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Review

A Systematic Review on Technologies and Industry 4.0 in the Forest Supply Chain: A Framework Identifying Challenges and Opportunities

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Abstract: *Background:* Forestry products and forestry organizations play an essential role in our lives and significantly contribute to the global economy. They are also being impacted by the rapid development of advanced technologies and Industry 4.0. More specifically, several technologies associated with Industry 4.0 have been identified for their potential to optimize traditional forest supply chains. However, to date, there has been limited research that has systematically investigated these technologies and the scientific evidence on their impact on forest supply chains. This research systematically reviews the state-of-the-art technologies applied in the forest supply chain and reports on the current (and/or potential) impacts of technologies on the transformation of the forest supply chain towards 'Forest Industry 4.0'. *Methods:* The systematic literature review methodology identified 45 peer-reviewed studies for inclusion that are analyzed, interpreted and discussed in this paper. *Results:* This study developed a framework on the forest supply chain in Industry 4.0. This framework has three components related to forest supply chains: current supportive technologies, improvements and characteristics of the forest supply chain in Industry 4.0, and the strategic outcomes in economic, environmental and social dimensions. The reported impacts of technologies in different phases of the forest supply chain are interpreted and discussed. *Conclusion:* The study results confirm that most technologies in Industry 4.0 have real or perceived positive impacts on the forest supply chain and reported obstacles and challenges are identified. The results of this study also contribute insights on the wide range of options in terms of technologies available to decision-makers to optimize the forest supply chain towards 'Forest Industry 4.0'.

Keywords: Industry 4.0; systematic literature review; forest products; forest supply chain; Industry 4.0 framework

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1. Introduction

The term Industry 4.0 has become one of the most popular new topics in technology among researchers. A wide range of research across multiple disciplines has discussed and conducted research related to Industry 4.0 [1]. According to a Google trend, the topic of Industry 4.0 has witnessed a rapid increase in interest over the last 10 years [2]. Indeed, most industries are exploring how Industry 4.0 may have significant impacts on the economic, social and environmental aspects of their supply chains.

As a concept, Industry 4.0 was initially introduced by the German government in 2011 [3]. Industry 4.0 is also known as 'smart manufacturing', 'Industrie 4.0' or 'the Fourth Industrial Revolution' [4,5]. It has been argued by its advocates that Industry 4.0 has the potential to stimulate a phase of significant industrial transformations comparable to the three previous industrial revolutions. The First Industrial Revolution introduced mechanical looms driven by steam engines from 1760 to 1850 [6]. The Second Industrial Revolution from 1870 to 1914 witnessed the growth of huge economies of scale in manufacturing [7]. The Third Industrial Revolution introduced the growth of electronics and modern ICTs such as automation systems [8]. The Fourth Industrial Revolution encompasses cutting-edge technologies and integrated systems such as the Internet of Things (IoT) and cyber-physical systems (CPS). The fundamental concepts underpinning Industry 4.0 are: the Smart Factory, CPS, decentralized self-organization, digitalization and virtualization and intelligent industrial manufacturing [9,10]. These concepts of Industry 4.0 were proposed to enable businesses to improve decision-making at the strategic and operational levels by analyzing large amounts of real-time data [11].

The concept of Industry 4.0 can use various technologies or techniques in its implementation [12]. Importantly, the new technologies included in Industry 4.0 stimulate changes in a wide range of business activities, leading to changes in supply chains [13]. They include Big Data, analytics, mobile technology, additive manufacturing, artificial intelligence, Cloud technology, IoT, radio-frequency identification (RFID), simulation, sensors, Global Positioning System (GPS), unmanned aerial vehicle (UAV) and blockchain [11,14,15]. In addition to these technologies, in some research papers the disruptive technologies related to Industry 4.0 have also been listed, which can be summarized as follows: virtual reality, 3D printing, cyber security, machine-to-machine communication, automatic identification, business intelligence and nanotechnology [1,16]. The concept of the IoT was created based on RFID-enabled identification and tracking technologies [12]. In this systematic review paper, a broad and inclusive definitional approach to this range of technologies was adopted to ensure relevant research could be identified and included. As a result, technologies related to Industry 4.0 were deemed to be those that supported collecting, storing, processing, analyzing and sharing data.

In examining the forest industry, it is evident that the demand for forest products is increasing around the world [17]. The forest supply chain refers to a temporal sequence of activities and processes from standing trees to the end-users that transform the woody raw material to final forest-based products [18,19]. The chain starts with raw material as the standing tree in the forest. In the forest supply chain, the woody material can be turned into logs, roundwood, lumber, panel and engineered wood, pulp and paper, biomass, bioenergy (for electricity and heat) and other forest product [18–21]. The production processes transfer the woody raw materials through a biorefinery, pulp mill, sawmill, panel mill and pellet mill [18,19]. Based on the forest supply chain in the literature, as shown in Figure 1, the processes include procurement, production, distribution and sales/market [18,19,22]. The activities include forest management, harvesting and transportation [19,23,24]. The independent entities involved in the forest supply chain are forest owners, harvesting enterprises, haulage companies, logistic (transportation) companies, storage sheds, terminals, power plants and bioethanol facilities [19,22].

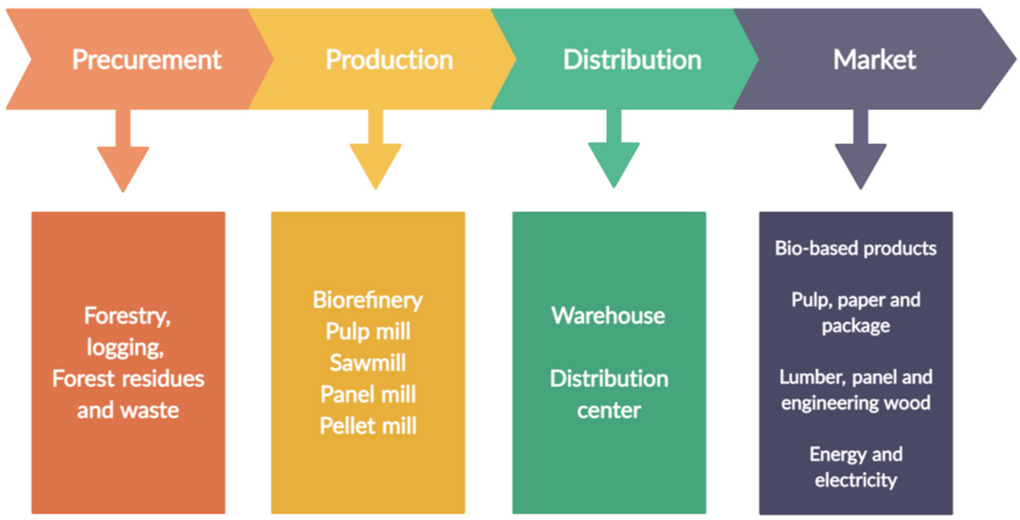

Figure 1. The processes of the forest supply chain, adapted from [18,22].

It is also evident that globally most forestry supply chains are not sophisticated using new technologies and the data that they produce. With the growth of the forestry industry around the world, there are some issues and challenges reported that are impacting the forest supply chain. For instance, there are some illegal activities in the forest supply chain. The FAO reported illegal logging and timber trade, especially from Russia and China, for the processing and manufacture of final products [25]. Illegal logging and wood laundering have also been reported in Mexico and the forest supply chain has inefficient low-tech practices [26]. Moreover, the non-optimal use of resources is also an issue in the forest supply chain [27]. In this untrustworthy environment, parties in supply chains would like to perform transactions in a transparent environment. Customers would like to obtain information about the raw materials of forest-based products to know whether the products are eco-friendly [28]. Recently, Industry 4.0 and technologies have been identified by some research has offering potential solutions to these types of issues and inefficiencies. Several studies have indicated that the implementation of new technologies could optimize the forest supply chain. For instance, the automated real-time tracking system could be the solution for the non-optimal use of resources in wood processing [27]. Several technologies associated with Industry 4.0 have been used or studied to optimize the forest-based supply chain, including blockchain, IoT, RFID, and smartphone applications. However, to the best of our knowledge, there is limited research that has systematically investigated the benefits of Industry 4.0 and its technologies in supporting the forest supply chain.

