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A systematic literature review on the forest health biomonitoring technique: A decade of practice, progress, and challenge

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The approach for monitoring forest health such as canopy layer, air quality, soil texture has evolved in tandem with the advancement of new technology such as lab analysis, remote sensing *etc.* The application of biomonitoring techniques for example species diversity and morphological observation, on the other hand, has been positive and has made its own contribution to forest management. Many studies have been conducted in the last decade (2011–2021), which use the biomonitoring techniques in assessing the forest health status. Therefore, this study aims to systematically review the forest health biomonitoring techniques in the last decade. This study used the PRISMA guidelines as the protocol to search and analyze all the papers. This study selected 72 out of 538 papers for a thematic analysis which eventually identified four main biomonitoring techniques, namely: 1) diversity distribution, 2) morphological observations, 3) trace elements, minerals and physiological measurements, and 4) behavioral observations. The biomonitoring techniques applied to monitor forest health has evolved with numerous ways that can support existing technologies, as well as help educate people on the necessity of protecting and safeguarding the natural forest environment. This also will give more options to the authority in monitoring the forest health and not only focusing on technology.

KEYWORDS

forest ecosystem, ecological indicator, environmental monitoring, forest health, biomonitoring

1 Introduction

Forest health has been defined by the production of forest conditions which directly satisfy human needs and by resilience, recurrence, persistence, and biophysical processes which lead to sustainable ecological conditions (Anderegg et al., 2020). The status of forest health has been declining globally, where global forest health has dropped nearly 60% from 1960 to 2019, mostly in the tropical region, due to urbanization and expansion of agricultural area (Williams et al., 2021). This is the same reason that brings forth climate change, which also affects forest health. The decline of forest health status signifies that forest ecosystems cannot provide the services or functions they normally supply to humans (Tebbett et al., 2021). The deterioration of forest ecosystem services implies a reduction in the forest's ability to sustain local human populations through ecosystem services such as soil stability, water control, and local economic growth, as well as to offer recreational and cultural amenity value (Delgado and Marín 2020). Hence, this will eventually affect people's quality of life and wellbeing. According to the Millennium Economic Assessment (MEA) (2005), human livelihoods are dependent on ecological services (particularly forest ecosystems), which help to support global employment and economic activity (food and timber production, marine fisheries and aquaculture, and recreation). Biodiversity loss, ecosystem degradation, and the resulting changes in ecosystem services have resulted in a fall in human wellbeing in some groups by intensifying poverty and increasing inequalities and inequities (Tallis et al., 2018). Therefore, it is important and critical for humans to be able to monitor, measure and determine the status of forest health. On the other hand, the techniques used to monitor and measure the forest health status are also important things to be considered. The monitoring techniques used must be holistic, practical, and able to act as an early alarm of any significant changes happening to the forest health (Abas 2021).

Forests are the most common terrestrial ecosystem on Earth and are found all across the world. Forests account for 75% of the biosphere's gross primary output and comprise 80% of the planet's plant biomass (Duncanson et al., 2019). Net primary output in tropical forests is predicted to be 21.9 gigatonnes of biomass per year, 8.1 gigatonnes in temperate forests, and 2.6 gigatonnes in boreal forests (Thakur et al., 2019). According to Newton et al. (2020), over 2 billion people rely on forests. Forests provide people with shelter, livelihoods, water, food, and fuel security. All these activities, directly or indirectly, involve forests. Some are easy to figure out—fruit, paper, and wood from trees, and so on. Others are less obvious, such as by-products that go into everyday items like medicines, cosmetics, and detergents. Therefore, it is important to monitor the forest health status so that the forest can always provide the service it has usually given and human livelihoods and wellbeing will always be protected (Diansyah et al., 2021). Forest health is usually defined as the production of forest conditions which directly satisfy human needs and have the resilience, recurrence, persistence, and biophysical processes which lead to sustainable ecological conditions. Numerous methods and parameters for monitoring biotic and abiotic forest components have been developed for example, the use of remote sensing (Lausch et al., 2018), measuring SO_2 and NO_2 concentrations (Davidson et al., 2020), satellite imaging (Woodward et al., 2018), and vegetative index (Rogers 2002). Biological indicators such as insects (Allen et al., 2019), fungi (Warwell et al., 2019), and plants (Finger et al., 2021) have also been used widely to monitor and assess the health of forests.

Although there are many ways to monitor forest health, the use of biological indicators is important due to several advantages such as: 1) reflecting the overall environmental integrity comprising physical, chemical, and biological monitoring; 2) imparting an integrated and holistic measure of ecological conditions by uniting stresses over a period of time; and 3) providing a better understanding of a healthy environment for the public than other methods (Medhi et al., 2020). Despite these advantages, efforts to review biomonitoring techniques systematically and constructively are still lacking, especially regarding forest health ecosystems (Swislowski et al., 2020). Rather than inferring exposure from chemical concentrations in air, water, or soil, biomonitoring analyses personal exposure to dangerous chemicals by detecting the substances or their metabolites in human specimens such as blood or urine (Bocca et al., 2019).

