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TIMBER TRACEABILITY AND SUSTAINABLE TRANSPORTATION MANAGEMENT: A REVIEW OF TECHNOLOGIES AND PROCEDURES

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Abstract: *There has been considerable research on sustainable forest management due to its importance in ensuring the long-term health of the forests and its industries. Traceability is an important tool to ensure that the wood and wood-based products are produced in a legal, sustainable, and ethical manner. Therefore, various technologies were implemented within the supply chain to monitor and trace the wood with the aim of fulfilling the traceability objectives. Using a systematic literature review, this paper provides a comprehensive state-of-the-art on the technologies and procedures used in timber traceability and transportation management. It debates traceability tradition and advanced methods such as smart marking, QR (Quick Response) codes, DNA fingerprinting, smartphone apps, RFID (Radio Frequency Identification), machine learning, and computer vision since these technologies enable the integrity of the supply chain by documenting the source of wood and following up on the wood in all the stages, beginning from the standing tree until the final customer. The paper also reviews the advancements in wood transportation management systems, including spatial databases, GPS (Global Positioning System), and fleet management systems, which ultimately lead to real-time monitoring and optimisation of transportation routes, leading to improved efficiency and minimal environmental impact. The review results acknowledge that financial constraints, infrastructure limitations, data management uncertainties, acceptance and compliance issues, and stakeholder commitment are still challenges to implementing traceability technology in the forestry sector. Moreover, this review not only highlights how traceability systems promote responsible forestry practices, ensure sustainable timber sourcing, and develop supply chain management, but also the advantages of utilising these technological advances at economic, social, and environmental levels.*

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1. Introduction

The challenges of the timber enterprises in the forest sector include critical concerns such as illegal logging, purchase, transportation, and manufacturing of wood [20]. Global research indicates that effectively combating illegal logging is possible with robust forest management controls, clear identification of wood origins entering the market, and comprehensive monitoring of timber sales, wood processing, and transportation. In addition, establishing collaboration between public authorities, law enforcement agencies, designated businesses, environmental organisations, and local communities is critical for achieving a sustainable forest management [84]. Traceability has become a worldwide concern that is quickly turning into a new standard for operating businesses and trading wood on worldwide markets [43], whereas the traceability of items and their attributes has emerged as a major concern in the worldwide supply networks [13]. Producers are aiming to reduce the risks associated with purchasing low-quality products, governments intend to determine what items they import, customers need reassurance that the items they consume are safe, wholesome, and long lasting, and the general public has the right to be up-to-date about what happens and, by extension, what producers, traders, and governments permit to happen in world-wide value chains. As a result, many traceability schemes are being built and applied across increasingly diverse value chains. They come, however, accompanied by critiques and challenges [9, 99]. In the last decade, timber-producing nations have created a diverse range of timber traceability systems [120]. This increased attention reflects, in part, a rise in the demand from foreign markets for items of lawful provenance. Buyers need to assess and mitigate the risk of sourcing illicit timber in their supply chains to comply with regulations such as the Lacey Act in the USA and the European Union Timber Regulation [105]. As a result, regimes in wood-exporting nations have become more attentive to exerting additional control throughout the wood supply chains and assisting the private sector participants in their nations in accessing these newly governed marketplaces [43]. When completely implemented, these traceability schemes ought to be capable of tracking single logs or batches of wood from the point of harvest all the way through the supply chain to local or worldwide sale [84]. Even though traceability systems introduce new regulations, private sector actors may instil their commodities with greater capacity to compete via systematising and simplifying administrative processes and quality assurance [22]. Businesses can also harness tracking applications to achieve narrow compliance with regulatory obligations, and to evidence it, in turn reducing their liability risk. Recognising the origin of the items, and every aspect of the supply chain, enables users of a traceability system to evaluate the legal, social, and environmental claims connected with those items [175]. Traceability applications, on the other hand, do not ensure the legality of the items; hence, a product may be traceable, but not always lawful. It is not easy to put in place wood traceability schemes, because wood supply chains are often very complex, and traceability procedures often have to be customised to the specificities of the supply chain, including the type of wood being processed, the methods and processing, the handling, and logistics, all of which represent major financial and labour costs [43]. In this process, traceability will nevertheless set a benchmark for how lessons learned, and good practices should be taken forward, as a guideline for the authorities of those countries that prefer to walk this path in the years to come. Technology-driven innovations that make use of big data collection, processing, and transmission, are making forest monitoring simpler, are able to trace the forest products from source to final use at less cost and in a more accessible format, and can make intelligent decisions about their use and management. Moreover, they improve governance by supporting swifter and more thorough research of social networks, rules, and regulations, as well as increased traceability and transparency throughout supply chains [164]. Before embarking on this systematic review, the author found previously published syntheses of similar subjects. One finding was that previous research has tended to focus on portions of the forest supply chain [163]. Another study reviewed the technologies implemented in the wood supply chain, but it did not consider some of them [61]. Some other authors focused more on technologies but did not describe the benefits of implementing them at the social, economic, and environmental levels [70]. The review developed by He and Turner [62] was mainly based on block chain technology. For this reason, this review is trying to analyse the most recent technologies, equipment, and best practices in timber traceability and sustainable transport management, as well as the outcomes of adopting those developments. Three research questions are proposed in this paper:

- Q1. Which technology/procedure has been used, and what are the advantages of this technology or procedure?
- Q2. What are the environmental, economic, and social outcomes of implementing these technologies and procedures?
- Q3. What are the challenges of these technologies?

The organisation of this systematic review is as follows: Section 2 details the methodology employed to identify, select, and analyse the research papers included in the study. Section 3 i) provides an overview of the selected papers, ii) provides the relevant definitions of timber traceability and sourcing, iii) identifies the advancements in timber traceability and sourcing, iv) highlights the developments in timber transportation management systems, and v) examines the strategic impacts of current technologies and methods, emphasising their advantages for timber traceability and transportation management. Additionally, it addresses the difficulties of integrating these technologies within the wood industry. Finally, Section 4 provides some conclusions and proposes directions for future research.

2. Materials and Methods

In this research, a methodical review was adopted on the techniques and processes used in tracing wood and transporting timber sustainably. To boost the quality of the review, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) technique for systematic reviews was used. The PRISMA statement was presented by Moher et al. [103] for the first time. A PRISMA systematic review is a method applied by scholars and professionals to produce a compact literature review report [90]. In previous years, many researchers have explored diverse PRISMA principles in different subjects, thereby giving an overall picture of the current literature [96, 132]. To conduct the literature review, the three recommended steps [96] were used, as outlined in Table 1.

While beginning a systematic literature review, the first thing to be done is to identify and recognise the important search terms. Consequently, a particular set of words was put together to be used in finding out where wood traceability technology is applied. The keywords and terms employed in literature searching are presented in Table 2.

Several databases and platforms like Google Scholar, Research Gate, JSTOR, IEEE, and Google were used for literature search. Consequently, a total of 7,687 relevant studies were initially identified of which 1,164 entries were removed as duplicates.

Stages in conducting a literature review Table 1

Stage 1	Exploring contemporary literature
Stage 2	Assessing the suitability of articles for inclusion
Stage 3	Extracting information and providing a concise summary

Search keywords/terms in web query Table 2

Topic	Search keywords/terms
Advances in timber traceability and sustainable transportation management	Wood traceability technologies, RFID, forest supply chain, QR codes, DNA barcoding, timber transportation, fleet management, GPS and GIS

After checking the titles and abstracts of these remaining 6,523 papers, a screening of their relevance to the study's goal was done, leading to a number of 6,093 studies. During the second phase of this systematic literature review, studies that explored technologies and methodologies used in wood traceability and sustainable transport management were considered. To satisfy this requirement, the full texts of the respective articles were checked separately, leading to a total of 430 articles that were regarded as eligible upon testing against the criteria. Of these, 305 full-text papers were excluded based on the set of inclusion and exclusion criteria proposed for this study, as presented in Table 3. Following the PRISMA methodology, 125 papers were incorporated into the study, as shown in Figure 1.