Prior to performing this systematic review, the research team identified pre-existing literature reviews that had been conducted on related topics. The existing studies have tended to focus on: the optimization solutions of digital technologies in the forest supply chain [19]; and only considered part of forest supply chain [23,24]. The review developed by [23] was mainly based on three activities of the forest supply chain [23]. The authors in [24] reviewed technologies implemented in wood supply but not the entire supply chain [24]. Noticeably, these previous reviews have only analyzed either a part of the forest supply chain or did not consider Industry 4.0 at all. Thus, it is necessary to identify research exploring how the new technologies in Industry 4.0 are or may improve the forest supply chain and the expected outcomes of the implementation of these technologies.

This research paper focused on the intersection of Industry 4.0 technologies and the challenges facing forest supply chains. The objectives of the study were:

(1) To investigate state-of-the-art technologies developed for or applied to the forest supply chain;
(2) To assess improvements of the forest supply chain provided by technologies in Industry 4.0 era;
(3) To provide an understanding of the benefits and impacts of technologies and Industry 4.0 with regard to the forest supply chain;
(4) To identify the key challenges and future research directions in the related area.

This systematic review is structured as follows. Section 2 presents the research method used to identify, select and analyze research papers for inclusion. Section 3 explains the framework based on the content analysis of included papers with interpretation and discussion. An analysis of the current supportive technologies and their benefits and improvement in the forest supply chain is included. The strategic outcomes of the forest supply chain in Industry 4.0 follows. Section 4 discusses the future challenges identified by the framework. Finally, Section 5 presents the conclusions with future research directions for future investigation.

2. Research Method

To address the research objectives, a systematic literature review was performed. A systematic review is an evidence-based literature review. It can identify the state-of-the-art knowledge of the research topic and helps collect relevant studies together without bias by summarizing and synthesizing the findings of the existing literature [29]. We chose the systematic review as the research method because our goal was to investigate the current situation of the forest supply chain in Industry 4.0. The systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [30]. Based on current systematic literature reviews on the related topics, this systematic review was adapted and conducted in five steps: (1) research question; (2) search strategy; (3) data selection; (4) analysis and synthesis; and (5) reporting [2,13,31].

2.1. Research Questions

Based on the objectives of this study, the research questions were formulated to report how the implementation of technologies and Industry 4.0 benefit the forest supply chain. Research question 1 focuses on the state-of-the-art technologies in the forest supply chain. Research question 2 seeks to understand how Industry 4.0 and related technologies help forest supply chain research. We formulated the following research questions as follows:

RQ1. What state-of-the-art technologies have been implemented into the forest supply chain?

RQ2. How do technologies provide improvements to the forest supply chain in Industry 4.0?

RQ3. What are the benefits and impacts of technologies and Industry 4.0 in the forest supply chain?

RQ4. What are the key challenges and future research directions?

2.2. Search Strategy

We created a search strategy to gather papers on related topics. Based on the research topic and objectives, the search string was focused on three main themes: 'Industry 4.0', 'technologies' and 'forest supply chain'. We defined three categories based on three themes: 1. Industry 4.0 concepts and technologies related to Industry 4.0; 2. supply chain; and 3. forestry industry. According to previous readings, we identified possible keywords under each category from the current literature. For category 1, we included searching terms extracted and adapted from [1,11,14–16]: Industry 4.0; integrated industry; industrial internet; IoT; Internet of Things; artificial intelligence; Cyber-physical systems; additive manufacturing; simulation; cloud technology; big data; data analytics; RFID; unmanned aerial vehicle; blockchain; augmented reality; virtual reality; robotics. In category 2, we included the searching terms: supply chain*; logistic*; transport*; procurement. For category 3—forestry industry—the authors used forest*; timber; wood; sawmill; biomass. The search string combined searching terms together using 'AND' as categories 1 and 2 and 3. We tested possible keywords in pilot searches before we finalized the searching string. For example, with search terms and conditions unchanged, removing the searching term 'cloud technology' did not change the number of papers in the searching outcome. We excluded it from the searching string. Figure 2 presents the final version of the search string used in this study. We decided to use peer-reviewed, high-quality papers to obtain high-quality results. Scopus and Web of Science are the most common and reliable databases with high-quality peer-reviewed multidisciplinary papers. We chose Scopus and Web of Science as two databases to gather the related studies. The search string in Figure 2 was applied to both databases.

("Industry 4.0" OR "IoT" OR "Internet of Things" OR "integrated industry" OR "industrial internet" OR "Cyber-physical systems" OR "CPS" OR "additive manufacturing" OR "simulation" OR "data mining" OR "RFID" OR "artificial intelligence" OR "big data" OR "data analytics" OR "unmanned aerial vehicle" OR "blockchain" OR "augmented reality" OR "virtual reality" OR robotics) AND ("supply chain*" OR logistic* OR transport* OR Procurement) AND (forest* OR timber OR wood OR sawmill OR biomass)

Figure 2. Search string used to search related articles.

We set inclusion criteria for data selection. Since the concept of Industry 4.0 was initially introduced in 2011, this review only considered research papers published from 2011. To obtain reliable and high-quality results, this review only accepted peer-reviewed papers written in English. We used the filter function in the database searching as follows:

(language: "English"; publication year > 2010; publication type: peer-reviewed journal article). Table 1 presents the inclusion criteria used in this review to select papers.

Table 1. Inclusion criteria to select papers in this review.

Criteria	Description
Language	English
Publication year	Not earlier than 2011
Publication type	Peer-reviewed journal article
Subject/content	Research related to topics of Industry 4.0 AND technologies AND forest supply chain

2.3. Data Selection

After searching in two databases, we retrieved 2532 records from Scopus and 1793 records from Web of Science. Figure 3 is the flowchart of the PRISMA 2020 statement [30]. We used PRISMA to identify the included study in this review. As Figure 3 shows, the search was performed followed by identification, screening and inclusion. The total number of searching results from two databases was 4325. 1046 duplicate records were removed and 3279 papers remained for screening. The screening stage used the inclusion criteria in Table 1 to select studies related to the topic. Two steps were conducted in screening. The first step was to screen the titles, abstracts and keywords of the articles. After the first step of screening, 177 articles remained to the second step. The second step was to assess the full-text articles for eligibility. 132 articles were excluded with specific reasons. Some articles mentioned Industry 4.0 but did not apply any technology in their research. After screening full-text articles, 45 papers were selected for data extraction and analysis. Table A1 in Appendix A is the list of 45 included articles of this systematic review. The list shows the author(s), year, title and journal of included articles.

The basic characteristics of included articles were summarized after screening. The basic characteristics indicate the trend of the related topic in academia. Figure 4 shows the number of articles found in each journal. The top five journals with the most included articles were *Biomass and Bioenergy*, *Silva Fennica*, *Forests*, *Journal of Cleaner Production*, and *Applied Energy*. These five journals were the ones that published the most research articles in the related area since 2011. Figure 5 represents the distribution of publications by year. The tendency of published included articles by year is increasing from 2011 to early 2021. One factor can be the increasing interest of the related topic in academia.

2.4. Analysis, Synthesis and Reporting

In this step, data extracted from each included study were analyzed based on the research questions. To understand the results, the basic characteristics of included studies were extracted and analyzed, e.g., the distribution of publications by years and the number of articles found in each journal. To answer the first question, the technologies considered in each article were extracted for analysis. The benefits and impacts of technologies and Industry 4.0 were analyzed for the second question.

The findings of this literature review are presented in Section 3. The results are presented based on the content analysis of selected papers. According to the results, a framework was presented with the content analysis.

