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Review

Overview of Health and Safety Risks in the Process of Production and Storage of Forest Biomass for Energy Purposes—A Review

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Abstract: With increasing demands on the quality and quantity of produced biomass, as the main element of the knowledge-based economy, people and the issue of safety and health protection at work are coming to the fore. The aim of the work is the synthesis and overview of the results of the analysis of the health and safety risks of the production of forest biomass in various production phases, starting with its cultivation, through the harvesting production and transport process, up to the issue of its safe storage until it is used for the production of primary energy. Based on the analyzed overview of the existing risks in the production and storage of biomass, it can be concluded that the largest number of works is dedicated to the technological process of storage and consumption of the produced forms of biomass. Of the risks in this phase, the largest number of works is devoted to the risks of the production of spores of phytopathogens and fungi threatening human health. Further research should be primarily oriented toward creating models and modeling the processes of the emergence of these risk factors and the dynamics of their growth.

Keywords: forest biomass; health risks; occupational diseases; biomass storage; phytopathogens

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1. Production of Forest Biomass as a Renewable Energy Source

Forest biomass has long been among the promising and renewable sources of energy. It is actually used as a source for the production of heat, electricity, biogas, and biofuels [1–4]. Biomass (including the biodegradable part of waste) is undoubtedly one of the most important renewable energy sources in the European Union. It makes up 63.3% of the total production of energy from renewable sources. Agriculture and forestry are therefore extremely important from the point of view of energy production from renewable sources [5–10].

With increasing demands on the quality and quantity of produced biomass, the main element of the knowledge-based economy is the person and the issue of safety and health protection at work. With the development of technology and automation, working conditions improve, but at the same time, the demands placed on workers increase. This is also why the number of occupational accidents in forestry and agriculture does not decrease fundamentally [11–17].

Potential sources for the production of biomass and forest chips from it are mainly harvesting slash, purpose-grown plantations of fast-growing trees, or energy stands, Small-wood from cuttings and thinnings, or the crown parts of harvested trees, unsuitable for the production of higher-quality raw-wood assortments [18–21]. Obtaining wood chips from trees grown for energy purposes, but also from harvesting slash, is a complex technological process and requires certain technical equipment. Work is influenced by various factors and brings many health and safety risks for workers [22,23]. Wood biomass is an important renewable energy source. Its share in energy production increases every year. The share of production of raw wood assortments, which are the primary source for the production of wood-based energy sources, is also increasing. According to FAO data, the share of produced wood-based energy sources in the total volume of produced wood products is approximately 11%. In the Slovak Republic, fuelwood assortments make up approximately 8% of all harvested wood assortments. The estimated biomass production in the world is more than 100 billion metric tons per year. Biomass production and its potential to produce renewable bioenergy varies among countries and world regions, and with availability of resources, biodiversity, technology, and economical factors [1,22].

With increasing demands on forest biomass resources and the amount of wood harvesting in forests with the context of sustainable management, economic issues and non-production functions of the forest are also coming to the fore. Setting the right ratio of available forest biomass resources for energy purposes will also be an important issue in the near future [24–26].

The aim of the work is to synthesize and overview the results of the analysis of the health and safety risks of the production of forest biomass in various production phases, starting with its cultivation, through the harvesting production and transport process, up to the issue of its safe storage until it is used for the production of primary energy. Emphasis is placed on works dealing with the research of risks in the long-term storage of forest chips in the climatic conditions of Central Europe, which in the long-term context can become a serious problem for human health. This problem arises mainly because of the frequent placement of stored piles of forest chips directly in the urban areas of villages and towns, often close to human dwellings. Not only the workers who work and handle the wood chips are at risk, but also the people living near the storage.

It will be possible to use the synthesis of the knowledge of this work to take effective measures to improve the current situation and minimize the impact of selected risks on people's lives and health. The review includes works that were registered primarily in the Web of Science and Scopus databases. Furthermore, all relevant sources that refer to legislation and relevant health limits have been added. For the search, keywords related to individual health risks were used (e.g., wood dust, phytopathogens, fire risk, pesticides, health accidents in forest harvesting, etc.).

2. Risks in the Process of Production and Storage of Forest Biomass for Energy Purposes

Risks threatening human health and safety during work in the process of production and storage of forest biomass can also be divided according to individual production phases: establishment and cultivation of plantations of fast-growing trees and intensive stands; production of forest chips from various forms of forest biomass; transport of biomass; and storage of forest biomass for energy purposes [27].