Table 3

The criteria used to include or exclude literature

Criteria	Inclusion	Exclusion
Year	1993-2023	Before 1993
Document Type	Book, Book Chapter, Reports, Conference Paper, Thesis	Reviews
Publication Type	Published articles	Article in press
Language	English	Non-English

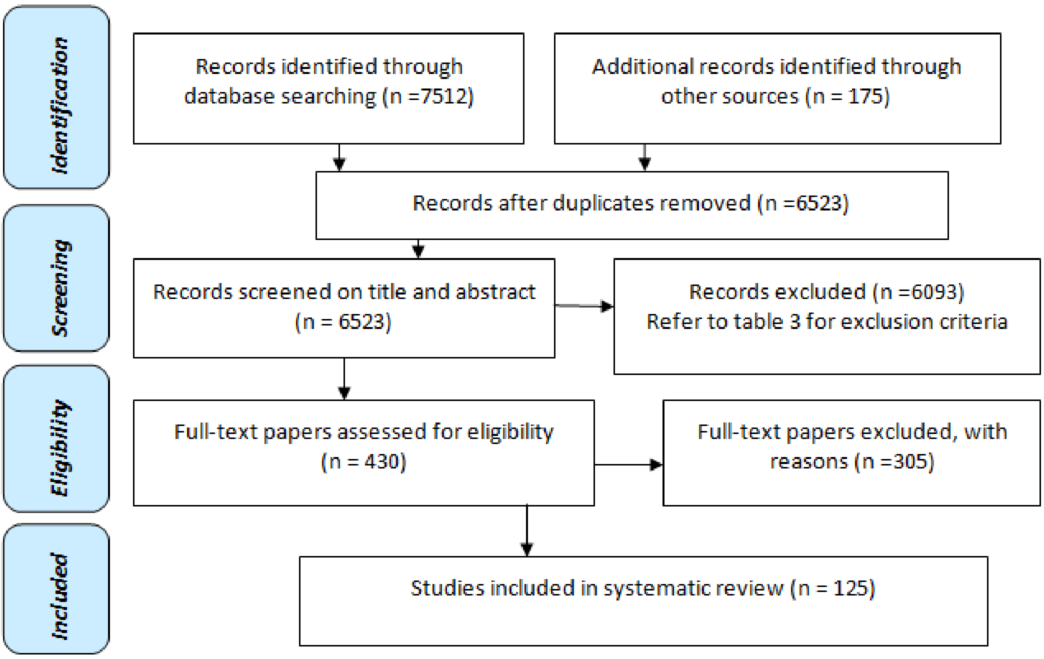

Fig. 1. *Flowchart of the systematic literature review, following the PRISMA 2020 guidelines*

3. Results and Discussion

3.1. Overview of Studies

Based on the outcomes of this systematic literature review, the findings are presented in this section. The review included 125 papers published in 87 academic journals, three published theses, 32 conference papers, one book, and two reports. According to the objective of this review, the selected papers were categorised based on different attributes such as the year of publication,the countries from which the papers came, the used technology, results, and outcomes that seemed relevant.

Figure 2 shows the year-wise distribution of the 125 selected papers from 1993 until 2023.The studies that were chosen satisfied the specified criteria for inclusion, and exclusion, as outlined in Table 3.

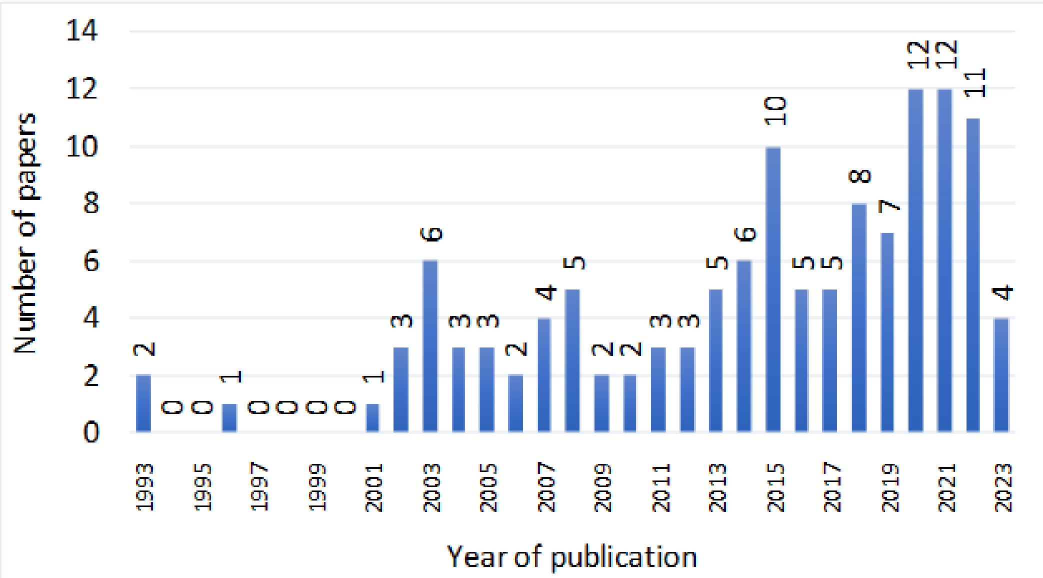

Fig. 2. *The distribution of papers categorised by their year of publication*

Research on wood traceability technologies and sustainable transportation management appeared to have increased after 2014. The publication period was limited with the aim to identify recent studies that were conducted related to the topic. There has been a steady increase in the number of articles published on the topic each year in recent years. This may be due to the fact that the illegal logging problem, transport issues of timber, and emergence of new technologies and management in forestry, particularly sustainable forestry at all scales, have gained more significance and attention both locally and globally.

Figure 3 shows the countrieswhere the selected papers were sourced. The sources were comprehensive worldwide, and included Europe, Asia, Africa, South and North America. However, Finland, Sweden, and Ireland seem to have the highestnumber of papers.

Figure 4 illustrates the distribution of papers by mentioning the technologies used for traceability. Based on the data extracted from the studies, the predominant technologies identified in the studies were RFID, barcodes, QR codes, DNA fingerprinting, and blockchain technology.

