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Review article

Métodos destacados para la protección de la madera

Prominent wood protection methods

Víctor Daniel Núñez-Retana[1], Marco Aurelio González-Tagle[1], Humberto González-Rodríguez[1], María Inés Yáñez-Díaz[1], Wibke Himmelsbach[1]*

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[1]Facultad de Ciencias Forestales, Universidad Autónoma de Nuevo León. México.

*Autor para correspondencia; correo-e: wibke.himmelsbach@uanl.edu.mx
*Corresponding author; e-mail: wibke.himmelsbach@uanl.edu.mx

Resumen

La madera es un material ampliamente usado en construcción, muebles, entre otras aplicaciones. Para mantener su calidad y durabilidad se emplean tecnologías de protección contra daños biológicos y los efectos del agua, la temperatura y la radiación que afectan sus propiedades físicas y mecánicas. En el presente trabajo se realizó una revisión de los tratamientos disponibles y se evaluaron sus ventajas e inconvenientes, además se definieron los criterios para su utilización. La temática se dividió en dos secciones: (I) los agentes degradadores de la madera, y (II) una clasificación de tecnologías de protección que incluyó tanto métodos tradicionales, como enfoques novedosos, tal es el caso de la nanotecnología. Bajo este enfoque, las conclusiones obtenidas apuntan a que diversos tratamientos químicos tradicionales reducen, sustancialmente, el daño biológico y la absorción de humedad en la madera. No obstante, deben considerarse los posibles efectos a la salud y al ambiente. Por otra parte, si se emplean tratamientos térmicos, la estabilidad dimensional de la madera mejora. El uso de compuestos nanométricos para la protección de la madera es una técnica muy prometedora y en creciente desarrollo. Sin embargo, es una tecnología de especial cuidado porque los nanomateriales tienen que ser tóxicos para los agentes causantes del biodeterioro, pero inocuos o menos peligrosos para los humanos y el ambiente.

Palabras clave: Degradación de la madera, durabilidad, nanotecnología, protección de la madera, tratamientos químicos, tratamientos térmicos.

Abstract

Wood is a material widely used in construction, furniture, and other applications. Technologies are used to protect its quality and durability against biological damage and the effects of water, temperature and radiation that affect its physical and mechanical properties. The present work reviews the available treatments, evaluates their advantages and disadvantages, and defines the criteria for their use. The theme was divided into two sections: (I) Wood degrading agents, and (II) A classification of protection technologies that included both the traditional methods and novel approaches such as nanotechnology. The conclusions obtained with this approach point to the fact that several traditional chemical treatments substantially reduce biological damage and moisture absorption in wood. However, potential health and environmental effects should be considered. On the other hand, the dimensional stability of the wood is improved through the use of heat treatments. The use of nanometric composites for wood protection is a very promising technique that is under increasing development.

However, it is a technology that requires special care because the nanomaterials must be toxic to the agents causing biodeterioration, but harmless or less hazardous to humans and the environment.

Key words: Wood degradation, durability, nanotechnology, wood protection, chemical treatments, heat treatments.

Introduction

According to FAO (2022), the annual global industrial production of wood in 2020 was approximately 3.9 billion cubic meters destined for fuel or roundwood, 473 million cubic meters were produced as sawn timber, and 367 million cubic meters, as materials derived from the wood. The demand for these products, mainly roundwood, is expected to reach 6 billion cubic meters by 2050 (Barua *et al.*, 2014).

Wood protection is crucial in the global timber market, which faces the challenge of preserving it against biodegradation and exposure to water. This challenge can be solved with the help of protection technologies (Chen *et al.*, 2020). As a response, methods have been developed to treat the wood using different protection strategies to improve its resistance to biodegradation.

In this regard, the quality, protection and resistance to degradation of wood products depends on such factors as humidity, temperature, wood density, and protection treatments (Gérardin, 2016).

UNE-EN 350 (*Asociación Española de Normalización*, 2017) classifies wood into four categories according to its ease of treatment: Class I, easy to treat; Class II, moderately easy to treat; Class III, difficult to treat; and Class IV, extremely difficult to treat. This standard establishes methods for assessing and classifying the durability of wood, understood as its ability to resist decay and decomposition against fungi, termites, and marine organisms (Reinprecht, 2016), and it is applicable even to treated or modified wood. The use of such a standard is crucial to provide a recognized standardized framework allowing comparison, as well as adding credibility by supporting the information with accepted standards and offering practical guidance through specific criteria and tests. In addition, its reference is essential to determine the commercial quality of the wood.

In this sense, in recent years, several works have been carried out to show affordable and environmentally friendly alternatives for the protection of wood. Some of these protection treatments are well-known and widely used in the industry, such as the traditional ones described by Peraza (2002), while others are more novel and involve nanotechnological techniques such as those described by Teng *et al.* (2018) and Jasmani *et al.* (2020).