The general risks that are always present at every stage of biomass production for energy purposes include the risks of work accidents, occupational diseases, property damage, and general danger. All these risks have a common denominator, which is the human factor and the approach of workers to the implementation of individual work activities. In general, it can be stated that occupational accidents are a common risk to human health in every production phase. The human factor is an important variable that fundamentally affects the quality of the work performed and the safety during it. However, work accidents often occur as a result of unforeseen circumstances and therefore their occurrence cannot be completely eliminated. The greatest risk of a work accident directly depends on the specific phase and the work activities performed in it. In general, the highest risk of a work accident in forestry is during the harvesting process. Analyses and statistics of the incidence of occupational accidents in forestry were processed in several works [28–34]. These works confirm that almost a third of all work accidents in forestry occur in the process of harvesting, with the most risky days of the week being Monday and Friday. The most frequently injured parts of the body are hands and feet. The second most risky work operation is wood skidding. In other words, the initial stages of the production of wood and biomass for energy purposes are the most risky from the point of view of work accidents. Statistics and analyses of the work accident rate are constantly supplemented and thus enable the formulation and adoption of effective measures for improvement in this area. In most cases of domestic and foreign small and medium-sized enterprises in the field of forestry, employers do not pay enough attention to the safety and health of employees, and regular health examinations of persons working in dangerous working conditions are not carried out [33,35–41].

The predominant cause of most forest harvesting accidents is the use of unsafe practices and non-compliance with established prohibited work practices. The majority of serious work accidents while working in the forest were caused by non-observance of safe working or technological procedures. In order to ensure safe working conditions, it is necessary to study and analyze real cases of accidents and work injuries, and then create a system of measures and requirements to prevent the occurrence of these phenomena. Due to the large number of fatal and serious work accidents in the processes of harvesting and skidding of wood, the importance of systematic education of workers who perform work in this industry is increasing. Above all, it is important to emphasize the correct work procedures, tools, and technologies, so that the risks of injury are minimized.

2.1. Risks in the Establishment, Cultivation, and Protection of Fast-Growing Tree Stands

In the establishment, cultivation, and protection of cultures of fast-growing trees, in addition to the group of work accidents, chemical harmful factors and biological harmful factors can also be characterized as health risks. Chemical agents are used quite often in the cultivation of fast-growing trees. Pesticides and insecticides are used to kill pests and insects. Herbicides, in turn, fight against weeds (Figure 1). Herbicides used contain phenoxy, glyphosate or triazines [42]. With the long-term use of areas for plantations of fast-growing trees, with repeated application of glyphosate, the survival of the planted individuals improves, but there is a gradual decrease in production [43]. All the chemical agents used to fight weeds have a demonstrably negative effect on human health. Glyphosate-based herbicides have a significant negative impact on human health, and their carcinogenic effect has also been proven, or has been listed as probable human carcinogens by the International Agency for Research on Cancer [44–48].

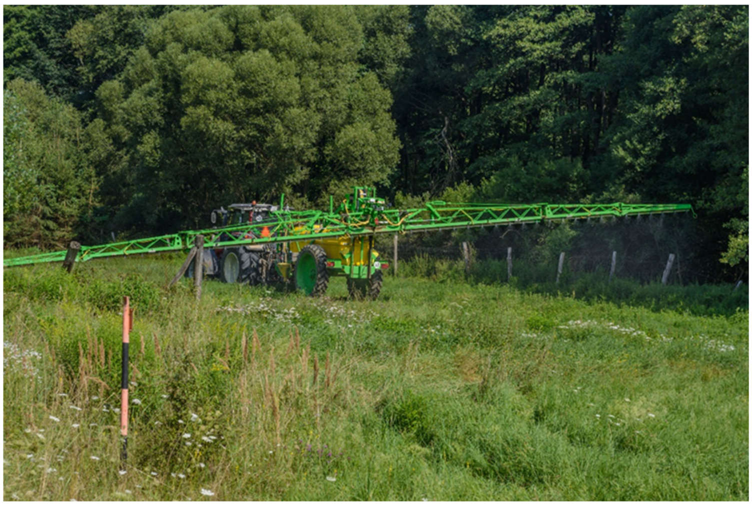

Figure 1. Weeding of the plantation area using pesticides.

The toxicity of glyphosate on human cells has been confirmed by several studies, some studies state that the safety of the use of herbicide preparations based on glyphosate cannot be unequivocally confirmed from the point of view of epidemiological studies [49]. A harmful effect on the eyes was also confirmed in 70% of workers who used Roundup herbicide [50]. A direct effect on the incidence of prostate cancer among workers who regularly worked with herbicides was also confirmed. The paper [51] examined the incidence of prostate cancer in a sample of 55,332 men who used 45 types of pesticides, identifying a normalized ratio of prostate cancer incidence of 1.14 (95% confidence interval 1.05, 1.24).

In the paper [52], among 44,932 workers who worked with glyphosate herbicides, they identified up to 5779 cases of cancer, of which the highest proportion was acute myeloid leukemia. Individuals who used glyphosate when working with the soil had a 33% higher probability of premature mortality than those who did not use this chemical [53].

Naturally, other chemical factors are also risky. The work [54] identified that 6 out of 27 chemical agents in used pesticides had an effect on the increased risk of myocardial infarction in women. Specifically, the substances involved were chlorpyrifos, coumaphos, carbofuran, metalaxyl, pendimethalin, and trifluralin. In work [55], they investigated the occurrence of respiratory diseases in a sample of 1335 farmers in Brazil who used pesticides. A total of 12% of them reported symptoms of asthmatic diseases and 22% of them reported symptoms of other chronic respiratory diseases. A similar proportion of respiratory diseases among users of 36 different types of pesticides was also found in work [56], where they identified 11 types of pesticides that had an impact on the onset and development of chronic bronchitis in 3% of people from a sample of 20,908 farmers, classifying Heptachlor as the most risky. A similar study also confirmed that 19 types of pesticides had an impact on the development of allergies [57]. Ref. [58] confirmed an increased risk of colon cancer when using pesticides with chlorpyrifos and aldicarb.