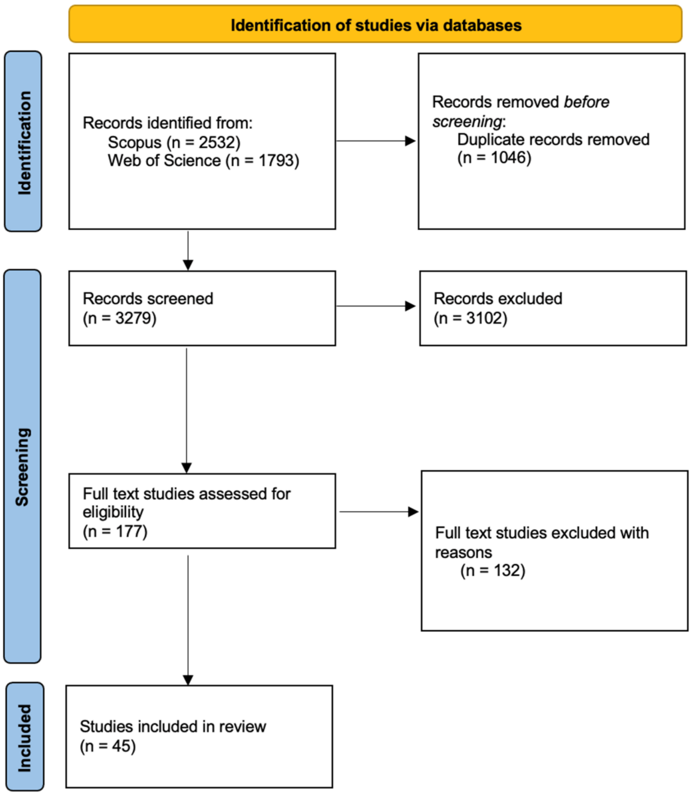

Figure 3. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart of this systematic literature review, based on the PRISMA 2020 guideline.

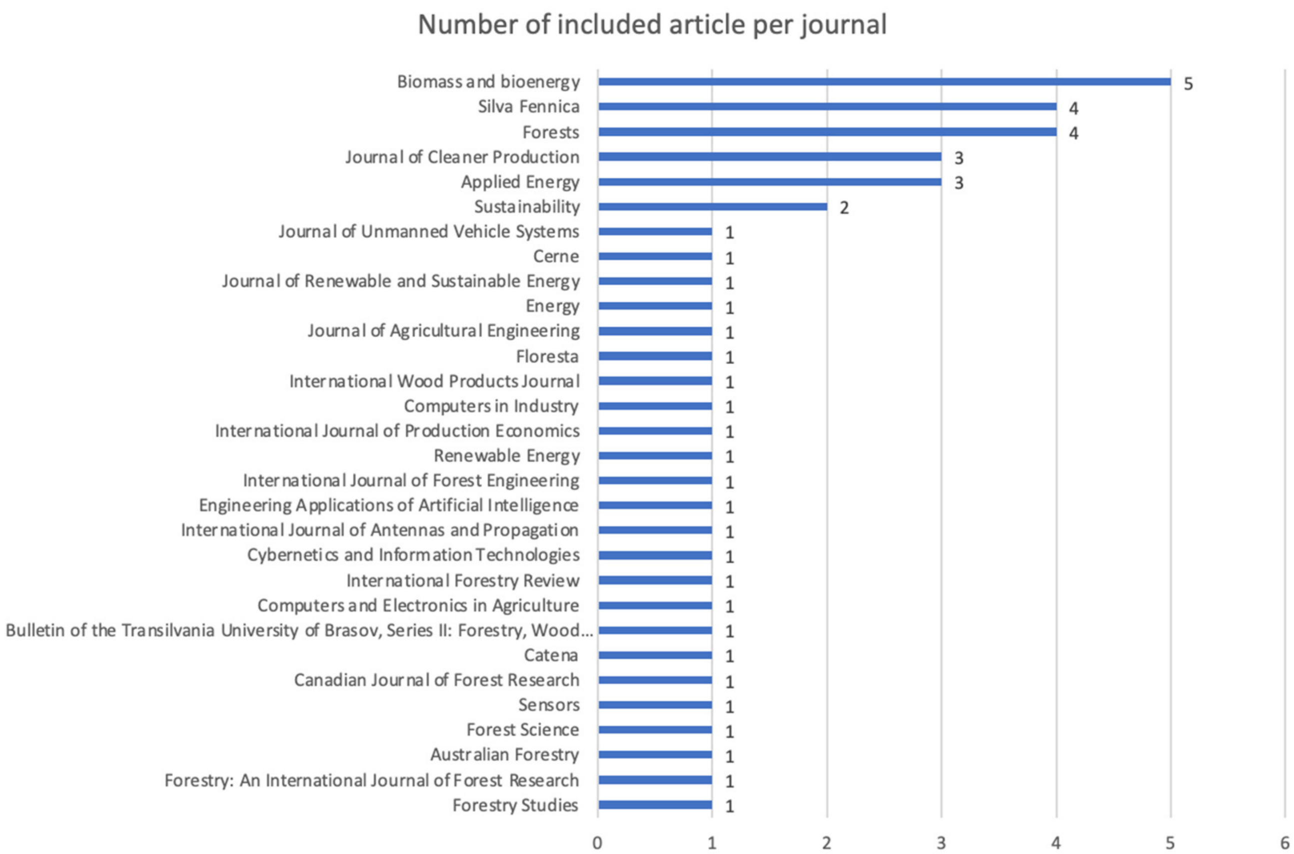

Figure 4. Summary of the selected articles sorted by journal.

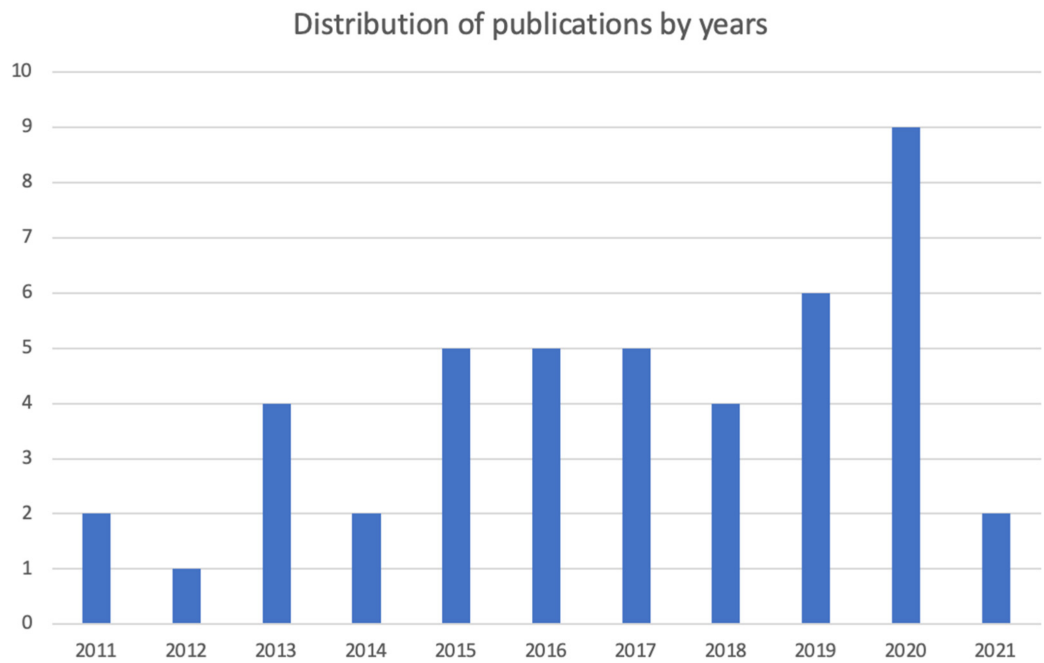

Figure 5. Distribution of publications by years.

