo et al., 2023). However, according to Klopcic et al. (2023), gaseous hydrogen has a faster filling and extraction time than metal hydride storage and a high gravimetric storage capacity of 100% at ambient conditions that requires less energy for compression than liquid hydrogen storage. Likewise, there is a huge gap in research on liquid hydrogen, which may be due to its extremely low liquefaction temperature under atmospheric pressure (Moradi and Groth, 2019).
Furthermore, there is a considerable gap in research regarding different types of hydrogen carriers, such as ammonia being most preferred and studied by 26% of the papers. This lack of research could be because of $NH_3$ high toxicity, which prevents it from being used for hydrogen storage (Klerke et al., 2008). However, a variety of energy sources, such as natural gas, coal, biomass, and renewable energy, can be used to manufacture ammonia (Moradi and Groth, 2019). Furthermore, only 13% of the studies discussed methanol-based storage, suggesting a
consistent but rather low level of attention to this chemical solution. However, \( \text{CH}_3\text{OH} \) has the highest density of the four liquid hydrogen carriers. Also, methanol can be transported and kept in liquid form at ambient temperature, unlike ammonia, which must be held at low temperatures (Song et al., 2022). The lack of specialized studies examining storage solutions incorporating methylcyclohexane (\( \text{MCH} \)) and perhydro-dibenzyltoluene (\( \text{H}_{18}\text{DBT} \)) suggests uncharted ground and research gaps in these particular chemical storage media for hydrogen. However, \( \text{MCH} \) may be easily incorporated into the current liquid fuel infrastructure (Obara, 2019). Furthermore, the substantial gap in research regarding \( \text{H}_{18}\text{DBT} \) may be due to its high kinematic viscosity under ambient circumstances. However, the advantage of \( \text{H}_{18}\text{DBT} \) is a high hydrogen storage capacity (Kwak et al., 2021). Moreover, entirely 13% of reviewed papers studied metal hydrides as a method of hydrogen storage. However, higher volumetric energy densities and improved safety characteristics make \( \text{MgH}_2 \) a superior hydrogen storage solution when compared to other methods Klop’ci’c et al. (2023). Other chemical compounds of hydrogen, ammonia borane (\( \text{NH}_3\text{BH}_3 \)), are less popular; perhaps explained in part by only 3% of the reviewed papers focusing on them (Moradi and Groth, 2019). Therefore, there are needs for further study in order to identify the benefits and drawbacks of every hydrogen carrier from various aspects, e.g., cost and storage density.

Regarding methods of storage, storage in tanks was the focus of 54% of the reviewed papers. However, according to Sens et al. (2022), tanks are essential for storing hydrogen because they can be customized to meet different needs at varying points in the supply chain. On the other hand, only 13% and 10% examined storage in cylinders and salt caverns, respectively. The reason for this huge lack of research on cylinders may be due to low efficiency (Züttel, 2004). However, flexibility and extensive use of high-pressure gas cylinders make them a desirable option for hydrogen storage. Furthermore, the gap in research on salt caverns may be due to the complex geomechanical analysis needed to design them. However, according to Abreu et al. (2023), high injection and withdrawal rates are provided by salt caverns, which make storage operations more effective. Moreover, the gap in research on salt caverns may be due to the complex geomechanical analysis needed to design them. However, high injection and withdrawal rates are provided by salt caverns, which make storage operations more effective (Abreu et al., 2023). Hence, additional research is required on these three storage methods.

A total of 77% of reviewed papers studied the application of hydrogen in transportation. Hydrogen has enormous potential to transform many forms of transportation, e.g., vehicles, trains, ships, aircraft. Hydrogen may be consumed in internal combustion engines to power cars or used in fuel cells to produce electricity. Vehicles running on hydrogen are very effective and produce very little pollution, which helps to lessen the need for fossil fuels (Sharma and Ghoshal, 2015). Furthermore, only 33% of studies focused on the application of hydrogen in industries. However, hydrogen is needed in various industries, e.g., in the aerospace sector as rocket propellant, in the pharmaceutical industry to help in drug development, in metallurgy to cut and weld metals, in the electronics industry to make semiconductor materials (Okolie et al., 2021). In Canada, industrial activity is a major contributor to air pollution. It releases a range of pollutants, e.g., carbon monoxide, contributing to global warming. Moreover, 28% of the studies focused on the use of hydrogen in the residential sector. This minimal attention from researchers may be due to significant costs, including a levelized energy price that is higher than ordinary grid rates Maestre et al. (2022).