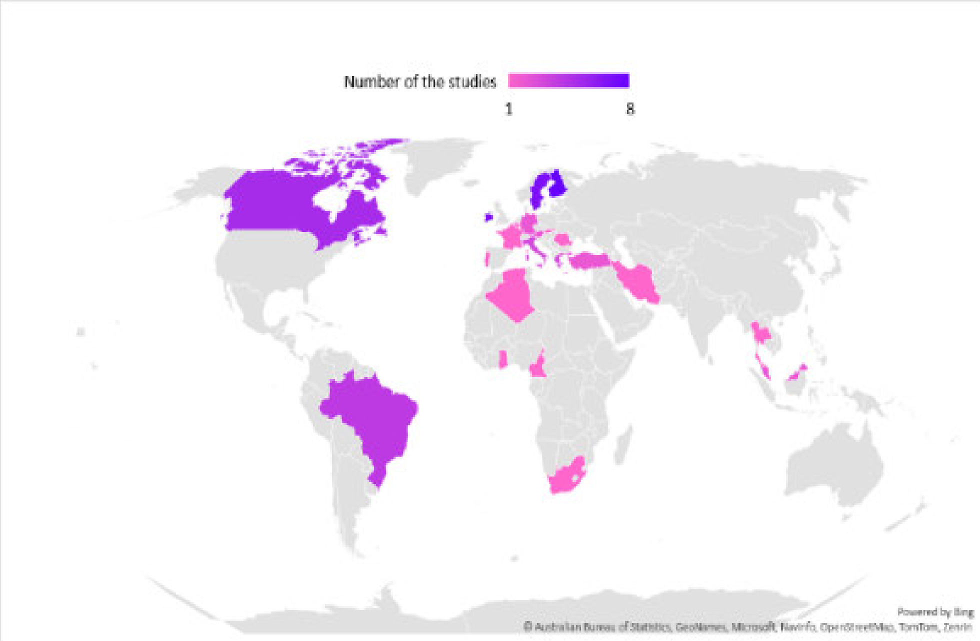

Fig. 3. *Number of the selected papers in each country*

3.2. Definitions Relevant for Traceability, Sourcing, and Marketing of Wood

Traceability systems guarantee the source of timber is legitimate and traceable and are an effective system to fight illegal logging. The long-term advantage of an effective traceability system is to encourage local milling byguaranteeing source availability, and eliminating rebels and low-quality items from the marketplace [169]. This section provides relevant definition for traceability, sourcing, and marketing in the context of the wood industry.

Traceability is defined as the ability to follow something through all the stages of production, i.e. harvesting, manufacturing, distribution, and marketing. This tracking system will usually incorporate relevant information per item through the supply chain, via a variety of technologies, such as "barcodes", "radio frequency identification" (RFID) tags, and other methods that also incorporate tracing systems [28, 107, 169].

A "chain of custody" assures that the certified parties document and record each phase of the production and circulation life cycle of timber as both a resource and an item. This system should ideally consist of a fundamental database that provides information to all clients via an uncomplicated login or comparable approach [158]. The data maintained inside this system should be clear and comprehensive in terms of both sustainability and compliance. The chain of custody will boost responsibility and simplicity of data verification, resulting in a shorter reaction time when crucial data is required (providing open entree to data at any step of the wood supply series) [124]. Potential clients should be capable to access applicable data about an exact sample or batch of wood with regard to both sustainability and amenability at any step of the supply series [56, 124].

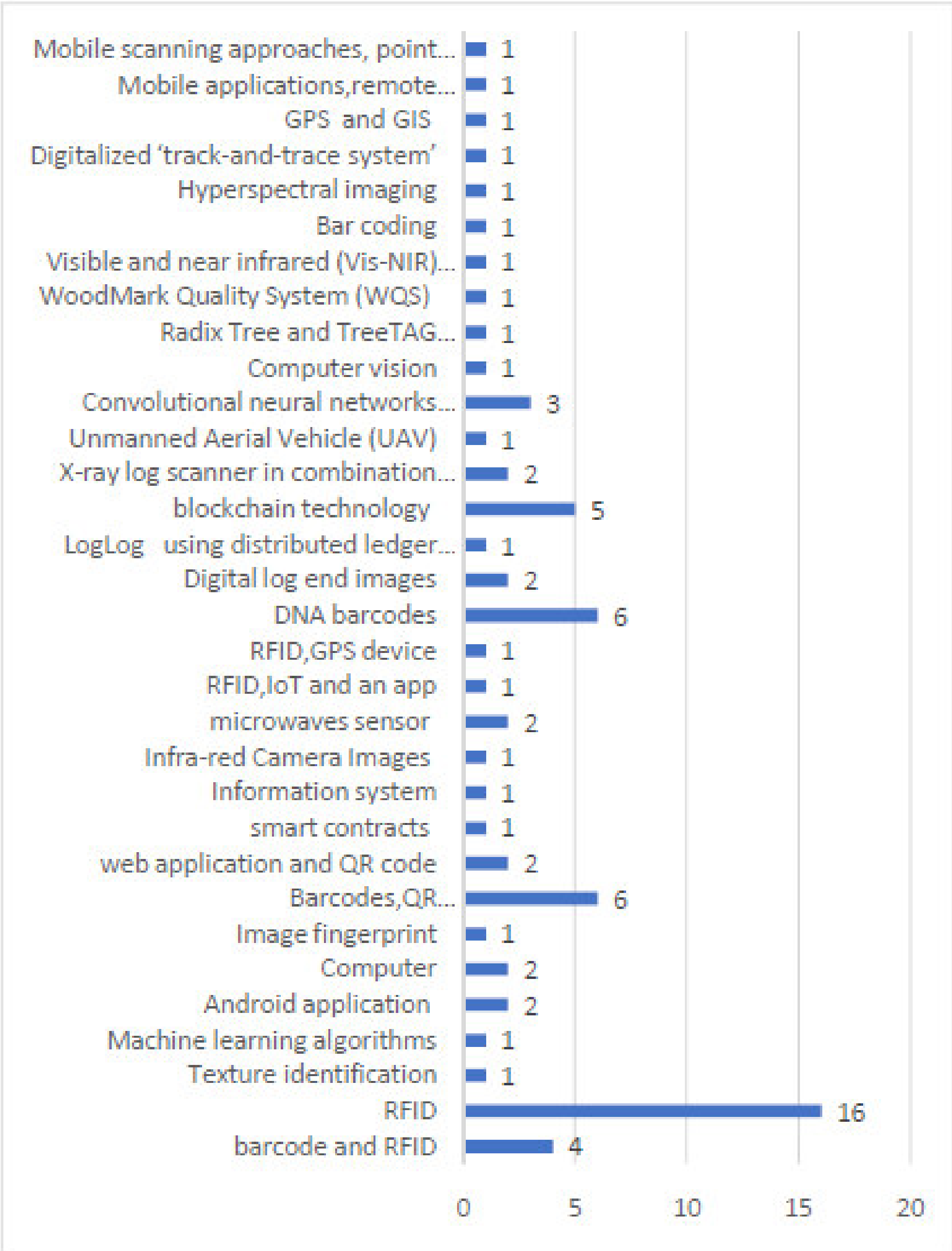

Fig. 4. *Numbers of papers mentioning each technology*

Responsible sourcing has developed into a supervision strategy for businesses and regimes to recognize, examine, and moderate any undesirable consequences along the supply series of their raw goods [23]. Responsible sourcing assists the supply chain sustainability [54]. Several EU participant states have consequently established sustainability standards for lawful and maintainable procurement of timber and solid biomass, constructed on the EU timber guideline for lawful sourcing of wood and the “Renewable Energy Directive” (RED) [111]. These needs can be shown through sustainable woodland administration certification structures, for instance, the “Forest Stewardship Council's” (FSC) Standards and Conditions or the “Program for the Endorsement of Forest Certification” (PEFC) [119]. Despite the fact that FSC and PESC contain all three dimensions of sustainability in their outlines, research on responsible sourcing in the biomass and wood industries has a tendency to emphasise ecological challenges. Conservation of biodiversity and safety of wetlands or main woodland areas are among the factors to consider [85, 111].

Green marketing: Environmentally sustainable goods and services must be developed and produced successfully in order to moderate the ecological impact of manufacturing activities and encourage cleaner production [30, 49]. Marketing is important for this process since marketing’s inputs are mandatory for establishing item ideas and designs [98]. Moreover, the production of green goods and services is sound for the goal of environmental sustainability only if it has the genuine option of reaching sustained prosperity in the marketplace [71]. Thus, marketing is also important in this process because it might improve the current status of developing a green marketplace by interacting with the customers, raising their awareness of ecological sustainability, and educating them about the benefits of green use of environmentally sustainable goods and services [137]. Consequently, advertisement is important in supporting both cleaner production and sustainable consumption [30].