3. Development of a Framework

This section develops a framework of the forest supply chain in Industry 4.0 based on the systematic review results and content analysis. In Figure 6, we present the conceptual framework of this study. The framework is structured into three components according to the aspects of the technology: (1) supportive physical and digital technologies to support the processes of the forest supply chain from raw material to end-users; (2) improvement and characteristics of the forest supply chain in Industry 4.0; and (3) strategic outcomes of the forest supply chain in the era of Industry 4.0. The following subsections in this section explain each component of this framework.

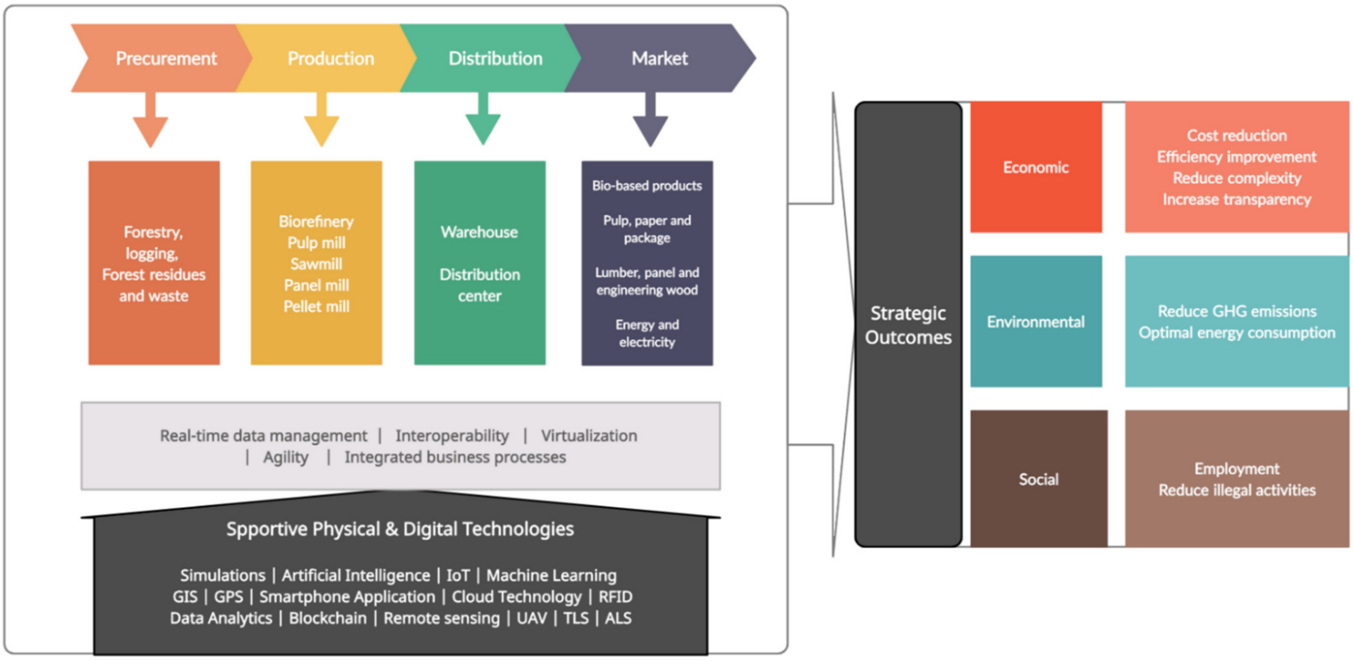

Figure 6. A framework of the forest supply chain in Industry 4.0.

3.1. Supportive Physical and Digital Technologies Implemented in the Forest Supply Chain

This subsection focuses on the supportive technologies applied in different phases of the forest supply chain towards Industry 4.0. Multiple technologies are applied to change or optimize the traditional operation of the forest supply chain. The results of the systematic review show that there 16 disruptive technologies have been applied to the forest supply chain to date. These technologies have implemented a range of phases, operations and processes of the supply chain in multiple ways. According to the data we extracted, as shown in Table 2, 16 physical and digital technologies were considered by the authors of the included articles. These technologies are simulations (Sim), artificial intelligence (AI), geographic information system (GIS), Global Positioning System (GPS), machine learning (ML), IoT, RFID, smartphone applications (SA), Cloud technology (CT), blockchain (BC), Bluetooth (BT), remote sensing (RS), data analytics (DA), unmanned aerial vehicle (UAV), terrestrial laser scanning (TLS) and airborne laser scanning (ALS).

Table 2. Technologies considered by the authors of the included studies.

Reference	Sim	AI	GIS	GPS	ML	IoT	RFID	SA	CT	BC	BT	RS	UAV	TLS	ALS	DA
[28]							X									
[32]	X															
[33]	X															
[34]	X															
[35]	X															
[36]	X															
[37]	X															
[38]	X		X													
[39]	X		X													
[40]	X															
[41]	X															
[42]			X	X												
[43]			X													
[44]			X													
[45]	X		X	X												
[46]			X													
[47]			X													
[48]			X													
[49]			X													
[50]			X													
[51]				X			X	X					X	X		
[52]													X			X
[53]								X							X	
[54]						X										
[55]					X											
[56]	X															
[57]	X															
[58]				X		X	X	X	X							
[59]		X														
[60]		X														
[61]			X													
[62]		X	X													
[63]			X													
[64]												X				
[65]							X									
[66]							X									
[67]							X									
[68]				X		X	X	X		X	X					
[69]	X															
[70]										X						
[71]										X						

Table 2. *Cont.*

Reference	Sim	AI	GIS	GPS	ML	IoT	RFID	SA	CT	BC	BT	RS	UAV	TLS	ALS	DA
[72]			X													
[73]			X													
[74]							X									
[75]							X									
Total	14	3	16	5	1	3	9	4	1	3	1	1	2	1	1	1

Figure 7 shows the chart of the number of articles mentioning each technology. According to the data extracted from the selected studies, the most used technologies considered in the forest supply chain in Industry 4.0 were GIS, simulation, RFID, GPS, smartphone applications, IoT and blockchain.