Yet, a variety of specifically designed residential buildings can be supplied with heat and power in both grid-connected and off-grid locations. Therefore, the recommended future direction of hydrogen application is to evaluate hydrogen, especially renewable hydrogen, as a substitution fuel in most air pollutants applications, especially in remote and indigenous Canadian communities that mainly consume diesel as residential fuel (Government of Canada, 2023).

To provide a clear insight as to the focus of the reviewed papers geographically, we projected the information under location column in Table 4, on the map in Figure 7. This figure illustrates that solely British Columbia, Alberta, Ontario, Nova Scotia, and Newfoundland and Labrador have been studied by 4, 4, 26, 1, and 1 papers (excluding papers #5, 7, and 25 not focusing just on province), respectively. Hydrogen generation from biomass, natural gas with carbon capture and storage, and renewable electricity have great promise in British Columbia. Also, the province has established a network of hydrogen refueling stations, a low-carbon fuel standard, and a mandate for zero-emission vehicles. In addition to having the largest carbon capture and storage facility in the world, Alberta is a significant producer of hydrogen from natural gas. The province can service both domestic and international markets by utilizing its current hydrogen infrastructure and knowledge. Hydrogen production from renewable electricity, particularly from offshore wind and tidal energy, has great potential in Nova Scotia. A high potential for hydrogen production from renewable electricity, particularly from wind and hydropower, exists in Newfoundland and Labrador. However, none of the other Canadian provinces and territories has been studied, while Saskatchewan is a leading producer of hydrogen from coal, natural gas, and renewable electricity. Similarly, Manitoba and Quebec can use biomass and hydroelectricity to produce hydrogen. In contrast, New Brunswick can
utilize renewable electricity to produce hydrogen. Hydrogen may be produced in Prince Edward Island employing biomass and wind energy. Finally, the Yukon, the Northwest Territories, and Nunavut can generate hydrogen from biomass and renewable electricity. Please see Figure 8 for the significant role considered for each province to meet the global environmental commitments of Canada in the national hydrogen strategy (Natural Resources Canada, 2020).
Table 5. Analysis of the reviewed papers from decision level and research characteristics dimension

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4.2 HSCD Decision Levels and Research Characteristics Dimension

Table 5 presents a comparison between the reviewed papers from decision level and research characteristics perspectives. This indicates 56% of papers studied storage in the domain of investment. This may be due to the challenges associated with hydrogen storage, including the requirement for substantial space and infrastructure, safety issues arising from flammability and leakage, and energy losses during the process of converting back to electricity. However, storage is essential to the hydrogen economy because it helps to stabilize the supply of hydrogen and manage the erratic nature of renewable energy (Gordon et al., 2023a). There are opportunities for innovation and cooperation in hydrogen storage despite the industry’s technological, financial, and environmental difficulties. Next, our research shows that only 23% and 15% of the research highlighted investment on transportation and distribution, which may be due to high costs and complicated infrastructure needs, e.g., specialized vessels, trucks, and pipelines, that may prevent hydrogen from being widely available and inexpensive. Although Gordon et al. (2023a) claim that in the hydrogen economy, transportation plays a crucial role in determining the cost, environmental effect, and delivery of hydrogen. It indicates a balanced strategy to fulfill market needs and guarantee timely supply to customers. Finally, just 23% of papers focused on financial commitment to developing refueling stations where customers’ demand is met, which may be due to the lack of societal acceptance and customer buy-in. However, utilizing low-carbon hydrogen applications can result in lower energy expenses and emissions. Therefore, conducting research about investment in the HSCD in Canada is a fertile research avenue.