Bioaccumulation, biochemical modifications, morphological and behavioural observation, population- and community-level methods, and modelling are the most prevalent biomonitoring techniques (Abas 2021). The significance of collecting, searching, and reviewing the biomonitoring techniques used to monitor forest health will help to create a better understanding and facilitate the identification of the research gaps that exist in this particular area (Muhammad et al., 2018; Zulaini et al., 2019). Therefore, this study aims to systematically review the forest health biomonitoring techniques. In order to achieve this aim, three research objectives have been outlined which are: 1) to explore the spatial and temporal patterns of the studies; 2) to analyze the contextual issues discussed in the forest health biomonitoring techniques; and 3) to discover the biomonitoring techniques used to monitor forest health in the last decade between 2011–2021.

2 Research methodology

2.1 PRISMA statement (Preferred reporting items for systematic reviews and meta-analyses)

The PRISMA statement (Moher et al., 2009) served as the primary guideline for this systematic review investigation. PRISMA is a minimal set of monitoring components based on evidence for systematic analyses and meta-analysis. The example of relevant studies that used PRISMA statement are; Abas et al. (2022) that analyzed the local wisdom of the indigenous people in nature conservation, Owen (2020) that explored the climate change adaptation globally, and Malek et al. (2021) that determined the social indicator for building a smart city. The PRISMA statement was chosen for this study because of its strict procedure emphasizing the reporting of randomized trial assessment reviews, which may also be used as a basis for publishing comprehensive reviews of other types of studies, including intervention evaluations (PRISMA 2021). PRISMA statement has been used to report the results of a systematic review evaluating the effects of an intervention, whether the review is limited to randomized controlled trials or includes other types of research.

2.2 Formulation of the research question

The study questions were developed using PICo. PICo is a key component of a question that developed to address knowledge gaps in a study. Caón and Buitrago-Gómez (2018) describe PICo as a tool that supports writers in developing appropriate research questions for review. PICo was often used in the field of health sciences and medical to develop an evidence-based clinical practice. PICo is built around three key concepts: population or problem, interest, and context. This study has incorporated three major features in the review based on these concepts: forest health monitoring (issue), forest health (interest), and biomonitoring approaches (context). Hence, this study asks the following questions: 1) What is the distribution pattern of biomonitoring techniques for forest health spatially and temporally? 2) What are the contextual issues discussed in this study? and 3) What is the theme that can be developed for the biomonitoring techniques used to assess and monitor forest health?

2.3 Systematic searching strategies

As shown in Figure 1, the systematic searching strategies included three main strategies: identification, screening, and eligibility.