Certification: Certification is a method in which a third party examines whether forest administration and use achieve a predefined ecological, commercial, and societal level and validates that the woodlands are managed in line with sustainability values [88]. Sustainable use of natural resources is defined as using them in a way and to a degree that does not degrade their ability to satisfy the requirements and aspirations of current and upcoming generations. The main idea behind certification is that customers would buy and, in certain situations, pay a premium for items originating from sustainable woodland management rather than those originating from non-permanently managed woodland or products whose origin cannot be proved [123, 165]. The FSC (“Forest Stewardship Council”)is a self-determining, non-administrative, non-profit organisation based in Germany that was created with the goal of establishing and raising consciousness of the necessity for a reliable connection with the world's forests [127]. Other national and regional certification agencies (for example, PEFC) exist across the world in addition to the FSC [93]. The FSC logo may be seen on a variety of wood and non-wood items, ranging from paper and furniture to medical supplies [173]. This group underlined the importance of establishing a scheme that could reliably recognise effective woodland administration as a source of sustainably produced wood products [81, 168, 173].

3.3. Advancement in Timber Traceability and Sourcing

3.3.1. Life Cycle Assessment

Tracking the efficiency of forest operations may help in the management and improvement of the forest based supply chain, which in turn can assist in the improvement of subsequent processes such as harvesting, transporting, processing, manufacturing,and storing [147]. To avoid illegal logging, timber tracking technology has been utilised to distinguish the timber unit and track the origin of logs or wood products [16]. It may also be utilised to look for information on timber in order to increase factory circulation management and build trust in wood products [143]. These technologies track timberthroughout all phases of the supply chain, beginning with marking the standing trees until the final user [44].

Life cycle assessment (LCA) is a technique used for analysing and evaluating the ecological consequences of a good, procedure, or action over the course of its lifespan [101]. LCA is a thorough way of evaluating a good's entire environmental impact,or, more broadly, the purpose for which the product is produced [21]. LCA is based on the existing ISO Standards 14040 and 14044 and consists of four primary mechanisms when utilising the methodology: 'goal and background description,' 'stock assessment,' 'effect evaluation,' and 'clarification' [146]. The fundamental principles analyse each of the inputs and outputs of a good at each step of its lifespan, including extraction, manufacture, transportation, and dissemination, use, reuse, and sustenance, reprocessing, and ultimate disposal [52]. Using one of numerous impact assessment methodologies, LCA is uneasy with consequences that influence universal concerns, for instance, world-wide warming, in addition to more specified harms that might damage people’s livelihoods and environmental healthiness such as for instance hazardous emissions [138]. This form of study is becoming increasingly relevant for producers and customers as governments drive a shift toward more sustainable manufacture, namely the de-carbonisation of fabrication schemes [141].

3.3.2. Technologies and Software Platforms Used for Wood Traceability and Sourcing

Stamping refers to marking the logs with a press and is the earliest way of considering log use, in which the log ends are struck with a hammer [42]. For further traceability, a unique code is employed, which is immediately appended to the log in the harvester head. This code can be linked to commerce and physical log data saved in a database. Although a camera can detect punches, environmental factors such as dirt and ice may cause problems with proper reading [169].

Using paint to mark logs is one of the oldest approaches to mark logs with dye, with the colour representing the code. The marking, which is similar to punching, can be done by hand or mechanically [76]. There are also issues with marking with dye on a drenched log-end, with snowfall and dirt, and with changing the colour [169].

Smart marking refers to a coding system that entails stamping patterns of dots or circles onto the ends of logs. These can be applied automatically by harvesting machines or using specific stamping equipment, and can then be scanned by portable or machine-mounted readers [24].

A Quick Response (QR) code has traditionally been used to track timber unit information, and it is a standard technique for timber tracking [171]. On the other hand, QR tags are not secure, as they may be readily duplicated or passed on from other items. Furthermore, these QR tags are challenging to see in some unfavourable situations, such as unclean, dusty, or rainy circumstances [8].

In 1952, the first barcode appeared in Philadelphia. Barcodes have become a widespread aspect of recent life, being used in world-wide commerce and on almost every item; they havecontrolled the marketplace for 40 years [95]. A barcodeis made up of a machine-readable code (in the form of numerals and a pattern of parallel lines of variable widths printed on an object or manufactured good) by a scanner [12]. Because of the nature of wood, the barcode tracking scheme is simple and cheap, but it is challenging to be widely used in wood commerce as well as in traceability [144, 171]. However, various barcode wood traceability applications exist, that use elastic labels with printed barcodes to monitor logged plants. Employees utilise a portable barcode scanner to scan, process, and disseminate information into a data bank once the tree has been cut [169].

Fingerprinting using DNA is typically based on yearly rings that are specific to each tree, whereas the informationis saved in a data bank along with models [39]. The genetic structure of tree populations relates to a geographical model, indicating that the source of wood may be detected and regulated by comparing the genotypes of timber samples to the genetic pattern found in sampling populations. The masses of different isotopes differ in the case of isotope fingerprinting [69]. Plants absorb many chemical components through water, soil nutrition, and photosynthesis. The distribution of isotopes presents various forms, and by linking these forms to different groups, it is possible to verify the source [75].

Micro-wave sensorsenable the acquisition of an internal mark of the timber goods, which was originally used for detecting timber attributes such as twists, cross-grains, and mechanical features of timber [169, 171]. The transmission of these types of waves through timber is significantly affected by the moisture content and the presence of characteristics liketwists and cross-grains, which vary more from one board to the next and are utilised for automated identification [50].

SmartTree app is a software for collecting wood traceability data, which was developed to assist operators in the field, from timber marking to cutting phases, by providing a simple and easy-to-use smartphone application [44]. The information entered into the app is saved in a local database before being synchronised with a remote server. Furthermore, the app collects data by making use of various internal smartphone components (for example, GPS and Bluetooth) [160]. The “GPS” receiver is used to figure out the location of the trees while Bluetooth is used to connect the smartphone to an external portable RFID reader. Remote server synchronisation requires internet access, and this process can be performed both in the field (if a connection to the internet is available) and after the field activities, when a signal from the internet becomes available [44].

RFID (Radio-Frequency Identification)is an indirect wireless gadget method that transfers data from a device via radio-frequency radiation placed on a good in order to perform automated identification and tracking. RFID technology has the goal of advancing the management of inventory and the supply chain. RFID tags can be assigned to goods and used for management and control [169]. The use of RFID is now the most advantageous method of identifying logs. Its readability in actual tests and demonstrations was nearly perfect. Another advantage over other approaches is that it is difficult to cheat. However, there is still room for improvement in this technology. The present trend for RFID technology is encouraging, and the price per tag is predicted to reduce [107]. Tracking in wood packing material may be assured with appropriate heat treatment, since radio technology now provides appropriate options. Aside from basic thermal management in wooden packing material, other information such as amount and wood origin can be included on the same label [128, 129, 169].

The biometric method identifies the entity by extracting some unique features, for example, the fingerprint of the timber block. Not only are the outcomes excellent, but the fingerprints are additionally secure and private [133]. Schraml et al. [148] scanned 886 Scots pine boards, then utilised the photographs as fingerprints to recognise single planks. The method's precision approached 100% [148].

Oriented Briefing techniqueis a quick and effective image comparison method that utilises the Gaussian pyramid to select the image's points of interest and identifies the patch's focus centroid to determine the most important points' positioning [142]. This approach is cycle constant and resilient to noise. Furthermore, such properties are intrinsic to the biometric qualities of a piece of wood and are therefore not communicable to anyone else. Thus, it is viable to trace a fragment of the wood's individuality [162].