It is clear from the above that the use of pesticides represents a wide spectrum of health risks for people. In addition, they have demonstrably adverse effects on the environment, ecology, and biodiversity in forest and agricultural ecosystems (e.g., [59,60]).

So far, there is no blanket ban on the use of these substances in the European Union, and access is left to the legislation of individual countries. Most countries routinely use these substances in the fight against weeds.

Biological factors in the establishment of plantations include the risk of being bitten by the common tick (Ixodes ricinus), which can cause severe disease [61,62]. Among the most serious diseases that can be caused by a tick bite are Lyme disease (borreliosis) and tick-borne encephalitis. The diagnosis of borreliosis is always established on the basis of the clinical picture and microbiological diagnosis [63]. Tick-borne encephalitis is an acute febrile disease affecting the central nervous system (meningitis and encephalitis), for which there are vaccines. The incidence of this disease in Europe has increased by more than 400% since 1974 [64]. Global climate changes also have an influence on this fact. Data show that the winter activity of ticks is increasing [65], their life cycle is accelerating [66,67], they are found at higher and higher altitudes [68,69] and are increasingly found in more northern regions of Europe [70]. In total, 50,486 cases of tick-borne encephalitis were recorded in Europe (excluding Russia) between 1990 and 2007, which represented an average of 2805 cases per year [64].

It follows from the above that even seemingly simple work activities outdoors can lead to a serious risk of endangering human health and life. As a rule, there are no serious work accidents when establishing plantations of fast-growing trees. Most of the time, these are only minor cuts of the upper and lower limbs. The main risk factors are therefore influenced by the biology and occurrence of ticks in a given location as well as the use of chemicals during the establishment and maintenance of the plantation (herbicides and insecticides). When applying them, all safety measures should be observed, and workers should be properly equipped with personal protective equipment. The risks in the establishment, cultivation, and protection of stands of fast-growing trees as a source of biomass for energy use are summarized in Table 1.

Table 1. Risks to human health in the establishment, cultivation and protection of fast-growing tree stands.

Factor	Risk	References
Herbicides Glyphosate, chlorpyrifos, aldicarb	Cancer diseases	[49–53,58]
Chlorpyrifos, coumaphos, carbofuran, metalaxyl, pendimethalin and trifuralin	Myocardial infarction, respiratory diseases, allergies	[54,55]
Heptachlor	Chronic bronchitis	[56]
Biological factors- Common tick bite	Lyme disease	[61–63]
	Tick-borne encephalitis	[64–70]

2.2. Risks in the Production of Biomass for Energy Purposes and Wood Chips

The production process of energy wood and forest chips can be divided according to the production location and also according to the chosen technological procedure and technologies. This also results in potential risks in this technological process. In addition to work accidents, which are a standard risk for all activities, there are also described biological risks resulting from tick bites when working in the field and the forest. Other factors in this phase include mechanical risk factors, stress due to cold and heat, exposure to wood dust and dirt, long-term excessive unilateral loading of the limbs, and psychosocial risks [71,72].

Regarding the mechanical risk factors in this production phase, our advice is mainly related to noise and vibrations, which affect the operators operating the machines for the production of biomass. Despite the legislative obligation of workers to use personal protective work equipment, often workers do not use this equipment or do not change them at the prescribed intervals. This is also why occupational diseases constantly occur. As a result of long-term exposure to vibrations, vasoneurosis, vascular problems, chronic pain and limited limb mobility occur [73]. Long-term exposure to noise is mainly associated with partial or complete hearing loss, sleep disorders, psychological problems, and headaches [74–77]. Professional traumatic angiopathy (vibration white finger) or vessel damage syndrome occurs as the first signal damage to the body by vibrating instruments [78]. Workers may be exposed to noise and vibration throughout the logistics process. At the same time, however, this risk factor is most significant in the process of harvesting and production processes focused on the production of individual types of forest biomass.

According to Slovak legislation, noise-induced hearing loss is classified as hearing loss according to "Fowler" in victims under 30 years of age of at least 40%. For aggrieved persons older than 30 years, this is every two years + 1%, until the aggrieved person reaches 50 years of age when the hearing loss must already exceed 50%.

Vibration disease is classified as a disease of the bones, joints, muscles, blood vessels, and nerves of the limbs caused by vibrations in contact with vibration sources. According to hygiene limits (Regulation of the Government of the Slovak Republic No. 115/2006 Coll.) in Slovakia, the limit value of the normalized sound level A is $L_{AEX,\,8h}$ for workgroup IV. = 87 dB [77].