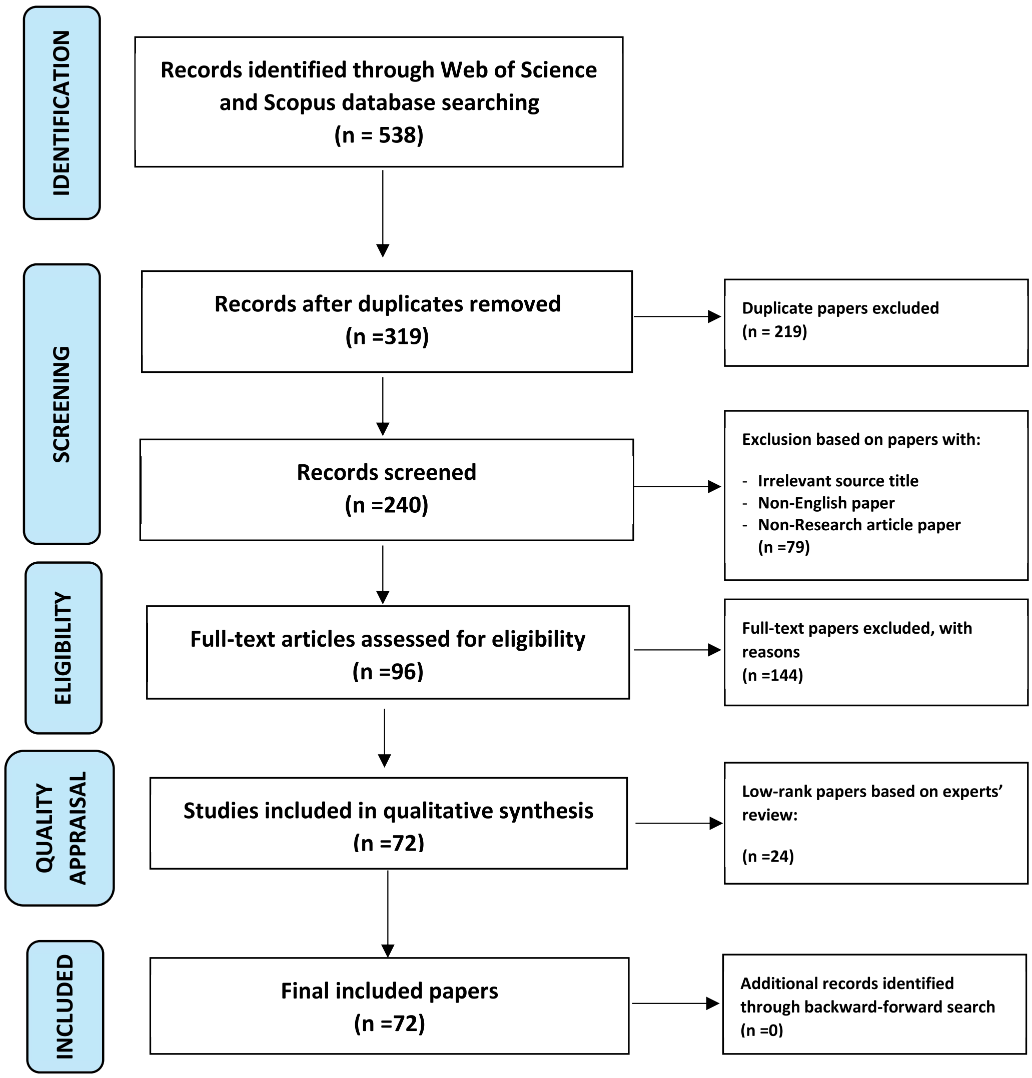

FIGURE 1
Flow diagram of the process.

TABLE 1 The search strings.

Database	Search strings
Web of Science	TOPIC: (forest health)
	Refined by: TOPIC: (biomonitoring OR biological monitoring OR biological indicator OR biological audit OR biological observation)
Scopus	TITLE-ABS-KEY (forest AND health OR forest)
	AND (biomonitoring OR biological AND monitoring OR biological AND indicator OR biological AND audit OR biological AND observation)

2.3.1 Identification

Identification is the process of searching for the appropriate keywords depending on the research questions. Three keywords, as well as their synonyms, related phrases, and variants, were employed in this investigation. The buzzwords were <forest health> and <biomonitoring>. The keywords were produced based on Okoli's (2015) research question, and the identification method relied on online thesauruses, keywords from previous studies, keywords recommended by Web of Science (WoS), and keywords suggested by experts. As demonstrated in Table 1, this study was able to enhance a series of keyword strings by searching for relevant publications in the WoS database and Scopus. WoS and Scopus are websites that offer subscription-based access to a variety of databases as well as detailed citation data for a wide range of academic subjects. The present researchers picked WoS and Scopus over other search engines since all journals in these two have gone through a rigorous editing procedure, assuring article quality before publication and preserving the publications' impact factor rankings (Scopus 2021; WoS 2021). The search technique employing both databases yielded 538 articles that were relevant to the study's research goals.

2.3.2 Screening

To eliminate duplicate records, all 538 articles were initially checked. Due to duplication, a total of 219 papers were removed from the database, leaving 319 articles. The remaining 319 papers were rescreened to confirm the review's quality; only publications having empirical data and published in a journal were considered. Furthermore, only papers published in English were included in the review to minimize misunderstanding. This procedure eliminated 79 articles because they did not meet the inclusion requirements. The remaining 240 articles were employed in the third procedure, which was to determine eligibility.

2.3.3 Eligibility

The third procedure is eligibility, in which the authors personally monitored the retrieved articles to ensure that all of the remaining articles (after the screening process) met the requirements. This was accomplished by reading the titles and abstracts of the papers. A total of 144 articles were excluded because they focused on ecological processes, social monitoring, forest ecological studies, forest conservation outreach, social-ecological systems, forest ecosystem monitoring, ecosystem services valuation and assessment, assessment of sustainable forest management, non-forest biomonitoring, focus on review, did not use empirical data, or were published as a chapter in a book. Hence, only 96 articles were through for the next stage.

2.4 Quality appraisal

The remaining articles were provided to two specialists for quality assessment in order to ensure the quality of the material. These two specialists are academics who have undertaken several studies on forest health. According to Petticrew and Roberts (2006), the remaining papers were divided into three quality categories: good, moderate, and low. Only papers classified as high and moderate were examined. The specialists concentrated on the methodology of the articles in order to calculate the quality rating. Both experts had to concur that the paper's quality had to be at least moderate in order for it to be included in the research. Before deciding whether or not to include or exclude articles from the review, they discussed any differences. Following this process, 50 articles were rated as high, 22 as moderate, and 24 as low. As a result, only 72 articles were eligible for review (refer to Annex 1).

2.5 Data abstraction and analysis

Thematic analysis was utilized in this study to create themes and sub-themes. According to Braun and Clarke (2006), thematic analysis is used to find the themes and sub-themes that exist within the abstracted data by noticing patterns and motifs, grouping, counting, and highlighting parallels and correlations. Any abstracted data that was comparable or related was grouped together. Following a thorough analysis, four topics emerged in this study: 1) diversity distribution, 2) morphological observation, 3) trace elements, minerals, and physiological measurements, and 4) behavioral observations.