Blockchain technologyis one of the earliest developments in the field of localised information technology [2]. The concept of this expertise dates back to 1991, when Stuart Haber and Scott Stornetta published the primary effort on a cryptographically safe block chain [87]. The term blockchain comes from the piece of information that this disseminated database features a chronological series of blocks, with each block containing a record of proper events on a network, paperwork, or deals [82]. The objective is to have the majority of system members validate the content of every block. Whenever a block is filled in and validated, it is not possible to delete or change it [184]. Each block might be defined as a section of encrypted data. In principle, anybody within the scheme may contribute data to the network of blocks and review the data at any time, but no one can alter the data unless they have appropriate authority [68]. As a consequence, all of the blocks produce a comprehensive and unchangeable past of the network's operations, which is collective with all system contributors. When a block is authenticated, it is added to a chronological series of other blocks, hence the term blockchain [68]. As a result, the blockchain is a chain that maintains demonstrable records of every individual deal, document, and so on that has ever occurred in the system [3, 68].

3.3.3. Sensing Platforms Used in Documenting Sourcing and Traceability of Wood

To achieve the objectives of site management, the forester needs to collect data and information about the site and, at the same time, to carry out operations such as thinning, tending, and cutting [11]. With the advancement of science and technology, equipment useful for operations has emerged [179]. There are various reasons for setting up a sensor-based forest monitoring system [118]. One of these is associated with production - the measurement of growth rates and harvestable yields of trees. Another is associated with ecological management - or measuring the inputs of rainfall and the outputs of plant transpiration (water demand), drainage, and runoff [16]. Ecosystem management also needs to monitor tree health and physiological stress to ensure that the forest system will remain viable for the indefinite future [166]. These monitoring systems are also needed to increase knowledge and control over climate change [80]. The same or similar sensors will be used in all situations, although with varying distribution densities and measurement frequencies. Several sensing platforms are used in the forestry sector to document and trace the wood [114]. This sectionprovides some examples of sensors that gather data and give wood biometrics for storing, transferring, and sharing finely sampled data that may improve wood traceability.

LiDAR sensing appears to be one of the most favourable methods for measuring timber volume and following its journey through the supply chain. The limitation is only the high cost [6, 114].

Proximal sensing platforms play a crucial role in improving mobility and cost efficiency through accurate estimates of wood volumes [41], including platforms involving Augmented Reality AR and mobile devices [114]. Estimates are provided in real time, and comprehensive data is stored and sent. As a result, these will aid with the sourcing and monitoring of wood [114]. Furthermore, the advancement of low-cost methods (for example: mobile LiDAR and AR-enhanced photogrammetry) will support gathering massive amounts of information. The limitation of these platforms is to translate this large amount of information to decision makers [114].

The Radix Tree platform from Global Traceability Systems allows purchasers to gather information from merchants in order to set up a chain of custody [115]. This platform additionally provides legality danger evaluations constructed on submitted data, which is a mandatory footstep for conformity with the European Union Timber Regulation (EUTR). It also aids customers in handling their goods and shipping inventories, offering safe encryption and confidential information storage, and bringing in data from numerous set-ups [115].

BVRio's Responsible Timber Exchange utilises large data to determine whether possible vendors are in compliance with legal wood regulations in the United States and Europe [115]. To evaluate the likelihood of illegality, the dataset uses not only authorised paperwork, for instance, logging licenses and plant functioning licenses, but also authorised records of woodland owners, loggers, and even woodland engineers engaged in a consignment. Buyers can use this data to assess suppliers based on the tracking of their wood and fulfilment of particular legal, conservational, cultural, and labour requirements [115].

UHF (ultra-high frequency) RFID transponders have been developed specifically for marking round timber [60]. Sensing elements, like moisture or heat detectors and passive transmitters, may be added to RFID systems to improve their functionality [35]. A functioning transceiver is a type of radio sender that runs by applying its own internal charger packs and transmits verification and measurement information to a foundation platform or through a connection of additional sensors. Active radio-founded wireless sensor technologies involve Bluetooth LE, ZigBee, and Dash-7 [60]. Some authors used NFC-enabled cell phones and wireless internet access for gate monitors to transfer data from RFID-tagged biomass containers. Broadly, vehicle monitoring in (near) actual time entails evaluating the truck's position and state (such as the engines condition or weight context) and sending the data to a server, where it is stored for analysis and testing [37]. For evaluation and representation, desktop or web-based geographic-information systems can be used. Web-based systems have the benefit of being internet-portable,using standardising services, and displaying immediately the location along with additional information from sensors [167].

3.3.4. Software Used in Documenting Sourcing and Traceability of Wood

Borz and Proto [17] evaluated a free AR-based application capable of gathering essential log parameters like diameter and length, which are usually necessary to calculate their volume. Despite the fact that the application was proven to offer very good accuracy outcomes and it is free, it does not include log scanning functionality [180].

The Forest Design Scanner software, on the other hand, supports log scanning. Borz and Proto [17] studied the time resources and effectiveness of scanning logs using this app, concluding that the time required to gather data on a single log is equivalent to that of a comprehensive traditional measurement [17]. If the accuracy standards are satisfied, there are various additional built-in characteristics that might make it a strong practical solution, like the ability to generate immediate-time predictions and store and send comprehensive data. As a result, these will aid with the sourcing and monitoring of timber throughout the supplynetwork [114].

Commercial RFID readers with specifically built software were used in saw mills for log identification [15]. To protect the readers from potential crashes, dirt, and dust, they were kept in strong aluminium casings [59]. The reader structures were outfitted with tough metal antennae. RFID reader setups were strategically placed above conveyor systems at two crucial points in two industrial facilities located in Finland and Sweden. These points include the log separation station, where logs arrive at the plant, and the plant consumption station, where logs are processed into boards. Because of the reader's position over the conveyor, the reader may be installed in plants with little alterations to the current conveyors [15, 59]. The amount of data created by preserving the whole past of single wood items (tree-log-board-upgraded goods) across the supply network is massive. To successfully utilise these details, a data structure that facilitates reliable information reclamation is required [15]. To boost the traceability data stocking efficiency, event data gathered from RFID users and the procedure schemes ought to be cleaned and compressed [15]. When an RFID tag comes into range of an RFID reader in an operational setting, the RFID reader application starts a continuous process to retrieve data. The resulting data stream consists of structured feedback tuples, which include specific parameters such as the reader identity (ID), the Electronic Product Code (EPC) following the rules set by the EPC Global standard, and temporal information showing the exact instant when the data was acquired. The EPC functions as a distinctive identifier that allows the precise recognition of specific items in the system, hence improving operational efficiency and simplifying smooth asset management [15].

The virtual SawMill is a robust graphic simulator of sawmill processes that may make use of digital logs obtained through CT scanning and saved in the Swedish Stem Bank [17, 116]. It would generate a 3D-model of the outside contours of the sawlog and its interior structure. Then the application generates cutting options. The application includes many analysis modules. Physical and economic findings of the sawing process areprovided. Furthermore, the software may leverage log data generated by the sawmill's 3D profile log scanners [24].