With multi-operation machines, machine operators are exposed to two types of vibrations: vibrations transmitted from the steering wheel to the hands and vibrations transmitted from the machine seat to the whole body [79]. In most of the works, none exceeding the permitted limits established by the legislation was found for modern machines [80]. According to the current Slovak legislation (Government Regulation No. 416/2005 on minimum health and safety requirements for the protection of employees from risks related to exposure to vibrations), the limit value of the normalized acceleration of vibrations transmitted to the whole body in the direction of the axis with maximum transmission is at the level of 1.15 $m \cdot s^{-2}$. The limit value of the resulting normalized acceleration of vibrations transmitted to the hands $a_{hv,8h,L}$ is 5 $m \cdot s^{-2}$. Exceeding these values was not confirmed for the analyzed chippers [80]. This long-term (several years) effect of such vibrations on a person and the effect on his health is problematically evaluated. When chipping with chippers, the technological parameters of the machine itself have the greatest impact on exposure to whole-body vibrations, while the wear of cutting tools did not show a statistically significant increase in these vibrations [74].

In work [81], they classified that a higher level of vibration is produced by chippers that are placed directly on the truck structure compared to chippers that are located mostly behind the tractor on a separate trailer. The highest level of whole-body vibrations was recorded when driving along the forest road to the prepared material for chipping and during chipping. A higher level of whole-body vibration was recorded when chopping hardwoods than softwoods. The hygienic vibration levels set by the legislation for chipping were exceeded only by the second chip producer (Jenz) in the case of chipping with a mower on the construction of a truck, both when chipping coniferous and non-coniferous trees (Table 2).

Table 2. Acceleration of whole-body vibrations produced by chipper Jenz and Kesla C4560LF in v m·s^{-2} (Sources: [80,81]).

Work Operation	Wood Species	Chipper Behind Tractor					Chipper on Truck			
		Average	Sd	Min.	Max.	Comparison Source [80] Chipper KESLA (Max.)	Average	Sd	Min.	Max.
Chipping (m·s^{-2})	Conifer	0.27	0.02	0.23	0.31	0.51	0.63	0.02	0.58	0.65
	Non-conifer	0.31	0.03	0.27	0.35	2.1	0.70	0.04	0.65	0.78
Movement (m·s^{-2})	Conifer/non-conifer	0.84	0.17	0.53	1.08		0.50	0.12	0.24	0.64
Downtime (m·s^{-2})	Conifer/non-conifer	0.05	0.02	0.02	0.08	0.34	0.13	0.02	0.10	0.14

The layout and impact of vibration acceleration on the hands depends on the layout of the control elements of the individual mowers, as well as on the work operation that is being performed. An increase in vibrations can occur, e.g., when the material gets stuck in the feeder, but also when chipping very thick pieces that need to be adjusted with a hydromanipulator [80]. The risk of increased vibrations acting on the hands must also be approached individually depending on the technological process during chipping (machine parameters, chipped material, and weather conditions).

As with vibrations and noise, workers with a chainsaw operator profession, workers with a physical age of 56–60 years, and workers with a working period of 26–30 years are among the most at risk [77]. The work [74] evaluated the noise on drum chippers Pezzolato PTH 1200/820 and PTH 800/820, which were placed on the construction of a truck and on a separate trailer behind the tractor, respectively. They found that higher noise was produced by chippers that were placed on a separate trailer. At the same time, it was confirmed that with chippers that have a closed cabin, and the operator is “isolated”, the action and limit values for noise exposure were not exceeded. Fundamental differences in the acoustic noise level were not detected depending on whether whole tree trunks were chipped or only harvesting slash and coarse material. Most modern machines with closed cabins already offer modern ergonomic solutions that significantly limit the negative impact of noise. The problem arises with mowers where the operator stands or sits outside the cab and operates the mower directly. Ref. [82] evaluated the Farmi CH260 chipper in this way. With this type of chipper, with different types of operations and chopped material, they measured the average value of the equivalent sound pressure value LAeq at the operator’s ear at the level of 98 dB, which is well above the legislatively established noise limit value. The highest recorded levels even exceeded the value of 120 dB, which is already close to the noise values normally emitted by a manual chainsaw.

As we have already mentioned, the harmful effect of noise in the work process is rather difficult to register and evaluate without accurate and long-term measurement.

An exact assessment of the harmful impact of noise, which accumulates in the organism over several years and becomes apparent only over a long period of time, would require long-term monitoring of one worker and several years of continuous measurement of noise exposure. This problem would be further accentuated by the fact that workers often work in different positions and operate different types of machines and mechanisms during their working career. These facts practically make it impossible to accurately assess the harmful impact of noise during long-term work activity. Retrospective evaluation of which machine and in which time period of the working career had the greatest share in the occurrence of occupational disease can be carried out.

The risk of inhaling wood dust by the mower operator is also associated with outdoor chipping work (Figure 2). A level of 5.0 mg·m^{-3} of air is considered a hygienic technical reference value for the concentration of wood dust.