Within the strategic domain, just 49% of the papers investigated locations of refueling stations, which can be the result of a significant level of uncertainty in the adoption of hydrogen technologies and market development. It is critical to position hydrogen refueling stations strategically for safety, environmental effect, market growth, and customer satisfaction, which entails being close to customers (Sgarbossa et al., 2023). Following this, 44% of the papers examined locations for storage facilities, an important factor, because the management of demand fluctuation can be easier handled by strategically located storage facilities that efficiently store inventory. Finally, the transportation domain of facility location was analyzed by only 18% of the total papers, although, the benefits of strategically placing transportation facilities leads to reduced distribution costs, enhanced environmental performance, and increased market penetration. Therefore, further research attention is required to address this class of strategic decisions.

Capacity selection for storage systems is studied by 51% of the papers, albeit storage capacity can provide stable support for both production level and human resource level (Isaac and Saha, 2023). The next most preferred capacity evaluation is of hydrogen refueling stations, studied in 38% of papers; however, by considering end-user demand, the capacity selection process for stations should utilize the capital for the development projects. Transportation and distribution capacities are explored by 13% and 8% of the papers, respectively. Nonetheless, it is important to reduce travel expenses and environmental emissions related to it. Furthermore, only 5%, 5%, and 0% of the papers delved into the decisions regarding allocation to storage facilities, transportation means, and refueling stations, respectively. In contrast, these decisions are significant to balancing the supply and demand for hydrogen. Likewise, it is vital to adjust the capacity for storage, transportation, distribution, and refueling stations according to the demand to enhance HSCD responsiveness, while none of them has been studied by over 18% of the papers. In a similar manner, technology selection, upgrading, and downgrading are not investigated by over 33% of the studies, despite the fact that technological adjustment enhance the HSCD sustainability. Therefore, additional research is needed to address capacity and technology selection and fluctuation, and facility allocations for the HSCD in Canada. Finally, decision regarding outsourcing various activities in the HSCD, e.g., transportation, has not been the focus of any of the papers. However, through the use of external suppliers’ specialized expertise and capabilities, outsourcing may enhance a the HSCD’s performance (Lahiri, 2016). Therefore, more research needs to be conducted on outsourcing aspects of the HSCD in Canada.

As for operational and distribution tactical decisions, they are addressed by 51% and 69% of the papers, respectively. On the other hand, tactical decisions about project planning, production planning, and inventory management are responded by 3%, 8%, and 0% of the studies. The viability of these decisions are impacted by data availability and quality, especially in large-scale HSCs. Conversely, the benefits of tactical and operational planning may lead to improved coordination and integration, lowering costs and risks through resource optimization, and more flexibility in responding to market circumstances. Thus, it is critical for additional attention to these levels of decisions.

Mathematical modeling and optimization are used by 31% and 33% of papers, respectively. However, mathematical modeling is a flexible tool that simplifies complicated phenomena through the practical applications of mathematics by enabling scenario analysis (Lingejärd, 2006). Linear programming can address problems in resource allocation, production planning, transportation, and scheduling. Non-linear programming, e.g., demand
fluctuations, and mixed integer non-linear programming, e.g., refueling station locations along with the amount delivered to them and the amount of demand in each station, would be helpful. Looking at the models closer, we realized 26% and 3% of the papers are deterministic and non-deterministic, respectively. Along this line, optimization helps making data-driven decisions. Furthermore, qualitative and quantitative, under others, are used by only 59% of the papers. When it comes to analyzing the HSCD, both qualitative and quantitative models have advantages. While quantitative models offer numerical solutions and optimization for weighing the costs, benefits, and effects of different alternatives, qualitative models offer insights into the structure and interactions of the system, which is helpful in generating scenarios (Riera et al., 2023). Therefore, there is a gap for more research in qualitative and quantitative studies, mathematical modeling and optimization, especially non-deterministic (e.g., stochastic, robust, and fuzzy) as this is inherent to the HSCD, being as yet in its infancy stage in Canada. Moreover, utilizing optimization and simulation software packages, e.g., CPLEX, GREET (The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation), EIO-LCA (Economic Input-Output Life Cycle Assessment), and RETScreen (Renewable-energy and Energy-efficiency Technology Screening) would propose some future direction.