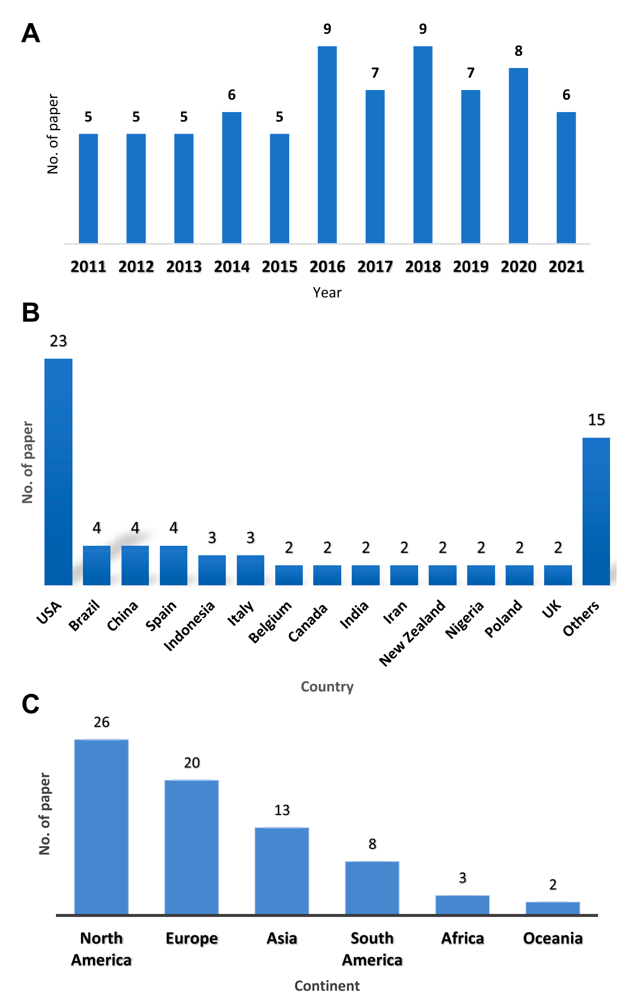

FIGURE 2
(A) Temporal distribution of the selected papers. **(B)** Country distribution of the selected papers. **(C)** Continent distribution of the selected articles.

3 Results

3.1 Spatial and temporal distribution of selected articles

A total of 72 articles were analyzed through a detailed screening procedure. Based on Figure 2A, the distribution of studies on the forest health biomonitoring techniques in the last decade (2011–2021) has been fluctuated but slowly increasing temporally. Most papers were published in 2016 and 2018 with nine papers respectively. Based on Figure 2B, all of the 72 papers were distributed among 29 countries, of which the United States of America (United States) had the most with 23 papers, followed by Brazil, China and Spain each with four papers. Figure 2C shows the distribution of the selected papers based on their continent of origin. The most papers come from North America with 26 papers and followed by Europe with 20 papers.