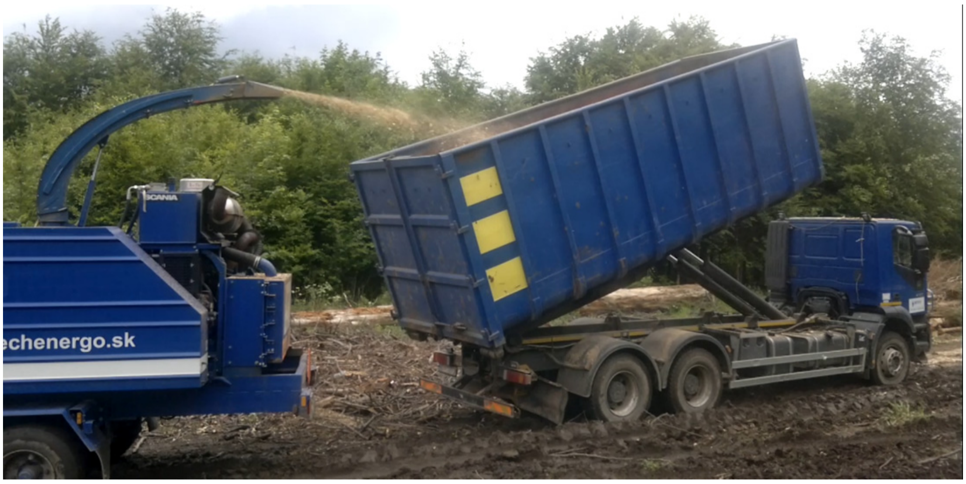

Figure 2. Swirling of wood dust in the wood chipping process.

The impact of wood dust on human health depends on many factors such as the type of wood, its chemical composition, and other factors. In addition to the effect of dust on the respiratory system, it also has a negative effect on the mucous membranes of the eyes, nose, mouth, and larynx [83,84]. The result of the great impact of small dust particles on the mucous membranes is their drying; on the other hand, dusts with higher humidity create conditions for fermentation, the formation of chemical reactions of dust particles with biological particles that are contained in the dust and also create a danger of developing allergies in the human body [85]. Wood dust can further cause [86,87] the following:

- Dermatoses—caused by mechanical irritation, chemical irritation, and allergic effects of some wood components;
- Respiratory problems—affected by particle size and type of wood (inflammation of mucous membranes and airways);
- Allergic respiratory problems—allergies to components of wood dust (asthma, bronchitis), allergies to molds and fungi in wood;
- Carcinogenic action of some types of wood.

The greatest danger for the respiratory organs is represented by the respirable (alveolar) component with a particle size below 10 µm, which reaches the lungs (lung tissue) through the respiratory tract and acts as a mechanical or chemical irritant. Most of the works published so far [88,89] deal with this risk mainly from the point of view of the concentration of wood dust in the working environment, but do not primarily address its composition, i.e., whether it is really wood dust, or is it a dust formed with an admixture of dirt and fungal spores and molds that normally occur on chipped material. So, we can say that during chipping, pure wood dust is not formed, but contains admixtures of impurities.

During the production of wood chips, wood dust often swirls in cloud concentrations, which, especially in combination with fuel vapors and engine heat, can create a dangerous explosive mixture that can endanger the life and health of workers, as well as cause damage to property and equipment [90,91].

Another health threat to workers in the chip production process is disease from long-term, excessive, and one-sided loading of limbs (Carpal tunnel syndrome). The disease arises in connection with the long-term physical exertion of workers and mainly affects the structures of the movement system of the limbs' bones, joints, tendons, muscles, nerves, and blood vessels [92,93].

In connection with the mechanization of work and the increasingly high degree of automation and robotization, as well as the increase in forestry, the nature of work is changing, and the problem of neuropsychological stress is increasingly coming to the fore. Over the last two decades, the share of multi-operational machines in forestry operations has increased significantly. These machines offer high comfort for their operators but place increased demands on them in the form of digital skills and mental stress. This can contribute to the deterioration of neuropsychological well-being and associated psychological disorders [94].

Operators of multi-operational machines are primarily exposed to excessive neuropsychological stress. They are forced to perform short work cycles, perceive, and evaluate a large amount of information, and make a large number of quick decisions. In work [95], they investigated the influence of external factors on the pulse frequency of harvester and forwarder operators. They found that operators' physical parameters, machine types, controller parameters, workplace lighting intensity, equivalent noise, and whole-body vibration affected approximately 72% of the sample with an elevated pulse rate. The issue of assessing psychosocial factors affecting workers in forestry is very difficult and requires the participation of several experts. However, with the current level of mechanization and technologies used, assessing the neuropsychic load is a necessity. It is necessary to implement this type of risk in occupational risk assessment systems and, based on the results, propose measures for their elimination, or complete removal [22]. The second important factor that can cause stress and subsequent neuropsychological disorders is workplace relationships. In a 2006 paper [96], a sample of more than 9000 forestry workers in Sweden and Finland investigated the relationships between workplace conflict management and self-reported measures of stress, ill health, burnout, and absenteeism due to overwork or fatigue. The lowest probability of occurrence and reporting of stress was detected among workers who resolved their conflicts through discussion. Conversely, there were workers who did not resolve conflicts at all or who resolved them in an authoritative manner.