The objective of this paper is to provide a general review of the main techniques currently available for wood protection and to evaluate their advantages and disadvantages. First, wood degrading agents will be discussed, followed by a classification of protection technologies ranging from traditional methods to modern and novel approaches such as nanotechnology.

Wood degrading agents

Table 1 presents a classification of the most important agents affecting the durability of wood, their effects and the most recent reference research proposing different protective treatments. In general, a distinction is made between biotic and abiotic agents. The former refer to living organisms, and the latter, to physical and chemical components of the environment.

Table 1. Factors influencing wood degradation, damages, and proposed protective treatments.

	Agents	Damages	Treatments proposed	Research of reference
Biotics	Xylophagous microorganisms	Mechanical properties Structural damage to the cell wall of the wood Coloring	Acetylation Furfurylation	Goodell *et al.* (2020) Broda (2020) Martha *et al.* (2021) Marais *et al.* (2022)
	Xylophagous insects (termites)	Destruction of the cell walls Mechanical damages Aesthetic damages	Impregnation of soluble resins or polysaccharides	Rust y Su (2012) Yang *et al.* (2022)
	Crustaceans and bivalves	Perforations in wood used in vessels	Impregnation of soluble resins or polysaccharides Nanotechnological treatments	Marais *et al.* (2022)
Abiotics	Water	Shrinkage and swelling Particle and compound dissolution Causes fungal growth Discoloration	Acetylation DMDHEU (1,3-dimethiol-4,5-dihydroxyethyleneurea) Nanotechnological treatments	Rowell (2020) Wang *et al.* (2021) Goodell *et al.* (2020) Marais *et al.* (2022)
	UV rays	Coloring Degradation of surface components (lignin, hemicellulose)	Impregnation of soluble resins or polysaccharides Heat treatment Nanotechnologcial treatments	McKinley *et al.* (2019) De Avila *et al.* (2019)
	Thermal decomposition	Elimination of volatile compounds Surface degradation	DMDHEU (1,3-dimethiol-4,5-dihydroxyethyleneurea) Heat treatment	Reinprecht (2016) De Avila *et al.* (2019)
	Degradation by chemical compounds (alkalis, detergents, acids)	Degradation of cellulose and hemicellulose fibers	Varnishes or protective coatings Impregnation of soluble resins or polysaccharides Nanotechnological treatments	Peraza (2002) Xu *et al.* (2020)

The main factors of wood degradation, understood as damage to the wood structure that can be initiated at both higher and molecular levels, include abiotic or atmospheric agents such as moisture, UV rays, and temperature, together with the presence of xylophagous organisms (Reinprecht, 2016). Exposure to sunlight and thermal decay affect the adhesion of coatings and the appearance of wood structures, leading to early replacement (McKinley *et al.*, 2019).

On the other hand, moisture variations in the environment favor the growth of microorganisms that damage wood and affect its quality and properties, especially outdoors and in contact with the ground (Marais *et al.*, 2022).

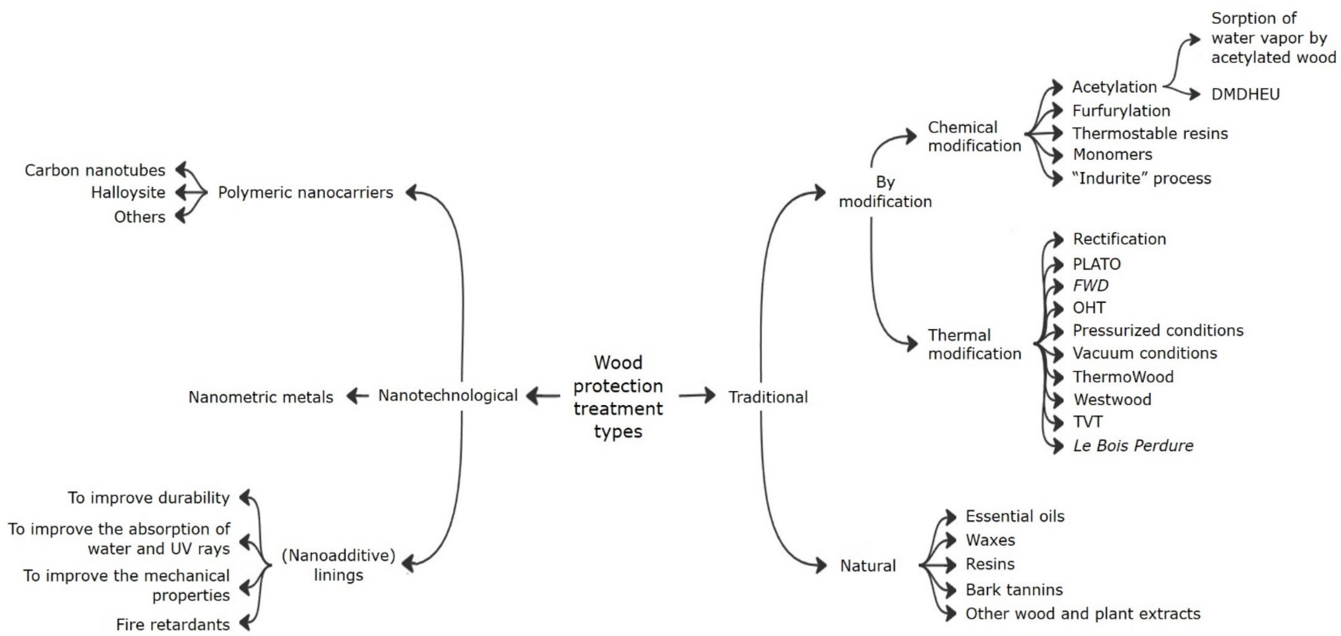
The main wood degrading agents are fungi, which cause different types of rot, such as white rot, brown rot, soft rot, mold rot, and blue stain, the latter having only an aesthetic effect on the wood. Fungi, with the exception of those causing blue stain, damage the structure of the wood, reducing its strength and visual appeal (Broda, 2020).