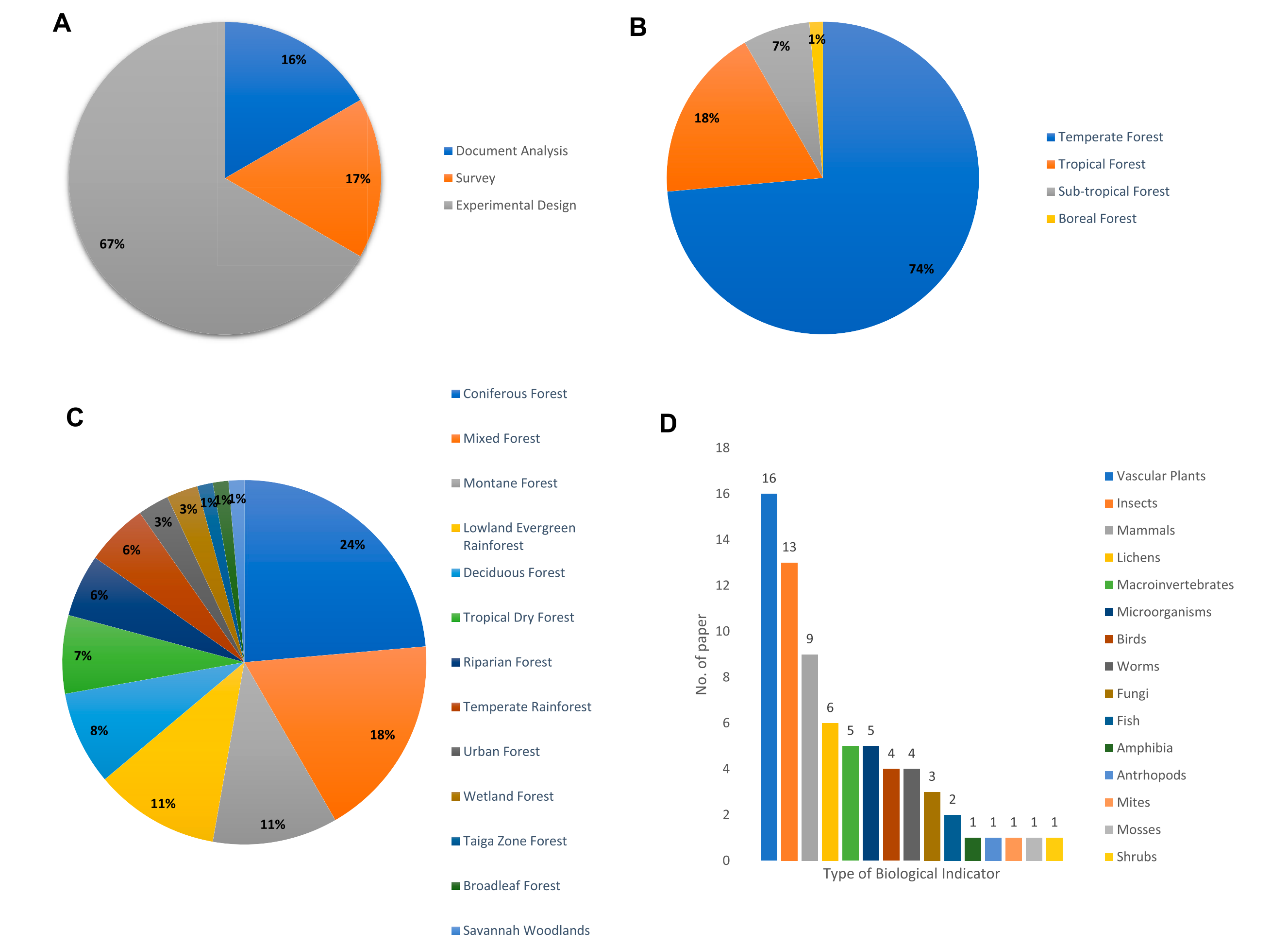

FIGURE 3
(A) Methods used from the selected articles. **(B)** Type of forest. **(C)** Sub-type of forest. **(D)** Type of biological indicator.

3.2 The forest health biomonitoring technique—Contextual issues

This study discovered four main contextual issues which were: 1) method used from the selected articles, 2) type of forest, 3) sub-type of forest, and 4) type of biological indicators. Based on Figure 3A, most of the selected articles used experimental design-type methods (67%) to study the biomonitoring techniques used for forest health assessment. In terms of type of forest, based on Figure 3B, 74% of the selected articles were studies on temperate forests, 18% on tropical forests. For the sub-type of forest (Figure 3C), most of the selected articles (23%) focused on coniferous forests, followed by mixed forests with 18%, lowland evergreen rainforests and montane forests both with 11%. Based on Figure 3D, 16 out of the 72 articles used vascular plants as biological indicators to monitor forest health, followed by insects with 13 articles, mammals with nine articles.

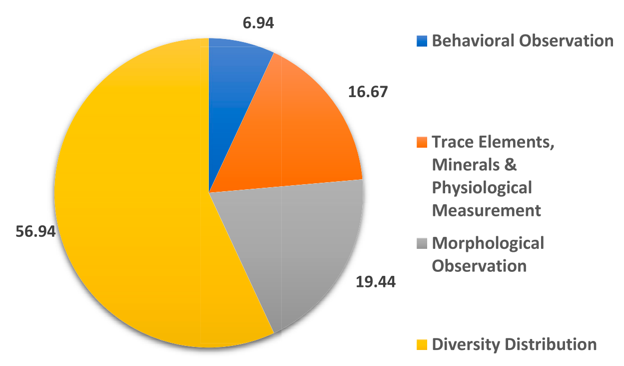

FIGURE 4
Type of biomonitoring techniques.

3.3 The forest health biomonitoring technique—Thematic analysis

This study discovered four main themes for the biomonitoring techniques used to assess forest health which were: 1) diversity distribution, 2) morphological observation, 3) trace elements and physiological measurement and 4) behavioral observation. Based on Figure 4, 56.94% of the selected articles studied the diversity distribution techniques, while 19.44% focused on morphological observation.