Zerizer et al. [182] developed a software application represented by an operator interface and server interface using Visual Basic 2008 [182]. In the application, each work station requires the setting up of a personal computer. The computers will be connected by network to a computer installed at the direction of production. The client application is installed on each PC and a server application is installed at the level of the central PC as well as all central databases. The software interface provides the operator with access to the data products on which the operation is to be done. To work, the operator must input the operation code that was given with the product range [182]. In addition to the data about the operation that will be presented automatically, the server enables communication with the operator interface, which may be accessed by clicking on the listen button once it is in position. This allows to collect production data from each operator interface in real time, allowing to track production, find product progress, and establish product traceability [182]. This software application for real-time monitoring of production is a second transformation, which is a continuation of the wood traceability of the raw to semi-finished product; it can better inform on the

progress of production and locate gaps, bottlenecks, and can also be used for planning automation of production line, which will only be more beneficial [182].

3.3.5. Tools and Software Used in Documenting Sourcing and Traceability of Wood

Advanced, lightweight mobile devices, along with affordable technologies that can quickly estimate log volumes are ready to overcome several limitations present in prior wood measuring methods [114]. In addition, GPS technology, which relies on satellites, improves traceability by accurately defining the limits of wooded areas and farms. It also tracks the movement of resources from their starting point to ports, processing plants, and final sales locations [164]. Mobile phones are increasingly being used for gathering information about the forest stock. Trestima and MOTI are two different mobile device applications that are currently available [147]. Trestima is a mobile forest stock app. Smartphone images are used for calculating and determining forest inventory information. Data is sent to the internet and analysed there, improving battery life. MOTI has a striking resemblance to Trestima, however with a distinct focus on catering to the needs of industry experts. The application does not need a connection to the internet because reports are stored on the phone's memory [147]. "MOTI" and "Trestima" are both tools that assist foresters in collecting data on the number of trees in a forest. Therefore, with the latest data on forest stocking, this information may be used as an initial step in efficiently managing the "FbSC" [147].

3.3.6. Machine Learning and Computer Vision

Machine learning, a subset of artificial intelligence, enables computers to learn from data without explicit programming [31]. It begins with event reporting to detect features and patterns, enhancing future analyses. Deep learning, a type of machine learning, uses artificial neural networks (ANNs) for nonlinear data transformations, improving learning efficiency with more data and increasing neural network layers over time [31]. In timber identification, convolutional neural networks (CNNs) are employed for cross-section (CS) image classification and feature extraction from timber log images. CNNs eliminate the need for pith position determination and rotational pre-alignment, performing comparably to traditional methods [65, 178]. Various advanced neural networks, including U-Net, Mask R-CNN, RefineNet, and SegNet, are compared for CS segmentation, with U-Net excelling on small datasets and RefineNet on large datasets, while SegNet and Mask R-CNN show varied performance [33].

Computer vision wood identification (CVWID) research focuses on image-based wood verification, achieving high accuracy in controlled laboratory settings. Effective classification requires characteristics that align with major inter-class timber structural deviations [136].

Visible and near-infrared (Vis-NIR) spectroscopy, widely used in various industries, assesses elements like humidity and weight, and classifies timber species [89]. Clustering analysis (CA) and principal component analysis (PCA) categorize timber samples, aiding in wood traceability. Wavelet coefficients reduced by lifting wave transform (LWT) and particle swarm optimisation-support vector machines (PSO-SVM) algorithms enhance geographic source and species estimation from raw spectra [89]. This technology offers non-invasive, rapid methods for timber tracking, ensuring accurate wood quality assessment and origin identification [89]. Table 4 in the source document details the utilisation, efficiency, features, and challenges of these technologies.

Table 4

The utilisation of the most popular technologies, their efficiency, and their features

Technology	Utilisation	Efficiency	Features	Challenges
Stamping	Marking logs	Less efficient	Easy to use	Environmental factors, not secure
Paint	Marking logs	Less efficient	Easy to use	Environmental factors, not secure
Smart marking (coding system)	Marking logs	Less efficient	Easy to use	Environmental factors, not secure
Barcode	Tracing logs and wood product	Less efficient	Simple and cheap	Not secure
QR code	Tracing logs and wood product	Less efficient	Easy to use	Not secure
DNA fingerprinting	Verify timber origin	Reliable efficient	Database of samples	Expensive
Microwave sensor	Automated identification of wood product	Experimental	Finding wood attributes	Experimental
RFID	Identifying logs and wood products	Reliable efficient	Difficult to cheat	Expensive but the price per tag is predicted to reduce
Biometric method	Identifying logs	Reliable efficient	Secure and high precision	Large dataset
Oriented briefing (ORB)	Tracing Logs	Reliable efficient	Quik and effective image comparable	Large dataset
Blockchain	Tracing logs and wood products	Reliable efficient	Comprehensive and unchangeable data	Large dataset
Smart Tree APP	Collecting data from marking trees to cutting phases	Reliable efficient	Identify tree location through GPS	It needs available Internet

3.4. Timber Traceability Across the Supply Chain

Ensuring traceability within supply chains is a key focus for various industries, regulatory bodies, and policymakers [44]. It is essential to any successful business in general, including the timber industry, because it allows companies to track logs from the time of the timber marking to the subsequent traceability of the wood product up to its final destination. As a result of this, traceability ensures accountability, transparency, and sustainability [3]. According to the information derived from the papers, timber traceability is employed at many stages of the supply chain, as shown in Table 5.

Traceability in various phases of the supply chain Table 5

Supply chain stage	Studies
Harvesting	[25, 44, 59, 77, 129, 149, 150]
Logistics	[27, 29, 58, 108, 129, 166]
Forestry certification and verification	[27, 89, 108, 178]
Processing	[7, 14, 25, 41, 44, 46, 84]
Manufacturing	[51, 100, 174]
Production	[9, 94, 154, 182]
Trade	[9, 161, 169-171]
Transportation	[9, 14, 38, 106, 134, 145]
Forest products	[14, 26, 41, 44, 50, 68, 83, 115, 152, 161]
Constructions	[48, 68]
Data management and documentation	[26, 33, 114]
Wood procurement	[65]
Manufacturing	[2]

3.5. Developments in Wood Transportation Management Systems

Technology is driving progress in data collection, processing, and delivery, making it easier to monitor forests and manage transportation, thus aiding in forest use and protection [164]. Key aspects of smart sustainable timber transportation include digital tools like transportation management systems, route optimisation software, and real-time monitoring to track vehicle capacity and optimise loading [104]. Using larger and heavier vehicles (LHV) [122, 172] and optimising vehicle filling enhances timber transportation efficiency, reducing trips and travel distance, thus improving wood procurement operations [121, 157]. Mokhirev et al. [104] utilised an algorithm based on Dijkstra's approach and dynamic programming to find efficient and cost-effective routes for wood transportation, considering transportation costs, road conditions, and environmental factors [104]. Other scholars employed tabu-search-based solutions to address vehicle routing and container scheduling problems, aiding freight forwarders in choosing the best transport mode and reducing empty truck moves by considering constraints like weight, time windows, and capacity [64, 181]. Their study highlighted the benefits of using foldable containers for wood product transportation [181]. Similarly, the Bees Algorithm has been beneficial for vehicle routing problems, showcasing its efficiency in planning timber transportation [72]. Stewart [159] applied Route Network Analysis (RNA) using GIS software, specifically ArcView Network Analyst [37, 98] for commercial forestry transportation. This method determines optimal routes based on road length, intersections, distance, vehicle speed, and slope, resulting in faster transportation [126]. It also utilises spatial databases and 3D modelling for accurate decision-making [159]. Mesquita et al. [102] discussed using mathematical models and optimisation approaches for designing forest road networks [102] and conducting hierarchical planning for forest transportation [79, 92]. In Finland, a statistical procedure provides sound data for time-consumption models in trucking activities, aiding in cost calculations, route planning, simulations, and training [117]. Sikanen et al. [153] used an internet-based logistics control system with GPS and map services, reducing costs by leasing the system from ASPs and enabling effective automotive management and logistics control through real-time data exchanges between mobile terminals and the central system [36, 153, 156]. GPS and map services improve navigation and operational efficiency by locating in-forest wood fuel storage piles and monitoring moving vehicles [38, 153]. A fleet management system (FMS) using onboard monitoring equipment, mobile terminals, and GPS enhances operational coordination and on-site management, leading to increased productivity and reduced operational delays [66, 67, 125]. The FMS provides detailed data on times, distances, fuel consumption, driver behaviour, and wood chip moisture content, enabling informed decision-making regarding wood fuel consumption and productivity [67, 125, 135]. Akay and Demir [4] used a hybrid fuzzy multi-criteria decision-making method to determine suitable vehicle types for forest product transportation, considering environmental damage, cost, and operational performance [4]. Environmental damage received the highest weight, followed by performance and cost, with various transportation scenarios assessed [4].