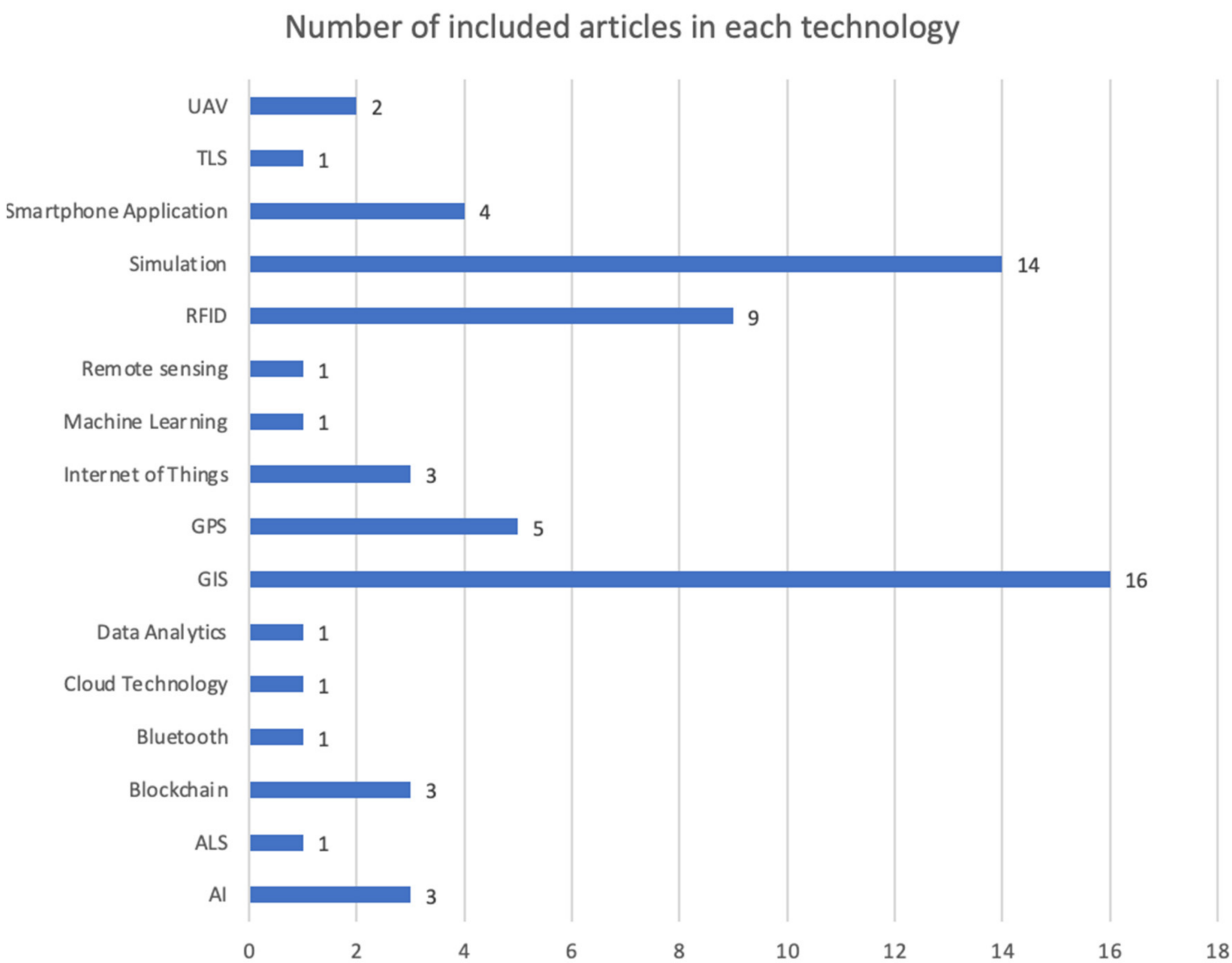

Figure 7. Number of articles mentioning each technology.

3.1.1. Tools of Supportive Technologies in the Forest Supply Chain

Several tools of GIS, simulation and GPS were considered by researchers in optimizing the forest supply chain. The simulation software are support tools that have contributed to visualize and optimize the forest supply chain. Simulations used simulation software as a tool to simulate the optimal options for the research problems. Three simulation software appeared more than once in the results: Witness® [32–35], AnyLogic® [36–39] and

ExtendSim® [40,41]. The simulation software are able to evaluate, compare and optimize their designed model. Two simulation models were mostly used by selected studies to achieve their objectives. These simulation models were the agent-based simulation model and discrete event simulation model. Karttunen et al. [39] used a combination of agent-based and discrete-event simulation models to compare an intermodal container's cost efficiency in truck logistics for the long-distance transportation of forest chips.

GIS software and GPS devices were used to collect territorial data and analyze the road networks of transportation. The results of the review show that most GIS are used for biomass supply to allocate biomass or to select bioethanol facilities (biomass energy plants). Raghu et al. [38] indicated that the benefit of using GIS for biomass-supply studies is that GIS can accurately calculate transportation truck parameters (travel distances, times and cost) and optimize routes. The results show that two GIS software were used in the forest supply chain: ArcGIS and QGIS. ArcGIS is a network analysis tool to perform spatial analysis [42–46]. The authors in [43] used the ArcGIS Network Analyst combined with the Dijkstra algorithm to find the least-cost paths based on distance, time or weighted cost [43]. The GIS software has also been used for road transportation network [44]. QGIS is an open source GIS software used for territorial analysis [47–49]. The authors in [47] used QGIS software and Google Maps Directions API to obtain territorial information for studying the economic potential of wood biomass. The authors in [49] used the QGIS network analysis library to compute the public road network. Some studies used the GPS to collect data of trucks' transportation movements [42,43,45]. GPS can track and monitor the movement information of truck transportation [43]. GIS is also widely used to identify an optimal location for forest biomass facilities or factories. Zhang et al. [44] developed an optimization model using GIS technology to collect the data of candidate locations of bioethanol facilities. Lin et al. [50] used a simulation model with GIS to locate the biomass-to-biofuel factories.

The authors in [45] used GPS to track movement information, resource measurement and managing forestry operations [45]. Two GPS devices were considered by the authors of the included studies: Trimble® ProXH coupled with a Trimble® NOMAD [45] and Visiontac VGPS-900 GPS receiver [42]. The GPS receiver can record the location and speed information of the trucks [42].

3.1.2. Supportive Technologies Implemented in Different Phases of the Forest Supply Chain

Table 3 shows the different technologies used in the different processes in the supply chain with references to included studies. According to the content analysis of included studies, the processes mainly focus on forest management, forest inventory, harvesting, planning, procurement, production, transportation, sales and the entire supply chain. Several integrated systems or methods combined with multiple technologies were developed to apply to the supply chain in the included studies. Multiple technologies were applied to forest management and inventory. Pichler et al. [51] built a 3D forest model based on UAV and TLS technology for forest inventory, forest management and harvesting. Puliti and Granhus [52] performed data analytics with UAV data on the operational management of regeneration forests compared to the model with ALS data. Siipilehto et al. [47] used the ALS-based method and a smartphone application called Trestima for forest inventory. Trestima is an image analysis application for stand-wise forest inventory [53]. Yu et al. [54] developed a collection platform called FEFCP using IoT technology (ZIGBEE protocol) to monitor, manage and control the forest environmental factors for forest management. The ZIGBEE protocol is a highly reliable wireless data transmission net (IoT technology) which is one type of wireless connection [54].

Some studies applied technologies to the planning and procurement of the forest supply chain. A machine learning approach was developed for sawmills to generate a learning model in wood allocation planning [55]. Fernandez-Lacruz et al. [40] used simulations on forest chip suppliers and integrated supply planning. Gautam et al. [56] used simulations to develop a novel approach on the operational level of the wood procurement system in the forest products industry. Windisch et al. [57] used simulation software to develop a business process model for forest biomass procurement.

Technologies also cover the harvest operations and pre-harvest. A new computer-aided approach was developed by Pichler et al. [51] on the basis of RFID for tree marking to replace standard survey procedures. The Treemetrics Forest application was used to store the tree parameters of RFID [51].

Several technologies are applied in the production phases of the forest supply chain. Šulyová and Koman [58] proposed a platform that applied IoT technology in wood monitoring wood processing in sawmills. This platform integrated RFID technology monitors, QR codes, a mobile application called SmartTree, a website, and a Cloud platform to provide real-time data to support management and better decision-making. Thomas and Thomas [59] proposed a designed approach using the artificial neural network in a simulation application used for a sawmill workshop. Alexandru Borz and Păun [60] proposed a system with object tracking, signal processing and AI to monitor wood operations in sawmills. Morin et al. [55] developed a machine learning-based model for wood allocation which could be a learning model for decision making in the wood-planning of sawmills. Zhang et al. [61] developed a decision support system using a GIS-based approach to select biofuel facility locations.

Fifteen included articles considered supportive technologies in the transportation of the forest supply chain. Araújo et al. [62] proposed an intelligent system using AI and the ArcGis software to adapt changes during the transportation process. Simulations were used to study the transportation method of forest chips and timber. Karttunen et al. [32] studied the optimal long-distance waterway transport logistics of forest chips by using discrete-event simulations. Vaatainen et al. [33] used a discrete-event simulation method to compare the truck performance indicators with different gross vehicle weights and payloads. Simulation software can calculate the processing time, weights, costs and working times of transportation methods in the supply chain [37]. Some studies considered using GIS data as simulation data to solve problems in transportation. Fernandes et al. [48] used GIS to perform an optimal route simulation to test the influence of wood stacking locations on forest transport costs. GIS and simulations are also able to estimate the transportation cost of forest chips and by-products [63]. Simon et al. [47] developed a tool using the territorial information obtained with QGIS, Python, and the Google Maps Directions API to simulate the economic potential of wood biomass. Smart sensors are used to measure and record large wood movement (transportation) [64].