4 Discussions

4.1 Biomonitoring technique of the forest health—Substantive issue

4.1.1 Diversity distribution

The diversity distribution monitoring techniques is used to assess and measure forest health by calculating the frequency of individuals of certain species, identifying species diversity, analyzing by using the existing indices, *etc.* Vascular plants have been used in several countries, such as Indonesia (Wulffraat and Morrison 2013; Fujiki et al., 2016), the United States (Shearman et al., 2015; Guyon and Battaglia 2018) and Brazil (Poorter et al., 2015) to monitor forest health through the forest communities stand index, canopy cover analysis through satellite imagery and forest inventory and analysis (FIA). Besides that, the diversity of insects has also been used to monitor forest health. For example, the diversity of dung beetles (Sullivan et al., 2018; Somay et al., 2021) and bark beetles (Rassati et al., 2016; Morris et al., 2018) have been analyzed and monitored to determine the soil moisture in the forest. Other than that, orchid bees (Suni, 2017; Allen et al., 2019), moths (Highland et al., 2013) and dragonflies (Dolný et al., 2013) were used to observe the forest fertility and humidity. The individual frequency of small mammal species such as rodents (Ahumada et al., 2011) and squirrels (De La Sancha 2014) have been used to monitor the forest humidity and temperature. A specific index (the Living Planet Index) using the diversity of mammals such as deer (Fisichelli and Miller, 2018) and forest specialists (Green et al., 2020) has been developed to monitor forest health. On the other hand, a study by López-Baucells et al. (2017) used fruit bats as an indicator of good forest condition due to their need for fruit to survive. The diversity distribution of lichens and fungi were also used to monitor the forest health status. A study by Coyle and Hurlbert (2016) used macrolichen richness to measure the environmental heterogeneity and a study by Song et al. (2012) used the epiphytic lichen species distribution to determine the impact of climate change on forest health. In terms of the use of fungi, the existence of fungi usually brings negative signals to the forest health status. Numerous studies, such as Xu et al. (2012), Warwell et al. (2019) and Zgrablić et al. (2016), have shown that the existence of fungi such as Armillaria spp., Sphaeropsis sapinea, *etc.* indicate that the forest health status is in a very poor condition. Macroinvertebrates are one of the most notable biological indicators for freshwater quality, especially for river ecosystems. However, there are a few studies such as Deborde et al. (2016), Kim et al. (2016), Brogna et al. (2018), Foomani et al. (2020), and Edegbene et al. (2021) which have shown a significant relationship between forest health and river water quality. There are also studies that use other biological indicator distributions such as birds (Laiolo et al., 2011; Wade et al., 2013; Gnass Giese et al., 2015), nematodes (D'Errico et al., 2014; Nisa et al., 2021), amphibians (Jongsma et al., 2014), microorganisms (Hermans et al., 2020), fish (Gottesman et al., 2020) and mites (Meehan et al., 2019).

Diversity distribution has been the most notable method used to monitor forest health through biological indicators because of the dynamics of living things that always strive in order to survive. Living things always seek to evolve and adapt to their surroundings which will lead to variations of species. This process has been happening since the beginning of living things on Earth. Vascular plants such as gymnosperms, angiosperms, ferns, *etc.* have the highest numbers in forests, which means vascular plants are the most efficient and practical biological indicator to use for diversity distribution (Moradi et al., 2019). Other than vascular plants, fungi and lichens are also favorites to be used as biological indicators to monitor forest health. Lichens are very dynamic in terms of species diversity distribution; they have a vast range in terms of sensitive species and tolerant species. Based on which species dominate the forest, indications of forest health can be determined (Abas et al., 2019). Forests are also known as the home of megafauna such as mammals, insects, birds, amphibians, *etc.* The range of diversity of animals in the forest is often used to determine its condition. Mammals, insects, birds, and amphibians always respond to the forest conditions such as forest humidity, soil moisture, and light intensity (Mohd-Taib et al., 2020).

However, organisms such as non-vascular plants, fish, and amphibians are still lacking in terms of studies for biomonitoring of forest health. According to Norhazrina et al. (2016), non-vascular plant diversity distribution, such as mosses, liverworts, and hornworts, have a significant relationship with the forest humidity and the light intensity under the forest canopy. Therefore, they can act as good biological indicators for forest health. Other than that, fish and amphibian diversity distribution are highly dependent on the river water quality, which significantly correlates with the soil fertility of the forest (Faruk et al., 2013). Fish and amphibians usually respond to the dissolved oxygen (DO) and pH values of the river water, where certain species such as toads and salmon can only be found in the upstream river due to its richness in terms of DO and neutral pH value (Faudzi et al., 2021).

4.1.2 Morphological observation

The monitoring techniques using morphological observation of the biological component in the forest ecosystem includes observing physical changes such as color, size, and texture. Numerous studies have observed physical changes in vascular plants, such as the decolorization of leaves due to the lack of water and low humidity (Kleinman et al., 2012; Kamoske et al., 2019; Finger et al., 2021) or disease and infection (Smith 2012; Feldpausch et al., 2016; Donald et al., 2020). Besides that, a study by Sánchez-Salguero et al. (2017) found a significant correlation between the radial growth of trees and the soil moisture in the forest ecosystem. Mulvey and Bisbing (2016) also found a significant relationship between leaf size and CO2 concentration in the forest, where excessive CO2 would increase the size of tree leaves. On the other hand, there are several studies that used the physical changes in insects such as ants (Krapfl et al., 2011; Skaldina and Sorvari 2017), elongate hemlock scale (Gómez et al., 2015), and termites (Kashian et al., 2018) to determine the soil moisture, soil pH and tree health. A study by Bal et al. (2018) observed nematode body moisture to determine the soil fertility in forests. Peterson et al. (2014) observed oomycete body color to assess the water quality of the river in the forest ecosystem.