Table 3 shows a summary of the most serious risks that arise in the technological phase of the production of biomass for energy purposes and forest chips. Again, the risks that can seriously damage human health prevail, especially if workers are exposed to exposure factors for a long time (over several years). Several risks are related to the technological process of disintegration of the wooden raw material (dust, noise, vibrations) and partly also to the lack of qualified labor.

Table 3. Risks to human health in the production of biomass for energy purposes and wood chips.

Factor	Risks	References
Noise, vibrations	Vasoneurosis	[78–80]
	Limited mobility of limbs, headache	[73–77]
	Hearing damage	[74,77,82]
Wood dust	Allergies	[85]
	Dermatoses, respiratory problems, cancer	[86,87]
	Explosion, fire	[90,91]

Table 3. *Cont.*

Factor	Risks	References
Long-term, excessive, and one-sided loading of limbs	Movement problems, Carpal tunnel syndrome	[92,93]
Neuropsychological stress, bad work atmosphere	Excessive load on the cardiovascular system	[95]
	Exhaustion, burnout syndrome, psychological problems	[96]

2.3. Risks in the Process of Storing Biomass for Energy Purposes

With the increase in the number of operations using wood chips as an energy source, issues of health and safety risks during their storage are becoming more and more common. From this point of view, the risks associated with the activity of fungi and molds in piles of wood chips (Figure 3) and the inhalation of wood dust when handling wood chips are evaluated as the most risky factors for human health [97–101].

Figure 3. Mycelia and fruiting bodies of fungi on a stored pile of wood chips.

Examples of smaller piles of wood species are Beech (*Fagus sylvatica*), Poplar (*Populus tremula*), and Spruce (*Picea abies*). In total, 12 genera or species of fungi and molds were identified in these piles. Statistical analyses did not confirm a significant dependence on the occurrence of fungi on the wood or the level in the pile. The most represented species of fungi and molds in the experimental piles were mainly *Mucor* sp., *Penicillium* sp., *Trichoderma* sp., and *Aspergillus fumigatus* [98]. In total, 25 species of fungi and molds were identified during the storage of 80% wood chips from Beech (*Fagus sylvatica*), and 20% Spruce and White Fir (*Picea abies*, *Abies alba*) in large-capacity piles in four urban-type heating plants, of which 24 may pose a risk to human health. The most frequently identified species were species of the genera *Aspergillus*, *Mucor*, and *Trichoderma* [100]. This research continued in the following years, while in 2017–2022 the most frequently identified microorganisms were *Penicillium* sp., *Aspergillus brasiliensis*, *Aspergillus unguis*, *Aspergillus flavus*, and yeast [101].

This poses a risk even if the chip storage is located in an urban area near houses or apartment buildings, which is quite common in the case of urban-type heating plants. Since fungal and mold spores can spread in dangerous concentrations up to a distance of 300 m from the pile, these residents are potentially at risk of this health risk without knowing and being informed about it [102].

The immediate use and consumption of produced forest chips is often not possible for various reasons. Technologies that demand a particular quality of wood chips are often installed in heating plants. These heat producers are increasingly demanding continuous supplies of high-quality wood chips. They mainly focus on the moisture content and calorific value of the fuel, which also limits its final price. These two basic properties can be fundamentally influenced by the method and length of storage of wood chips.

It was found that the amount of spores in the air drops below 1000 CFU·m^{-3} (Colony Forming Unit·m^{-3}-colony forming unit (CFU) per cubic meter) up to a distance of 300 m from the pile. It is therefore possible to consider this space as a threatened zone, with a potential health risk [102].

Most of the fungi identified in the chip storage process pose a potential hazard to human health when inhaled by humans. Inhalation occurs quite often when handling wood chips (loading, unloading, dispensing into a container, etc.). Fungi of the genus *Aspergillus* sp. and *Fusarium* sp. cause invasive mycoses (infections) that affect internal organs and organ systems [22,27,103]. Species of *Aspergillus* sp. can cause lung disease aspergillosis in the form of pulmonary aspergilloma, which can cause up to 20% mortality [104]. Fungi of the genera *Mucor* sp. and *Fusarium* sp. are a threat, especially for people with weakened immunity. They can cause various infections (e.g., "mucormycosis") and are considered important allergens [105,106]. The production of dangerous mycotoxins was also confirmed in the genus *Penicillium* sp. They also cause allergic diseases in some people [107]. Fungi of the genus *Trichoderma* sp. cause infections in immunosuppressed people [108].