Several studies considered using RFID to monitor the performance of the supply chain and trace forest wood (product) and biomass. Björk et al. [65] developed an RFID reader prototype for forest harvesting to trace logs from trees to sawmills using RFID-marking to connect the physical objects (wood) with their database counterparts. This prototype allows the automatic tracking of wood. Ranta et al. [66] developed an RFID-based tracking system called RfIDER to trace forest biomass which used RFID to manage biomass logistics to provide reliable, accurate and real-time information to biomass owners. In a similar paper, Sipilä et al. [67] proposed a passive RFID technology prototype for automatic identification, the tracking of wood products and the control of the supply chain. Furthermore, this prototype is passive, small and battery-free, which can be permanently embedded into wood. RFID-related technology was integrated with other technologies such as IoT, blockchain, QR codes and smartphone applications used for the traceability and tracking systems of (woody or biomass) products. Appelhanz et al. [28] developed an RFID traceability information system with databases and web applications to process and collect information on eco-friendly wood furniture for customers.

Some studies have attempted or successfully applied supportive technologies to the forest-based supply chain. Figorilli et al. [68] developed a blockchain technology prototype for the traceability of wood in the forest wood supply chain. This prototype involved an integrated system, Infotracing, using blockchain technology for the electronic traceability of wood from standing trees (timber marking) to final users (customers). It integrated multiple digital technologies, including RFID sensors, blockchain, IoT, GPS and smartphone applications. The RFID traceability information system developed by Appelhanz et al. [28] can provide transparent information on the whole supply chain to gain the customer's trust.

There are limited studies on the technologies applied in the distribution networks or warehouses of forest supply chains. This result shows that the distribution of forest-based products has not received much more attention within academia.

Table 3. Technologies used in the different processes of the forest supply chain.

Processes	Technologies
Forest management	Simulation [36,69] IoT [54] UAV [51,52] Data analytics [52] TLS [51] GPS [51] Smartphone application [51]
Forest inventory	ALS [53] UAV [51] TLS [51] Smartphone application [53]
Planning	Simulation [40] Machine learning [55]
Procurement	Simulation [56,57] Blockchain [70]
Harvesting	Simulation [56] UAV [51] TLS [51] RFID [51] GPS [51] Smartphone application [51]
Production—sawmill	Simulation [36] AI [59,60] Machine learning [55] IoT [58] GPS [58] RFID [58] Smartphone application [58] Could technology [58]
Production—biofuel factory	Simulation [50,61] GIS [50,61]
Production—bioethanol factory	GIS [44]
Production—biomass energy plants	GIS [46]
Transportation—forest chips	Simulation [32,35,39,42,43,63], GPS [42], GIS [39,42,43,63]
Transportation—wood/timber	Simulation [33,37,45,48], GIS [44,45,48,62] GPS [45] AI [62] Remote sensing [64]
Transportation—forest biomass	Simulation [47], GIS [47] RFID [66]

Table 3. *Cont.*

Processes	Technologies
Sales	Blockchain [71]
Entire supply chain	Simulation [34,38,41,49,72,73], GIS [38,49,72,73] RFID [28,65,67,74,75] Blockchain [68] IoT [68] GPS [68] Bluetooth [68] Smartphone applications [68]

3.2. Improvement and Characteristics of the FbSC in Industry 4.0

In this subsection, we present the second component of the framework. The supportive technologies provide several improvements to the forest supply chain. These improvements could be summarized in several domains: real-time data management; interoperability; virtualization; agility; and integration. The technologies improve or provide new characteristics for the forest supply chain in the context of Industry 4.0.

Real-time data management: With the supportive technologies implemented, the stakeholders in the forest supply chain are capable of making better decisions based on real-time information. IoT-based technology can provide real-time information between departments, smartphones, smartwatches and managers among parties in the forest supply chain to accelerate operational analyses, finding flexible solutions and better decision making [58]. IoT technology is also able to monitor forest environmental factors in real time [54]. The real-time FUELCONTROL® system provides the same monitoring function to monitor biomass quality [38]. RFID systems provide real-time information to managers as well [51]. The RFID tracking systems are able to provide real-time information, which allows stakeholders to allocate biomass according to customer needs [66].

Agility: The agility of the forest supply chain refers to the management of competency, flexibility, and speed among supply chain managers. For instance, the simulations provide statistical analysis to improve the agility of wood procurement systems [56]. Agility could be facilitated by real-time data management.

Interoperability: Interoperability refers to the technologies that are able to share seamless data and information sharing among the entities and organizations in the forest supply chain. Multiple technologies fulfill an enabler role to dynamically optimize the forest supply chain in Industry 4.0, such as IoT and RFID. These technologies achieve interoperability between sensors and actuators in the forest supply chain.

Integration: Integration means that the parties in the forest supply chain work closely together. Interoperability leads the integration. For instance, IoT's integrated blockchain tracking system achieved horizontal integration across the forest supply chain [68].

Virtualization: Visualization can be achieved through technologies such as UAV and TLS technology. The new computer-aided approach developed by Pichler et al. [51] is able to generate a 3D forest model of forest inventory that can replace the traditional survey procedure.

3.3. Strategic Outcomes

Strategic outcomes refer to the desired benefits and impacts of applying these technologies to forest supply chains in the era of Industry 4.0. This subsection discusses the expected benefits and impacts of the forest supply chain in Industry 4.0. Based on the analysis of the results of the systematic review, the strategic outcomes have three dimensions: the economic, environmental and social levels. Under each domain, the main outcome focuses were categorized. In Table 4, a summary of strategic outcomes in the different domains and focuses are presented with references. The strategic outcomes provide economic benefits, including cost reduction, efficiency, increased transparency and reduced complexity. For instance, RFID systems provide economic benefits to the forest industry because they provide real-time information to managers to enable better decision making [48]. This subsection presents the strategic outcomes. The strategic outcomes in environmental benefits include reducing greenhouse gas (GHG) emissions and optimal energy consumption. Some research has focused on the social benefit by applying technologies to the forest supply chain, including increasing job opportunities and reducing illegal activity.

Cost reduction: The outcome could be reducing several costs among parties of the forest supply chain. Mobini et al. [41] concluded that using bark as drying fuel instead of sawdust can reduce cost by approximately 1.5%. Fernandes et al. [48] indicated that the closer wood is stacked to the carbonization plant, the lower the transportation cost is. An integrated system with IoT technology can reduce operating costs in the wood processing of sawmills [63]. The intelligent system was developed by [62] to minimize the cost of timber transportation for different routes and trucks. Simulations were used in multiple studies to reduce the costs of the supply chain. A simulation-based model was developed to find the optimum inventory policy to minimize the total inventory cost in the forest products industry [36]. According to the discrete-event simulation conducted by Fernandez-Lacruz et al. [40], the supply cost could be reduced by increasing the utilization of forest biomass. Vaatainen et al. [33] confirmed that the tendency of the size increase in gross vehicle weights in timber trucking could reduce trucking costs and exhaust gas emissions.

Efficiency: The forest supply chain become more efficient in the era of Industry 4.0 with the development of supportive technologies. Intelligent technologies could increase timber harvesting efficiency [51]. RFID-related prototypes and tracking systems provide benefits at the economic level to improve efficiency as well. They provide real-time data to stakeholders/managers for efficiency improvement at the management and operational level of the supply chain. There is great potential to improve efficiency by using new technology and weight limits for heavy vehicles when transporting forest chips and forest industry by-products [63]. In a similar study, Prinz et al. [35] found that new vehicle types with an increased chip load capacity can improve the forest chip supply's fuel economy and efficiency.