The change of morphology of organisms such as color, texture, or size of a certain structure usually happens when there are sudden changes in the surroundings. This is similar to when the human skin turns red after sunbathing. According to Osman et al. (2021), due to excessive CO2, vascular plants such as angiosperms usually adapt their structure by increasing the leaf size and wingless seeds. Besides that, due to decreasing forest humidity, some vascular plants will change the color of their leaves or bark as a sign of lack of water (Nizam et al., 2009). Animals also have the ability to change morphological characteristics such as their skin color, body parts size, *etc.* However, according to Li et al. (2021), changes in morphological characteristics of animals take a long time to happen and, in terms of monitoring forest health, this is only practical for long term monitoring.

4.1.3 Trace elements, minerals, and physiological measurement

Biological components can be monitored by analyzing trace elements, minerals, heavy metals, PAH, *etc.*, and also by assessing physiological changes such as the integrity of the cell membrane, the efficiency of chlorophyll, *etc.* Through these techniques, lichens have been widely used as the biological indicator to determine forest health. Lichens from forests were collected and analyzed to measure the concentrations of heavy metals such as Cr, Ni, Cu, Zn, Cd, and Pb (Kłos et al., 2011), concentrations of S and N (Cleavitt et al., 2015), the efficiency of the chlorophyll (Loppi and Baragatti 2011) and the integrity of the cell membrane in the lichen (Will-Wolf et al., 2018). Also, monitoring has been carried out on heavy metals such as K, Fe, Mg, Ca, Zn, Pb, Cd, and Cu from the internal organs of mammals, such as the liver of wild boar (Kasprzyk et al., 2020), the colon of rats (Naderi et al., 2017) and the blood of livestock (Amadi et al., 2020). Physiological changes of microorganisms have been observed to understand and assess forest health using the integrity of their cell membrane (Dhyani et al., 2019) and their genetic sequences (Shi et al., 2019). Besides that, other studies analyzed the content of heavy metals in mosses (Berisha et al., 2017), used fish blood to evaluate the genotoxicity (Bühler et al., 2014), and vascular plants to determine the iodine concentration (Roulier et al., 2018).

According to Abas et al. (2020), trace elements can be found in some biological indicators, such as lichens. Lichens have unique features, such as the absence of a waxy cuticle on the thallus, allowing elements to enter the thallus. This makes lichens very good biological indicators that can accumulate air borne particles from their surroundings. Trace elements can also be found in animal's internal organs such as the liver, brain, lungs, intestines, *etc.* (Rahman et al., 2020). Besides that, according to Becklin et al. (2016), a plant's physiological features such as chlorophyll and cell membrane usually have reduced capacity under the stress of pollutants which can be one way to assess forest health.

4.1.4 Behavioral observation

The change in the behavior of certain organisms or biological components, such as reproductive rate, mortality rate, fatality rate, *etc.*, can determine the current status of forest health. The fecundity rate of vascular plants has been observed to aid understanding of how forest health status has changed (de la Cruz et al., 2014; McMahon et al., 2019). On the other hand, the fatality rate of birds has been monitored to assess the temperature and humidity of a forest (Bianchi et al., 2016). The growth pattern of shrubs has been mapped and analyzed to determine the soil fertility in forests, which also correlates with forest health (Myron et al., 2021). Besides that, the zigzag sawfly eating pattern has been studied to analyze forest fertility and health (Zúbrik et al., 2017).

The relationship between a change in behavior of an organism and the status of forest health has been found to be significant. According to Xu et al. (2021), living things such as large mammals, reptiles and birds usually react and respond to sudden changes in their surroundings. A rise in temperature in an area, especially a forest, typically will significantly change the mortality and fatality rate of the vascular plants due to their dependency on soil moisture and air humidity to grow and survive (Osman et al., 2021). Other than that, animals such as insects are usually less active in reproduction in rain and wet seasons but become more active when it is bright and in the warm season (Alston et al., 2020). However, when it comes to large animals, it is quite difficult to monitor their behavior because there are no significant changes over short periods, and longer periods of monitoring are needed to observe any significant changes in their behavior (Rahman et al., 2020).