Figure 9. Analysis of reviewed papers from sustainability dimension

4.3 HSCD Sustainability Dimension

Figure 9 demonstrates the analysis of the 39 papers within the framework of sustainability, i.e., environmental, social, and economic (Ghahremanlou and Kubiak, 2020). All three dimensions of sustainability are evaluated by just 16 papers (written in the center of the figure), which is less than half of the total number of reviewed papers. The next most studied dimension is environment, 9 of the papers. The environmental-social, economic-social, and environmental-economic dimensions are investigated by 4, 0, and 4 papers, respectively. Furthermore, papers #1, 2, 3, 7, 11, and 23 did not consider sustainability at all, please see Table 6 for further details. However, Sakthi et al. (2024) emphasize studying all dimensions of sustainability, clarifying how significant it is to investigate each dimension and their combinations, and which are open directions for additional examinations in the HSCD in Canada.

Table 6 shows different components of the criteria air emissions that are harmful to the climate, CO, NO₂, Particulate Matter (PM), O₃, SO₂, Pb, are investigated by 28%, 41%, 8%, 13%, 23%, 10%, respectively. This means that criteria emissions were not sufficiently studied in the reviewed papers. However, criteria pollutants are important to the extent that the U.S. Environmental Protection Agency has regulated them in order to safeguard public health. These pollutants generated by sources such as cars have a variety of negative effects on human health and the environment; thus, efforts to minimize their levels are necessary (U.S. Department of Energy, 2023b). On the other hand, the non-criteria air emissions harmful to the climate including total organic gases, volatile organic compounds, total hydrocarbons, methane (CH₄), air toxics, and Greenhouse Gases (GHG), are examined
by 74%, 21%, 23%, 72%, 3%, and 77% of the papers, respectively. Although scrutinizing non-criteria pollutants in the Canadian HSCD are highlighted by the U.S. Department of Energy (2023b) due to their contribution to the creation of ozone, being classified as air toxics with consequences for respiratory health and cancer, and greenhouse gases’ negative impact on climate change. Finally, both resource depletion and destruction of habitats were not reviewed at all. Therefore, further research needs to be conducted on various factors of criteria and non-criteria emissions along with the processes harmful to environment in HSCD in Canada.

No study has been done on the revenue generation within the economic aspect of sustainability. However, the revenue generated by hydrogen products plays a crucial role in shaping the economic viability of hydrogen energy in various sectors. Furthermore, none of the cost items has been examined by over 23% of the papers. The cost of tanks, cylinders, and salt caverns for storage, pipelines, trucks, railways, and vessels for transportation, pipelines and tanks for distribution, and refueling stations are studied, respectively, by 23%, 3%, 5%, 21%, 13%, 3%, 0%, 15%, 10%, and 23% of the papers. However, Le Duigou et al. (2017) claim these costs have a great impact on the viability and profitability of hydrogen as an energy vector. Lastly, social factors, employment creation, safety, and energy equity are investigated by 8%, 49%, and 0% of the papers, while employment is significant for regional economic development, safety is a critical social component, and energy equity is emphasized in Canada’s hydrogen strategy due to number of remote communities in the country (Sakthi et al., 2024).

5. Forward Horizons

5.1 Academic Recommendations

Figure 10 offers recommendations to academic communities for further studies in three different categories: (i) Hydrogen Supply Chain Downstream (HSCD) components, (ii) decision levels and research characteristics, shortly written as decision levels, and (iii) sustainability, derived from Tables 4, 5, and 6. Development of the HSCD in Canada requires the assessment of various available transportation means in Canada, including rail (e.g., Mackenzie Northern Railway), trucking (e.g., Alberta 1), pipelines (e.g., Trans Mountain), and vessels (e.g., port of Vancouver). Examination of GH$_3$, LH$_3$, and other chemical storage alternatives considers cost, safety, environmental impact, and density as another horizon for further investigation. Techno-economic studies focusing on customized tanks, and research aiming to reduce hydrogen cylinder costs and enhance energy density are other open research avenues. Exploration of existing salt caverns, establishing multifuel refueling stations, and substituting hydrogen (especially green hydrogen) in polluting industries is also open for additional research. Conducting research on hydrogen as a household fuel in regions such as Newfoundland and Labrador and hydrogen generation from wind energy for isolated settlements, particularly in jurisdictions where limited research has been conducted seem promising research avenues.