Increase transparency: The environment of the forest supply chain becomes more transparent for secure transaction between parties in the supply chain. The RFID traceability information system (with databases and web applications) provides information on products collected across the whole supply chain from the raw materials to final products [28]. The purpose of this system was to provide the transparent information of the whole supply chain to gain the customer's trust. Morten Komdeur and Ingenbleek [70] reached a similar conclusion that the blockchain has significant effect on purchasers' trust regarding purchasing timber products. The blockchain technology prototype for the traceability of wood provides a transparent environment for confident transactions alone with the wood supply chain [68]. The untrustworthy environment came along with the growth of the economy and technology. The integrated systems combined with multiple technologies can be the solution to improve transparency.

Complexity reduction: The operations and activities are simpler than the traditional forest supply chain. Two included studies have focused on using technologies to reduce the complexity in the forest supply chain. The machine learning approach for wood-planning proposed by Morin et al. [55] can simplify the data computation phase of wood allocation. Using an artificial neural network (ANN) for simulation applications is simpler and less time-consuming for researchers/managers to perform simulations in the forestry industry [59]. The result shows that the machine learning-related method is a way to simplify the process of decision making in sawmills. However, there is only a small number of studies that have used machine learning in sawmills. Machine learning or AI has not been well studied or applied in the forest supply chain. It may be potentially beneficial for the entire supply chain to study this avenue in future research.

Reduce GHG emissions: The purpose of several studies was to reduce transportation and facility emissions in the logistics of transporting forest-based products. Raghu et al. [38]

observed that the real-time monitoring of biomass quality helped save 2% of the GHG emissions from the supply chain. The trend of the increasing gross vehicle weight in timber trucking was studied, and the results show that it can reduce exhaust gas emissions [33].

Optimal energy consumption: One strategy outcome of the forest supply chain in Industry 4.0 was finding an optimal way of energy consumption by implementing the emerging technologies. For instance, Zhang et al. [44] developed an integrated decision support system to determine optimized energy and GHG emissions for candidate locations of biomass facilities.

Reduce illegal activities: Reducing illegal activities could be one of the strategic outcomes at the social level. Pichler et al. [51] suggested that using RFID for tree marking can be a solution to reduce illegal logging. In similar studies, an RFID log tracking system can prevent illegal logging activities [74]. As a result, RFID-related technology can be the most promising solution to eliminate illegal wood material trading activities worldwide. RFID systems can track wood or biomass to monitor activities throughout the supply chain.

Employment: The increase in job opportunities is one of the social benefits as well. Technologies can increase job opportunities among parties of the forest supply chain. Lin et al. [50] focused on social benefits by using the method of the simulation model with GIS data to locate the biomass-to-biofuel factories to provide 16% more job offers.

Table 4. Summary of strategic outcomes extracted from the included studies.

Strategic Outcomes	Main Focus	Reference
Economic level	Efficiency	[33,35–37,39,45,63,65,73,75]
	Cost reduction or profitability	[28,33,35,37,39–41,43–45,47–49,58,61–63,65,73,75]
	Reduce Complexity	[55,59]
	Transparency	[43,44,51,70]
Environmental level	Reduce greenhouse gas (GHG) emissions	[33,38,44,61,65]
	Energy consumption	[44,61]
Social level	Increase job opportunity	[50]
	Reduce illegal activity	[51,71,74]

4. Challenges

The results show that technology can be beneficial as the forest supply chain transfers to Industry 4.0. These technologies improve the real-time data, interoperability, virtualization, decentralized, agility, integration between all different parties in the supply chain in Industry 4.0. The supportive technologies play an enabler role in the forest supply chain in the era of Industry 4.0.

The forest supply chain faces several challenges for implementing Industry 4.0 and emerging technologies. New technologies are available at the technical level for the forest supply chain. However, some technologies are rarely used in practice or commercially, especially by small and medium-sized enterprises [24,76]. The adoption and adaptability of emerging technologies can be one of the challenges in the forestry supply chain.

One reason for the limited implementation of technologies is their high cost of implementation. Investment in new technologies can be a major challenge in the forest supply chain, especially with regard to digital equipment, network infrastructure, blockchain and decision support systems. Most cutting-edge technologies and infrastructures require financial support from the government for research and development. Figorilli et al. [68] concluded that the implementation of blockchain increases the cost for of wood products supply. The same conclusion was drawn by Vilkov and Tian [71], as the application and systems of blockchain are complex and using them to prevent illegal timber trading is expensive. The costs for marking the trees with RFID tags are much higher than the standard method [51]. With the development of technologies in the future, there is a chance to reduce the implementation cost of new technologies and find less expensive materials for new technologies. Governments and organizations need to support the research and development of technologies for the forestry industry. When investments are involved, risk management and assessment are also required to protect these investments.

Legislative permission can also be another challenge because some technology is restricted by some countries' governments and policy. Blockchain-related technology and systems are not permitted or accepted in some countries and regions [71]. Furthermore, transparent timber trade-based on the blockchain does not gain much interest from legal authorities and organizations because of the increased transparency [71].

Cyber security is another challenge. Massive data are collected from multiple digital devices among the entities of the supply chain. With the high level of transparency and interoperability of the forest supply chain in Industry 4.0, there are some privacy and cyber and data security issues which lead to data leaks and cyber security problems. The improvement of cyber security such as via anti-virus software and technology is necessary in network development.

5. Conclusions

In this study, we investigated the academic papers on technologies and Industry 4.0 in the forest supply chain. A systematic literature review was performed as the research method. With a careful and specific selection process, 45 articles were selected that are were highly relevant to Industry 4.0 and technologies in the forest supply chain. A framework was presented based on the results of the systematic review. The current supportive technologies and their benefits and improvements in the forest supply chain were extracted with analysis and discussion. The characteristics of the forest supply chain in Industry 4.0 and its strategic outcomes were discussed as well. Building upon this investigation, research questions and objectives were outlined in Sections 3 and 4.

The supportive technologies discussed in Section 4 provide significant improvements in real-time data management, interoperability, virtualization, agility and the integration of the forest supply chain. The strategic outcomes of the forest supply chain with emerging technologies in Industry 4.0 can be summarized in economic, social and environmental dimensions, including cost reduction, efficiency, increased transparency, complexity reduction, reducing greenhouse gas emissions, optimal energy consumption, increasing job opportunities and reducing illegal activities. There is an increasing number of articles being published on the topic of Industry 4.0 and technologies in the forest supply chain. Approximately 46% of the included studies mentioned that the cost reduction or profitability is the benefit of their considered technologies. However, there were only three studies focused on social benefit. The forest supply chain in Industry 4.0 faces several challenges regarding the implementation of technologies. Most technologies in the included studies are available at the technical level but rarely used commercially.

The main contribution of this study was to highlight how emerging technologies have changed or can be used to support the forest supply chain in the era of Industry 4.0. This study was the first systematic review focusing on the benefits and impacts of technology and Industry 4.0 in the forest supply chain. It presents the benefits and impacts of Industry 4.0 and technologies to the forest supply chain. Moreover, this research provides a platform for further improvement regarding the forest supply chain in Industry 4.0. The topic of Industry 4.0 is still a new area. This study provides a framework and formulation for businesses to explore the concept further.

There are some limitations to this study. This review only included studies written in English. Some studies written in different languages may have highly relevant content for this study but were excluded. Also, there might be potential flaws in the searching process. Despite the fact that we spent a considerable amount of time searching and selecting the articles, we may overlook some papers during the searching process.

There are suggestions for further research directions in the related area:

- Identifying the reliability and risk of systems and network infrastructures in Industry 4.0 applied in the forest supply chain;
- Assessing the adaptability of Industry 4.0 for small and medium-sized enterprises in the forest supply chain;
- Investigating the barriers to small and medium-sized enterprises in the forest supply chain to implement new technologies in Industry 4.0;
- Investigating the solution to improve cyber security in the forest supply chain;
- Assessing emerging technologies to eliminate illegal logging/timber-trading activities worldwide.