The initial heating of fresh chips is caused primarily by the respiration of still-living parenchyma cells. When the chips are heated above 40 °C, cell respiration stops. Further heating of the pile is demonstrably caused by the metabolism of fungi and bacteria. Fungi survive up to a temperature of about 60 °C, but thermophilic bacteria raise the temperature of the chips to a value greater than 75 to 80 °C, at which point their activity stops. Despite this, long-term stored biomass can reach temperatures greater than 100 °C. Above this limit, the processes of thermochemical conversion and chemical oxidation begin, which can lead to spontaneous combustion. Even when the temperature reaches more than 80 °C, the chips are not disinfected, because the microorganisms survive in a state of rest. After subsequent cooling, they become active, and the temperature of the pile may rise again. The speed at which the temperature of the wood chips increases depends on various criteria, among which we mainly include water content, structure and density of the material (size of fractions), amount of stored material, type of storage (covered/open), dirt, climatic factors, and initial infection of the wood chips with fungi [109,110].

These facts extremely increase the risk of fire, which can cause damage to property and human health. This risk is often further increased by the incorrect location and spatial arrangement of the woodchip storage in operations (Figure 4), together with non-compliance with safety regulations (e.g., incorrect location of the ash dump, storage of a large volume of woodchips without creating the least one internal line, missing area intended for spreading ignited woodchips, insufficient equipment for fire extinguishing, protection against the entry of unauthorized persons, etc.).

Much attention has not yet been paid to the evaluation and quantification of the amount of wood dust generated during different types of chip storage and handling. Most of the works published so far deal with this risk, especially in the process of wood chipping, which we discussed in Section 2.2. However, there are relatively few works dealing with exposure to wood dust in the process of woodchip storage [111,112]. It is probably related to the equipment and time requirements of such research, while a number of other factors can affect the results. There is also work where wood dust from wood chips was identified as the cause of an explosion, with consequences for human health and lives [113]. It is also important to mention that dust particles are generated in urban-type heating plants not only from the storage and handling of biomass, but also from the process of burning it. According to Government Regulation no. 356/2006 Coll. on the protection of the health of employees from risks related to exposure to carcinogenic and mutagenic factors at work, the technical guideline value for the concentration of wood dust = 5.0 $mg \cdot m^{-3}$ during a work shift [27]. The United States Environmental Protection Agency [EPA] states that unhealthy air for human health is a concentration of PM2.5 dust particles at the level of 55–150.4 $\mu g \cdot m^{-3}$ in an average of 24 h. Very unhealthy concentrations are from 150.5 to 250.4 $\mu g \cdot m^{-3}$ [114]. According to the World Health Organization (WHO), from 2021, healthy air is considered to be where the daily average concentration of PM2.5 particles does not exceed 15 $\mu g \cdot m^{-3}$ [115].

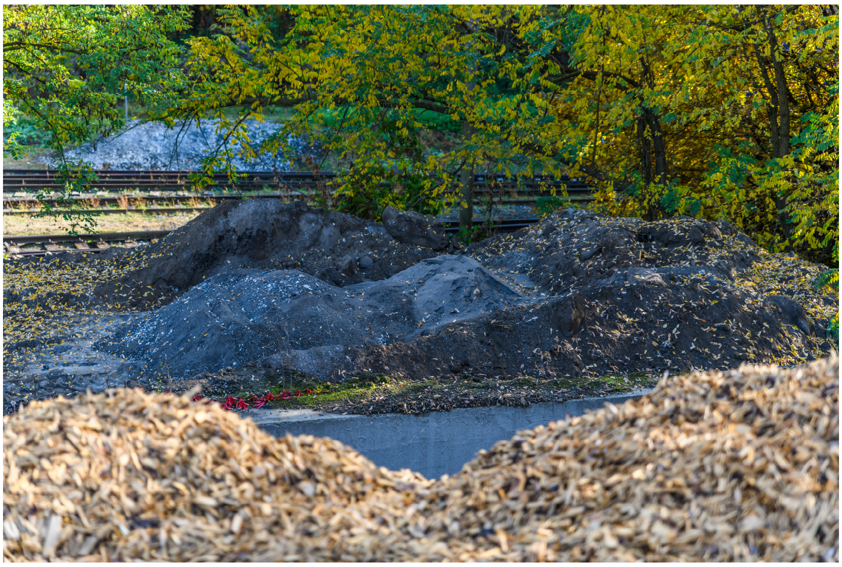

Figure 4. Inadequate spatial arrangement of the chip storage—a pile and a nearby ash dump.

In the paper [116], the authors evaluated the danger of the dust component during the storage of biomass in large-capacity silos (50,000 m^3 and more). They found that in this type of biomass storage, dust particles together with fungal spores can create a dusty mixture that can be dangerous to the health of operators working with this biomass and can even form a highly flammable and explosive mixture in case of contact with a source of heat or fire. According to [117], the explosive mixture of wood dust from biomass is at a concentration in the range of 100 g/m^3 to several kg/m^3. In the cited work from 2015 [116], up to 50% more dust than the minimum explosive limit was detected. There is thus a risk of explosion when filling a large-capacity silo.

Table 4 provides an overview of risks and factors that cause them in the process of storing biomass for energy purposes.

Table 4. Risks to human health in the process of storing biomass for energy purposes and wood chips.