In the decision levels of the HSCD, critical factors such as storage, transportation, distribution, and refueling stations need extra attention from scientific community from investment, facility location, capacity selection/reduction/expansion, allocation, and technology selection/upgrading/and downgrading aspects. Incorporating inventory control, operational decisions, and project and production planning in mathematical models, e.g., multiperiod, multi-objective, deterministic, and non-deterministic, and optimization, may provide new insights. The use of optimization and simulation software packages, e.g., CPLEX and GREET, to ensure efficiency and accuracy in decision-making processes across all decision levels in the HSCD seems another direction for research. On the other hand, the sustainability assessment of the HSCD including environment, social, and economic dimensions are needed. Environmental assessment should be focused on criteria pollutants, non-criteria pollutants, and harmful processes to the environment. Economic factors require attention of researchers on revenue from sell of hydrogen energy, storage, transportation, and distribution expenses, along with other economic performance measures, e.g., net present value. The social component should narrow the studies on employment, safety, and energy fairness. For detailed recommendations, please see Figure 10.

5.2 Policymaking Recommendations

We offer recommendations for policymakers in Figure 11. The HSCD infrastructure development in Canada entails collaboration between provinces and territories to create a seamless hydrogen distribution system. This project explores cutting-edge technological developments while making use of the current transportation networks. Therefore, financial incentives are recommended, including grants and tax exemptions, to encourage the stakeholders toward creation and application of various hydrogen storage and delivery options. With an emphasis on technology and energy transition, resources should be allocated to the study of various hydrogen storage options and the evaluation of their effects on expenses, security, and the environment. Furthermore, support for research and development, especially focused on creating specialized tanks for different energy carriers and technologies is
required. Establish procedures for monitoring optimization of the performance of hydrogen distribution and storage networks, demonstrating a dedication to the advancement of efficient and sustainable energy solutions.

Table 6. Analysis of the reviewed papers from sustainability dimension
With an emphasis on technology and energy transition, resources should be allocated to the study of various hydrogen storage options and the evaluation of their effects on expenses, security, and the environment. Furthermore, support for research and development, especially focused on creating specialized tanks for different energy carriers and technologies is required. Establish procedures for monitoring optimization of the performance of hydrogen distribution and storage networks, demonstrating a dedication to the advancement of efficient and sustainable energy solutions.

A multifaceted approach to reducing environmental impact is part of the sustainability assessment process. This requires legislation to encourage the use of green hydrogen in sectors of the economy that produce air pollutants, with the goal of drastically lowering emissions. The economic viability of hydrogen as a propane or heating oil substitute should be examined, taking into account the financial impact on households. So too, encouraging incorporating hydrogen-generated electricity from renewable sources to support energy sustainability, especially in remote communities that rely on diesel fuels.

5.3 Industry Recommendations

Figure 12 recommends eight directions to practitioner communities to help towards building the HSCD in Canada. Establishing a comprehensive HSCD requires building partnerships between construction companies, logistics companies, and energy corporations to create the infrastructure development and integration. Industry participants must simultaneously think about adapting current infrastructure or allocating particular resources for hydrogen transport in order to optimize hydrogen mobility. Sustainable development still depends on funding research and development (R&D) projects, especially those that address storage issues like developing tank technologies and making hydrogen cylinders more efficient.

Additionally, enterprises are urged to investigate the implementation of hydrogen-based processes, which offer fresh revenue opportunities and complement sustainability goals. This tactical change has the potential to significantly reduce air pollution and further global environmental objectives. Companies should think about regional hydrogen growth in unexplored regions and forming alliances with research institutions in order to strategically position themselves in the changing energy landscape. In the quickly changing field of hydrogen technologies, this cooperative approach promotes innovation, strengthens market leadership, and guarantees a competitive advantage. In order to ensure that hydrogen efforts remain viable over the long term, special emphasis should also be made on creating customized solutions for streamlining operations and carrying out sustainability analyses.
Figure 10. Academic horizons for the HSCD in Canada
Infrastructure Development

1. Promoting cooperative efforts amongst provinces and territories to create a unified infrastructure for hydrogen distribution, making use of already-existing transportation networks and investigating technology breakthroughs.
2. Providing monetary assistance or tax breaks to encourage the creation and application of a variety of transportation options for the delivery of hydrogen.
3. Fostering partnerships between public and private organizations to build multipurpose fuel stations and storage facilities.