This study provides a reference to help stakeholders understand the state-of-the-art technologies and the applicability of these technologies in the forest supply chain and understand the specific benefits of Industry 4.0 for the forest supply chain. These topics may be important for future research.

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Appendix A

Table A1. List of included articles in the review.

No.	Author(s)	Year	Title	Journal
[56]	Gautam, S. et al.	2015	Value-adding through silvicultural flexibility: an operational level simulation study	*Forestry: An International Journal of Forest Research*
[64]	Spreitzer, G. et al.	2019	SmartWood: Laboratory experiments for assessing the effectiveness of smart sensors for monitoring large wood movement behaviour	*Catena*
[36]	Shahi, S., and Pulkki, R.	2015	A simulation-based optimization approach to integrated inventory management of a sawlog supply chain with demand uncertainty	*Canadian Journal of Forest Research*
[32]	Karttunen, K. et al.	2012	The operational efficiency of waterway transport of forest chips on Finland's Lake Saimaa	*Silva Fennica*
[33]	Vaatainen, K. et al.	2020	The influence of gross vehicle weight (GVW) and transport distance on timber trucking performance indicators—Discrete event simulation case study in Central Finland	*International Journal of Forest Engineering*
[40]	Fernandez-Lacruz, R. et al.	2020	Simulation-based cost analysis of industrial supply of chips from logging residues and small-diameter trees	*Forests*
[41]	Mobini, M. et al.	2013	A simulation model for the design and analysis of wood pellet supply chains	*Applied Energy*
[37]	Kogler, C. et al.	2020	Simulating Combined Self-Loading Truck and Semitrailer Truck Transport in the Wood Supply Chain	*Forests*

Table A1. *Cont.*

No.	Author(s)	Year	Title	Journal
[58]	Šulyová, D., and Koman, G.	2020	The Significance of IoT Technology in Improving Logistical Processes and Enhancing Competitiveness: A Case Study on the World's and Slovakia's Wood-Processing Enterprises	*Sustainability*
[59]	Thomas, P., and Thomas, A.	2011	Multilayer perceptron for simulation models reduction: Application to a sawmill workshop	*Engineering Applications of Artificial Intelligence*
[47]	Simon, F. et al.	2021	Modelling and simulation of the wood biomass supply from the sustainable management of natural forests	*Journal of Cleaner Production*
[42]	Simwanda, M. et al.	2015	Modeling biomass transport on single-lane forest roads	*Forest Science*
[43]	Sosa, A. et al.	2015	Managing the moisture content of wood biomass for the optimization of Ireland's transport supply strategy to bioenergy markets and competing industries	*Energy*
[55]	Morin, M. et al.	2020	Machine learning-based models of sawmills for better wood allocation planning	*International Journal of Production Economics*
[38]	Raghu, K. C. et al.	2020	Lifecycle Assessment of Biomass Supply Chain with the Assistance of Agent-Based Modelling	*Sustainability*
[54]	Yu, Z. et al.	2014	IoT forest environmental factors collection platform based on ZigBee	*Cybernetics and Information Technologies*
[44]	Zhang, F. et al.	2017	Integrating GIS with optimization method for a biofuel feedstock supply chain	*Biomass and Bioenergy*
[48]	Fernandes, D.L. et al.	2019	Influence of wood stacking location on forest transport costs	*Floresta*
[49]	Laurén, A. et al.	2018	Improving the financial performance of solid forest fuel supply using a simple moisture and dry matter loss simulation and optimization	*Biomass and bioenergy*
[69]	Broz, D. et al.	2017	Forest management decision making based on a real options approach: An application to a case in northeastern Argentina	*Forestry Studies*
[50]	Lin, C.C. et al.	2020	Forest biomass-to-biofuel factory location problem with multiple objectives considering environmental uncertainties and social enterprises	*Journal of Cleaner Production*
[72]	Aalto, M. et al.	2019	Feedstock availability and moisture content data processing for multi-year simulation of forest biomass supply in energy production	*Silva Fennica*
[73]	Aalto, M. et al.	2017	Dynamic simulation of bioenergy facility locations with large geographical datasets-a case study in European region	*Bulletin of the Transilvania University of Brasov, Series II: Forestry, Wood Industry, Agricultural Food Engineering*
[34]	Windisch, J. et al.	2015	Discrete-event simulation of an information-based raw material allocation process for increasing the efficiency of an energy wood supply chain	*Applied energy*
[61]	Zhang, F. et al.	2016	Decision support system integrating GIS with simulation and optimization for a biofuel supply chain	*Renewable Energy*

Table A1. *Cont.*

No.	Author(s)	Year	Title	Journal
[39]	Karttunen, K. et al.	2013	Cost-efficiency of intermodal container supply chain for forest chips	*Silva Fennica*
[63]	Laitila, J. et al.	2016	Cost analysis of transporting forest chips and forest industry by-products with large truck-trailers in Finland	*Biomass and Bioenergy*
[57]	Windisch, J., et al.	2013	Business process mapping and discrete-event simulation of two forest biomass supply chains	*Biomass and Bioenergy*
[68]	Figorilli, S. et al.	2018	A blockchain implementation prototype for the electronic open source traceability of wood along the whole supply chain	*Sensors*
[71]	Vilkov, A., and Tian, G.	2019	Blockchain as a solution to the problem of illegal timber trade between Russia and China: SWOT analysis	*International Forestry Review*
[35]	Prinz, R., et al.	2019	Analysis of energy efficiency of forest chip supply systems using discrete-event simulation	*Applied energy*
[45]	Marinello, F. et al.	2013	Analysis of a double steering forest trailer for long wood log transportation	*Journal of Agricultural Engineering*
[53]	Siipilehto J. et al.	2016	Reliability of the predicted stand structure for clear-cut stands using optional methods: airborne laser scanning-based methods, smartphone-based forest inventory application Trestima and pre-harvest measurement tool EMO	*Silva Fennica*
[51]	Pichler, G. et al.	2017	Comparison of remote sensing based RFID and standard tree marking for timber harvesting	*Computers and Electronics in Agriculture*
[66]	Ranta, T. et al.	2014	Radio frequency identification and composite container technology demonstration for transporting logistics of wood biomass	*Journal of Renewable and Sustainable Energy*
[65]	Björk, A. et al.	2011	Monitoring environmental performance of the forestry supply chain using RFID	*Computers in Industry*
[28]	Appelhanz, S. et al.	2016	Traceability system for capturing, processing and providing consumer-relevant information about wood products: system solution and its economic feasibility	*Journal of Cleaner Production*
[67]	Sipilä, E. et al.	2016	Experimental study on brush-painted passive RFID-based humidity sensors embedded into plywood structures	*International Journal of Antennas and Propagation*
[46]	Woo, H. et al.	2018	Optimizing the location of biomass energy facilities by integrating Multi-Criteria Analysis (MCA) and Geographical Information Systems (GIS)	*Forests*
[75]	Sundberg, P. et al.	2018	Traceability of bulk biomass: Application of radio frequency identification technology on a bulk pellet flow	*Biomass and Bioenergy*
[74]	Kaakkurivaara, T., and Kaakkurivaara, N.	2019	Comparison of radio frequency identification tag housings in a tropical forestry work environment	*Australian Forestry*
[70]	Morten Komdeur, E., and Ingenbleek, P. T.	2021	The potential of blockchain technology in the procurement of sustainable timber products	*International Wood Products Journal*
[60]	Alexandru Borz, S., and Păun, M.	2020	Integrating offline object tracking, signal processing, and artificial intelligence to classify relevant events in sawmilling operations	*Forests*

Table A1. *Cont.*

No.	Author(s)	Year	Title	Journal
[62]	Araújo, C. A. et al.	2017	A multi-agent system for forest transport activity planning	*Cerne*
[52]	Puliti, S., and Granhus, A	2020	Drone data for decision making in regeneration forests: from raw data to actionable insights1	*Journal of Unmanned Vehicle Systems*

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