Factor	Risk	References
Phytopathogens	Mycosis Aspergillosis Infections, allergies	[22,103] [104] [105–108]
Wood dust	Allergies Dermatoses, respiratory problems, cancer Explosion, Fire	[111,112] [86,87] [113,116,117]
Selfheating	Spontaneous ignition, fire due to improper storage arrangement	[101,109,110]

3. Discussion

Based on the analyzed overview of the existing risks in the production and storage of biomass, the largest number of works is dedicated to the technological process of storage and consumption of the produced forms of biomass. Of the risks in this phase, the largest number of works is devoted to the risks of the production of spores of phytopathogens and fungi threatening human health [118]. Work [100] confirmed high numbers of phytopathogen colonies even in chip samples taken from a depth of 0.5 m. In two heating plants, the highest numbers of colonies of identified fungi and molds were quantified in samples from a depth of 0.5 m. It is obvious that the sampling location has no significant influence on the occurrence of health-threatening microorganic fungi and molds. In the case of larger piles, even a shallower depth of 0.5 m does not have a significant effect on the occurrence of toxicogenic micromycetes. A smaller part of the work is devoted to the risks of self-heating of biological material and the related risk of fire. The emphasis on further research should be directed precisely to the creation of models and modeling of the process of the emergence of this phenomenon [119]. Work [120] evaluated four storages in urban-type heating plants from the point of view of fire protection. In all evaluated storages, there was a demonstrably increased safety risk, especially the risk of fire, mainly due to the incorrect location of the ash dump, and the storage of a large volume of wood chips without the creation of at least one internal line, while there was evidently intense heating of the stored material in the piles, and there was also a lack of space for spreading ignited chips. The storages were not sufficiently equipped with water for extinguishing, secured against the entry of unauthorized persons, and did not have correctly placed prohibition signs. Considering the fact that all these storages are located in the urban areas of the municipalities, some even near houses and residential buildings, this finding was a serious security risk.

The least amount of work in this area is devoted to the risks associated with production and the threat of wood dust.

Less attention is paid to the risks that threaten human health and property in the process of biomass production itself for energy purposes. In part, this fact results from the fact that often the very production of assortments that serve as sources for biomass for energy purposes is only a secondary activity of the forestry operation in addition to the production of wood for more valuable processing purposes, and thus relatively few authors devote themselves to the analysis of risks in this area. The greatest attention is paid to the ergonomic parameters of the machines that produce wood chips and the negative impact of noise and vibrations that affect the operators of these machines. In most cases, as long as the operator works in a closed safety cabin of the machine, the permissible ergonomic limits are not exceeded [74,77]. Respectively, they are exceeded only momentarily in the event of some extraordinary event (e.g., a stuck part of the log in the woodchipper's feeder, etc.) [80]. Health risks exist in cases where the operator does not sit in the cabin and is thus directly exposed to the adverse effects of noise, vibrations, and wood dust [88]. There are fewer works devoted to health risks that arise as a result of the long-term effects of workload in the process of biomass production (e.g., neuropsychological problems, diseases of the musculoskeletal system from long-term excessive workload, etc.).

The risks that arise in the process of establishing intensive stands and energy plantations are rather analyzed through works that are devoted to agricultural production as a whole [121]. Some of the health risks that arise, for example, as a result of tick bites are also analyzed earlier in works that analyzed other activities within forest stands and permanent grasslands [61–64].

Suggestions for the following recommendations arise from the results of this review:

- Update legislative regulations for the building and operation of facilities that use wood chips as the main raw material, taking into account health and safety risks;
- Develop and apply a system of positive and negative motivation through internal guidelines, with the aim of improving the quality of work performed in forestry;
- Legislatively resolve self-employed persons in the field of safety and health protection regulations at work;
- Renewal of the system of preventive medical examinations in specialized departments of occupational medicine;

- Intensify controls by the competent authorities, but also by the employer, for compliance with the rules of safety and health protection at work and the correct use of protective equipment;
- Develop safety limits for concentrations of spores of phytopathogens and safe distances at workplaces with biodegradable material and include them in the relevant legislation;
- Explicitly establish the need for personal protective work equipment in risky operations;
- Improve risk awareness among workers and people who come into direct contact with stored, biodegradable material;
- Legislatively establish the need for necessary spatial and fire-fighting equipment in the operations of urban-type heating plants when storing forest chips in large-capacity piles.

4. Conclusions and Future Directions

Currently, the issue of risk analysis in the process of production and storage of forest biomass for energy purposes is being developed mainly for the technological process of biomass storage and consumption. The risks and their negative effects on human health and threats of damage to property are generally known.

Further research should be primarily oriented toward creating models and modeling the processes of the emergence of these risk factors and the dynamics of their growth. Currently, the research also focuses on the possibilities of eliminating or possibly minimizing health and safety risks in the process of storing biomass for energy purposes. The first works with experiments aimed at minimizing the production of spores of phytopathogens and the possibility of reducing the risk of fire were published only recently [122]. The fact also remains that many establishments are uninformed about these risks, or they underestimate them in the professional training of employees, as well as in the provision of personal protective work equipment. A special area is the impact of these negative factors on the population near the operations. This area is still not sufficiently explored. Further research in these areas is gradually underway and its results should be known in the next few years.

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