4.2 Biomonitoring technique of the forest health—Current progress and practices

The present trend in biomonitoring technology has demonstrated a major influence as an alternate tool for measuring forest health status. The species richness of flora and wildlife in the forest itself is the most commonly used biomonitoring approach. According to Nisa et al. (2021), the composition of the forest's flora and wildlife may simply monitor its health state. For example, a forest with a large diversity of plants would have more fertile soil and will attract a greater range of animals (Naderi et al., 2017). Aside from that, a large diversity of species in a forest indicates that the ecosystem service and function are optimum. According to Abas (2021), biodiversity is commonly acknowledged as the primary driving factor in ecosystem function. Numerous of studies have been conducted to investigate the impact of tree species variety on several forest ecosystem services, including primary production (Moradi et al., 2019). Furthermore, according to Finger et al. (2021), a large diversity of fungi and lichens in the forest indicates that the forest is in a very active and healthy state. According to Hermans et al. (2020), animal and fungal diversity play an important role in forest health, where the diversity of animal and fungal species affects many important processes, such as the availability of nutrients for tree growth, promoting timber growth, preventing soil erosion, recycling nutrients, and controlling pest populations.

4.3 The challenge for the biomonitoring technique of the forest health

The biomonitoring technology is still relatively new in comparison to other existing monitoring techniques for detecting forest health (Faruk et al., 2013). The biomonitoring approach has a lot of promise, and it is not just limited to the utilisation of species diversity in the forest ecosystem. Several studies use changes in behaviour and appearance of organisms to measure forest health status (Shearman et al., 2015). In addition, the trace element concentration inside the organism and its physiological changes may be tracked to evaluate how the forest health has altered (Berisha et al., 2017). However, these techniques are currently insufficient for use in biomonitoring research, with the majority of studies focusing on species variety in the forest to establish the health status (Kashian et al., 2018). This might be due to a shortage of botanists or zoologists who utilise the research topic to establish the forest health condition, as well as the observation process taking a very long time to conduct and finish, so the study will exhaust their money budget, time, and people resources (Brogna et al., 2018).

4.4 Strength of the studied articles

This study has found three main strengths from the studied articles which firstly, the studied articles were coming from all over the continents. This show that the results that this study has shown are inclusive and cover all type of ecosystem around the globe. Secondly, the studied articles have covered and explored every type of forest that exist on the Earth biosphere. This means that every possible type of forest ecosystem has been represented in this study. This is very important to ensure that the themes that have been developed can be applied onto every type of forest that exist on Earth. Lastly, the type biological indicator that has been used to monitor the forest health is well-diverse and has explored every possible biological indicator that can used to determine the environmental quality. This means that the themes that have been developed are relevant, precise and inclusive. Determining the type of biological indicator that used to monitor the forest health is the main aim of this study, therefore it is important for it to be inclusive and well-represented.

4.5 Limitation of the studied articles

The study on the biomonitoring technique for forest health has shown several strengths and advantages. However, it also has several limitations where it can be improved in the future study. Firstly, the studied articles were mostly coming from the United States. The domination of article from United States proved that the study from other countries especially countries from the Asia region, South America and Oceania are still lacking and scientist from those countries are encouraged to explore the biomonitoring technique for the forest health in their particular locality. Secondly, all of the studied articles were written and published in English language and also been searched and screened from the Scopus and Web of Science database. Some of the articles that study on the biomonitoring technique of their local forest health may written in their native language and published on the local publisher database only. This is due to the language boundary and also the requirement from PRISMA statement which the article that selected for the study must published in the open access database with rigorous reviewing process.

4.6 Future research direction in forest health biomonitoring technique

As a result, for the limitation of the studied articles, also acknowledging the strength of it, this study found several future research directions in forest health biomonitoring technique that can explored by scientist and researcher in this field. Firstly, researcher and scientist from Asia, North America and Oceania should explore and do more study on this particular field where there are still lacking in term of number of the study. Especially for the country that have the tropical rainforest where the biological component is provenly much diverse and rich. Secondly, the method uses in assessing forest health through biomonitoring technique can be diversified where research method such as observation can be used also though it will consume much more energy and time. Lastly, the effort on translating the biomonitoring technique into the standard forest health monitoring guidelines should be taken seriously by the authorities and researcher.

5 Conclusion

This study confirms that there are several limitations and challenges to maximizing the use of biomonitoring to determine the forest health status. Firstly, information on the biomonitoring techniques used for the boreal forest type is lacking. Secondly, the biomonitoring techniques are dominated by plants, fungi, or small animals such as insects. However, studies of biomonitoring using large animals such as reptiles or mammals are still lacking due to the long period it takes to achieve significant results. Lastly, the decline of biological indicators in the forest due to anthropogenic activities and climate change has limited the choice of biological indicator for biomonitoring techniques to assess forest health status. We recommend that scientists and researchers explore boreal forest biological indicators for future studies. Plus, an established method for long term biomonitoring needs to be explored that can use large animals such as reptiles and mammals to assess forest health status. Also, there is an urgent need to conserve and preserve forest ecosystems to ensure the sustainability of biological indicators in the forest. Lastly, it is critical to have a standard parameter using biological indicators to determine the forest health quality globally. All these discoveries show that this study has succeeded in filling the gap and answering the questions raised earlier. It also opens a new dimension for research and discovery in the study of biomonitoring techniques for forest health.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

AA is the only author for this article and all the works in this article is done by AA. AA also approved and read the final manuscript.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.970730/full#supplementary-material

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