Technology and Energy Transition

1. Allocating resources for studies on various hydrogen storage solutions and how they affect costs, safety, and the environment.
2. Encouraging research and development in customized tanks for various energy carriers and technologies in order to improve the effectiveness of hydrogen distribution and storage.

Sustainability Assessment

1. Developing and implementing regulations to encourage the use of green hydrogen in air pollution-causing businesses in an effort to lower emissions.
2. Evaluating hydrogen’s economic feasibility as a fuel substitute for provinces that rely on propane or heating oil while taking the costs to households into account.
3. Promoting energy sustainability and lowering carbon footprints by integrating hydrogen-produced electricity from renewable sources, especially in remote communities that depend on diesel.
4. Promoting research that thoroughly evaluates the effects that various hydrogen supply chain system topologies and operations have on the environment, the economy, and society.
5. Utilizing findings from sustainability evaluations to develop laws and policies that strike a balance between social well-being, environmental preservation, and economic growth.

Figure 11. Government horizons for the HSCD in Canada
6. Conclusions

Canada is pursuing being carbon-free by 2050. Furthermore, it is advantageously situated to respond to the energy crisis in Europe escalated by the Russia-Ukraine war due to its natural resources to produce hydrogen. With Europe importing hydrogen from Canada it will change the configuration of the hydrogen supply chains downstream (HSCD) in Canada. Therefore, this paper compiled and analyzed all the relevant 39 papers published prior to October 2023, systematically. Our investigation extracted insights through examining the papers from (1) the HSCD components and geographical focus, (2) decision levels and research characteristics, and (3) sustainability standpoints. Accordingly, we contributed by recommending forward horizons for scientific, legislative, and practitioner societies in Figures 10, 11, and 12. Furthermore, we performed a bibliometric analysis reflecting a growing emphasis on research and scholarly publishing in Canada and International Journal of Hydrogen Energy being the main cornerstone.

Firstly, forward academic horizons outlined in the scientific sector underscore a holistic approach to the HSCD, covering transportation means, storage alternatives, and sustainability assessments. This comprehensive strategy aims to establish an efficient and sustainable hydrogen supply chain in Canada. The decision levels of the HSCD are required additional attention from academic community. Extra sustainability assessments, focusing on
environmental, social, and economic dimensions of the HSCD, promotes a responsible development and distribution of hydrogen in Canada and beyond.

Secondly, in the government sector, the emphasis should be on incentives for encouraging collaborative infrastructure development, utilizing existing transportation networks and supporting the establishment of adaptable refueling stations and storage facilities. Financial incentives, public-private partnerships, and a commitment to technology and energy transition ensure the dedication to creating an effective hydrogen distribution system in Canada. Additionally, a multifaceted approach to sustainability through regulations encouraging the use of hydrogen and studies on the economic viability of hydrogen as a substitute energy, reflect a commitment to reducing emissions and promoting energy sustainability. Thirdly, the industry sector ought to concentrate on partnerships between construction companies, logistics firms, and energy corporations for the establishment of a sustainable HSCD. Furthermore, sponsoring research and development initiatives for storage technologies can add to the competitive advantages of corporations in the field.

This research has some limitations which can be utilized as future research directions for researchers interested in performing a systematic review analysis in HSCD. Further details of end users of hydrogen energy, e.g., heavy vehicles and light vehicles, may provide additional insights. Another direction is breaking down the operational decisions as well as breaking down the mathematical models, optimization, and qualitative research methods into their subcategories, e.g., linear models, stochastic optimization, and survey.

**References**


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Authors contributions

Farzam Farahmand contributed to investigation, research methodology, conceptualization, and writing – original draft. James King conducted investigation on evaluation criteria, analysis, conceptualization, and data collection. Davoud Ghahremanlou proposed the research idea, and performed investigation, research methodology, conceptualization, writing – original draft – review & editing, supervision, and project administration. Priya Sakthi contributed to investigation and visualization. Mohammad Reza Moghadas Jafari helped in data collection and visualization. All authors have thoroughly read and given their approval for the final manuscript to be published.

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Competing interests

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Informed consent

Obtained.

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Data sharing statement

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