Remote monitoring control systems with sensors and GPS modules in logging trucks, commonly used in Europe, measure various parameters in different operational modes for timber haulage [5], as shown in Table 6 .

Murphy [109] found that truck route scheduling models, specifically an integer programming model, significantly improve efficiency and reduce costs [109]. This model optimises truck routes [140], reducing fleet size by 25-50% and costs by up to 47%, with similar results in Chile and Sweden [109]. It also reduces average working hours, operational costs, and total distance driven.

Driver assistance systems for log-hauling trucks enhance maneuverability and reduce hazards, with feedback and feed-forward control strategies reducing the swept path width (SPW) by up to 80% and 50%, respectively, on rural and curvy roads [183]. Marinello et al. [97] used CAD simulations and 3D software to analyse trailer maneuverability, reducing development time and costs, and allowing dynamic simulations [97].

Table 6

Parameters measured by remote monitoring control system for timber haulage [5]

Measured parameters		
Haulage productivity [$m^3 \times h^{-1}$]	Delays duration [h]	Total journey time [h]
Transport distance [km]	Engine time of operation [h]	Total braking time [h]
Logging truck speed [km/h]	Total time required for hydraulic [h]	CO_2 total emitted [kg]
Load volume [m^3]	Daily output [m^3]	CO_2 emissions per kilometres travelled [kg]
Shift duration [h]	Total time spent idling the engine [h]	Total amount of fuel consumed [Liters]
Total time spent idling the engine [h]	Fuel usage [Liters per 100 kilometres]	Fuel usage [Liters per 100 kilometres]

FlowOpt, a decision support system for Swedish forestry, integrates a GIS-based map user interface, facilitating coordinated planning between truck and train logistics and among multiple companies [47]. It reduces problem-solving time, data analysis, and report generation, aiding forest managers in planning [47].

Linear programming and optimization models identify efficient backhauling routes, minimizing unloaded distances and supporting strategic, tactical, and operational planning [19]. The technology went beyond basic production and provided decision support in strategic, tactical, and operational planing, enabling better long and short-term decision-making and joint planning among forest companies, owners, and transport firms [19, 53].

3.6. The Strategic Outcomes

It is shown in this study that using Traceability Adoption has some positive implications for economic, environmental, and social trends, as illustrated in Table 7.

The importance of sustainable transportation management in the context of long-term ecological and economic sustainability emphasises the optimization of logistics, technologies, systems, procedures, and tools in order to achieve economic savings, reduce environmental impacts, and enhance social sustainability [110, 176] as shown in Table 8.

3.7. The Challenges

The outcomes of the research demonstrate plenty of hurdles that must be handled to establish trustworthy and efficient traceability systems with the aid of technology in wood. Such difficulties arise because of factors such as costs, the absence of necessary infrastructure, interoperability constraints, data management and confidentiality issues, uptake and adherence to standards or laws, as well as capabilities needed on the part of people involved in different stages of timber processing until final clients. Overcoming these challenges is important for ensuring the effective adoption and use of traceability technology in the wood sector. The evidenceof technology barriers in wood traceability and transportation is shown in Table 9.

Table 7

Synopsis of strategic results of implementing advancements in timber traceability derived from the encompassed studies

Tactical outcomes	Primary emphasis	Studies
Economic level	Improved product quality	[14, 33, 83, 94, 130, 171]
	Enhanced supply chain management	[59, 106, 108, 114, 129, 130, 182]
	Cost saving	[8, 48, 68, 108, 114]
	Improved production control	[14, 59, 65, 174, 182]
	Increased efficiency of inventory management	[14, 115, 129, 139]
	Increased traceability efficiency	[7, 9, 46, 89, 94, 107, 114, 115, 129, 130, 178]
	Improved market access	[9, 68]
	Asset trade	[9, 170, 171]
Environmental level	Sustainable forest management	[10, 40, 59, 65, 83, 108, 115, 130, 178]
	Forest conservation	[9, 26, 112, 139]
	Reduce waste	[83]
Social level	Transparency and accountability	[2, 9, 10, 30, 45, 46, 58, 59, 68, 107, 108, 129]
	Compliance with regulations	[14, 27, 34, 108, 170]
	Improved worker safety	[114]
	Stakeholder engagement	[9, 151]
	Ethical customer choice	[7, 8, 27, 45]

Synopsis of strategic results derived from the encompassed studies Table 8

Tactical outcomes	Primary emphasis	Technology/procedure	Studies
Economic level	Efficient fleet management	Information technology, Mobile terminals in combination with GPS and map services, GIS, EC Road	[18, 38, 66, 67, 130, 135, 156]
	Improving operational efficiency and management	Digital timer and data recording forms, national timber sales allocation procedure, mathematical models, GIS, GPS, 3D design software and CAD simulations, Digital model	[36, 86, 97, 102, 126, 131, 177]
	Improving the terminal layout and railway transport options	Simulation model	[55]
	Reduce road damage and lower repair and vehicle operational costs	Mobile weigh bridges and hauling rigs, GPS and GIS, 3D design software and CAD simulations	[1, 97, 156]
	Reduce transportation cost	Aerodynamic improvements, optimise vehicle filling, algorithm, mathematical models, GIS, Analysis tool, larger vehicles and increasing load capacities, programming model	[73, 74, 102, 104, 109, 126, 156, 157, 172]
	Improving log loading efficiency	Cameras and Adobe Photoshop CS5 Extended® software	[155]
	Improve the efficiency of wood procurement operations	larger and heavier vehicles (LHV)	[121]
	Increase transport efficiency	larger vehicles and increasing load capacities, agent-based technology, Route Network Analysis (RNA) using (GIS)	[53, 159, 172]
	Accurate and lesser time of timber transportation planning	Bees Algorithm, mathematical models, FlowOpt system, linear programming and optimisation models, agent-based technology, GPS and GIS	[19, 37, 47, 53, 72, 92]
Environmental level	Reduce air pollutants(biofuels)	Life-cycle assessment (LCA)	[63, 91]
	Reduce fuel consumption, greenhouse gas (GHG) emissions and CO_2	Motor technology, modeling of fuel consumption, aerodynamic improvements, optimize vehicle filling, larger and heavier vehicles (LHV), remote monitoring of forest trucks using the FMS Plus CAN-bus device, larger vehicles and increasing load capacities	[57, 74, 78, 121, 157, 172]
Social level	Reduce accident	(GNSS) and (GNSS-RF), driver assistance system	[183, 185]
	Data-driven decision-making	Route Network Analysis (RNA) using (GIS), mobile terminals, and GPS, fuzzy multi-criteria	[4, 67, 126, 159]
	Stakeholder engagement	FlowOpt system, agent-based technology	[47, 53]

Technologies challenges identified by some researchers Table 9

Technology	Challenges	studies
UHF RFID	Electromagnetic properties of fresh wood. Reading of transponders in the presence of heavy machinery	[59]
RFID	The rough environment of forest operations can lead to the loss or destruction of RFID tags during extraction and processing of trees. High cost of tags. Interoperability and Standardisation of RFID systems across different stakeholders in the supply chain can also be a challenge.	[46, 129]
Blockchain	Blockchain systems face limitations in storing substantial amounts of data, necessitating efforts to maintain satisfactory performance metrics while preserving data integrity. As the volume of transactions and data grows, scalability becomes a significant challenge for blockchain networks.	[2, 68, 108]
UAV (Unmanned Aerial Vehicle)	Trained and specialised workforce and system costs	[130, 139]
Convolutional neural networks (CNNs)	The need for a large dataset of log end images for training the CNN models. The requirement for accurate segmentation of the log cross-section in the image. The complexity of comparing and matching the extracted features.	[33, 178]
visible and near infrared (Vis-NIR) spectroscopy	The necessity of a diverse array of large samples for precise prediction	[89]

Cost: Kaakkurivaara found in his study that RFID was the most efficient and reliable method for traceability purposes in the Thai timber industry, and the opinion of the workers noticeably changed after the experiment. RFID was the preferred technology in terms of its reading ability and ease of use. However, the cost of RFID tags needs to be reduced [77]. On the other hand, some methods were low-cost and practical,but they lacked security and reliability [171]. Finding a tag design that fits both the working requirements and cost-effectiveness targets of the firm simultaneously is a major challenge [166]. DNA markers can be expensive and time consuming to analyse, which can limit their practicality for large-scale wood traceability programs [113].

Infrastructure and interoperability: There are challenges to implementing an efficient traceability system in the forestry sector. For example, the lack of ICT infrastructure and interoperability is a major obstacles to achieving a reliable and scalable traceability system [106]. Ordinary identification systems employed in industries create implantation issues, according to the widely changeable nature of the material and the specific aspects of the production process [50]. RFID tags on sawn wood, such as crossties, can provide several benefits for logistical procedures and traceability. Despite this, there are a number of difficulties to cope with as a result of bad usage scenarios, considering the amount of moisture motion and wood decomposition, the humidity, and the quantity of water in a log of wood decrease the antenna efficiency of the RFID tag, necessitating a greater radio frequency signal to work. That is required to select the best suitable tags and researching the ideal techniques for installing them [145].

Capacity and skills: The introduction of innovative technology into a wood harvesting operation and the timber supply chain includes the need for a staff that is technologically skilled and specialised, a workforce that is flexible to new technologies and modifications in conventional operations in the wood supply chain and the risk of bottlenecks in the system [100, 130]. On the other hand, high-cost methods such as DNA fingerprinting and isotopic fingerprinting were accurate and safe but required specialist training and an appropriate database. The remote sensing and digital cameras were not effective for keeping track of individual logs but offered critical information across borders and nationally [171].

Adoption and compliance: It would be beneficial for global wood traceability, developing a unique standardised system for tracking log data and information would be highly beneficial. Making use of standard traceability protocols and quality control measures will enable wood supply chain actors to become independent and to ensure the accuracy and reliability of the results [169].

The ORB algorithm was used to capture the image's fingerprint as the wood tag and calculate the rate at which these tags are matched to identify the particular wood. It showed excellent speed and resilience, with an accuracy of 98.5 percent. Nevertheless, it bases its findings on a publicly available dataset of 2,941 images, which might not include every possible wood species [162]. DNA markers have the potential to become an important tool to trace wood [75]. But ,there is some work that needs to be done to reach a robust, useful and easy -to- use tool. A most obvious and important gap is the lack of a proper database of reference samples of DNA from sources that are known. The difficulty is that, if the wood is coming from a place where there is basically no genetic information available, it is somewhat impossible to tell if the wood is, for example, from the Amazon Rainforest or from a plantation. Contamination is another problem. A wood sample is easy to contaminate during the collection, processing, and analysis. Prevention of contamination and validation of the results are very important [113].

Blockchain technology holds the potential to revolutionise supply chain management. Nevertheless, as the technology is still in the early stages of adoption, further empirical research is required to explore how it can be more widely deployed to enhance and support traceability [3].

Data management and privacy: adoption of new technical solutions and creative digital data management processes that allow flexibility, instant feedback, and quick decision-making and guarantee the availability of information needed [104, 170]. The lack of integration and standardisation of entries and rules, poor interaction with government systems, absence of electronic identity requirements and security information problems are the computational issues affecting the operation of the wood supply chain [32]. Blockchain systems for tracking supply chain provenance are not yet fully capable of addressing all the specific business requirements of the timber industry [108]. Although traceability technologies rely on data collection and exchange, maintaining data security and privacy is important to prevent unauthorised access to or hacking of information. Large amounts of data from bar coding technology need to be handled and analysed on a robust data management and analysis system [94].

Stakeholder engagement: Implementing traceability includes collaboration between governments, industrial users, consumers, and associations that are interested in developing new technologies [15]. This needs to establish effective cooperation tools for the wood supply chain [26]. New technologies integration into the timber traceability system can improve the efficiency and accuracy of the process, but it requires careful planning and management to overcome the challenges [164]. For that, stakeholders in the wood supply chain should be open-minded to new technologies and changes of the traditional processes [130]. The researchers ended by saying that: focus on what is feasible for all the stakeholders within the supply chain - what is easy to learn, helpful, easy to use, valuable, and useful is worth investigating [151].

Other factors: The RFID UHF tags are a reliable marking tool for standing trees in the forest. However, the operative capacity of tags can be affected by the type of tag and the position of attachment on the tree in the forest. Tree growth can physically affect the tags, and the physical interaction of resin emissions can also cause tags to be infinite [128]. The practical situation of the working environment in the forest, such as recovery from storm damage and uneven terrain, can make the survival of tags more difficult [129].

4. Conclusion

This study aims to explore the technology of wood traceability within the forest supply chain through a two-step systematic literature review using the PRISMA methodology. By filtering thousands of research papers using search queries from Google Scholar and other sources, over 100 papers were selected, with more than 125 shortlisted for their relevance to traceability technology across the entire supply chain and their coverage of the research questions in Section 1. The findings demonstrate that wood traceability can be significantly enhanced in terms of speed, accuracy, and reliability through the use of various technologies throughout the supply chain. These technological advancements help manage, monitor, and reinforce traceability from origin to end product, allowing consumers to make informed choices about wood products. This can lead to better control over deforestation, lawful logging, and other hidden activities. While the review acknowledges that the technologies discussed are not yet operationalised, it highlights their potential to promote responsible and sustainable wood usage.

Benefits include improved product quality and differentiation, regulatory compliance, worker safety, stakeholder participation, and ethical consumer choices, contributing to a sustainable forestry industry. The paper also discusses limitations and challenges in implementing traceability technology, such as costs, infrastructure obstacles (data management, adoption and compliance, and stakeholder engagement), and other drawbacks. Addressing these issues is crucial for the future of the forestry industry, as traceability systems will pave the way for more sustainable practices and higher quality wood products. However, the review is limited to English-language papers, potentially missing relevant studies in other languages, and there may be errors in the search process. Future research should evaluate the risks associated with technological applications in the forest supply chain, particularly in transportation management, assess employee adaptation to new technologies, and explore ways to improve these technologies. This work offers valuable insights for stakeholders on the adoption and actual use of new technologies in the forestry supply chain, highlighting the importance of further exploration in this field.

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