Insects also damage wood, the most economically relevant being termites. Although only a small percentage of these cause damage, their global economic impact in 2010 was estimated at US $40 billion (Rust and Su, 2012). In addition, marine borers, such as crustaceans and bivalves, bore into the wood of ships, destroying it over time (Marais *et al.*, 2022).

Development and Discussion

In order to establish a certain type of wood protection treatment or preservative to be used, several aspects must be considered. These include the type of wood to be preserved (coniferous or broadleaf), the level of risk of deterioration to the particular service environment, the function the wood will serve (structural, ornamental, container, etc.), and the required service life.

On the one hand, there are hardwoods that are resistant and do not require any treatment for protection. On the other hand, there are softwoods with less natural durability. Figure 1 shows a classification of wood protection technologies.



Based on Gérardin (2016), Sandberg *et al.* (2017), Teng *et al.* (2018), Papadopoulos *et al.* (2019), Teacă *et al.* (2019), Jasmani *et al.* (2020), and Khademibami and Bobadilha (2022).

Figure 1. Treatments used for wood protection.

Traditional treatments by chemical modification

In chemical modification treatments, as a traditional treatment, the cell wall of the wood is reacted with low molecular weight active monomers or oligomers under certain conditions such as high temperature heating. Chemicals can also be introduced into cell cavities such as lumens and vessels in such a way as to block the physical channels and reduce the access of water into the cell walls of the wood (Xie *et al.*, 2013).

In this regard, it is worth mentioning that acetylation is a chemical process in which the free hydroxyl groups of the wood cell wall are converted into acetyl groups and all the weight gained by the acetyl is converted into units of occluded hydroxyl groups. This technique can significantly reduce water absorption and improve resistance to fungal and insect attacks (Yang *et al.*, 2022). However, acetylation presents some disadvantages, such as partial lignin degradation, and deformation and cracking of refractory woods. This, in turn, leads to poor quality and performance (Martins *et al.*, 2019).

Another method is furfurylation, which consists of impregnating the wood with furfuryl alcohol, obtained by processing furfural, a compound derived from biomass by-products. This technique reduces water absorption and, therefore, fungal attack (Martha *et al.*, 2021). However, its limitations include the fact that the weight of the catalyst must be small for it to penetrate the pores effectively (Bi *et al.*, 2021).

Furfurylation is suitable for wood species with higher porosity and loose and tidy structures (Dong *et al.*, 2016). Wood treated with furfuryl alcohol has higher hardness and stiffness, good appearance and texture similar to tropical timbers. It can be used for decking boards. Acetylated wood, on the other hand, has greater biological durability and dimensional stability. Therefore, it is good joinery products and for various structural applications (Mantanis, 2017); however, the manufacturing costs are higher (Bi *et al.*, 2021).

Among the impregnating materials, resins are a widely used and versatile group in the protection of wood. Their main purpose is to stabilize or reinforce the dimensions of the wood because they polymerize or cross-link easily (Wang *et al.*, 2021). However, their use may present disadvantages, such as possible degradation due to weathering, difficulty in achieving uniform application, and the potential environmental impact associated with chemical compounds present in certain resins (Stefanowski *et al.*, 2018).

Schardosin *et al.* (2020) point out that impregnation with kerosene emulsions could be a substitute for acetylation, if the objective is to reduce water absorption. However, they also indicate that particle size influences the penetration of the wax into the wood.

Traditional treatments by thermal modification

Thermal modification of wood began in 1915 in Wisconsin, USA, but did not become known throughout the world until the 1970s and 1980s. The process usually occurs at a temperature of 150 to 240 °C, and its main objective is to improve dimensional stability and microbial resistance (Hill *et al.*, 2021). However, these treatments have certain drawbacks. First, they significantly affect the fracture toughness of the wood (Khademibami and Bobadilha, 2022); in addition, they modify the color of the wood, especially that of tropical woods. The current challenge is to find the balance between improved protection against agents, the loss of resistance, the preservation of the original color, and the improvement of the equipment used in the application of these treatments (Gu *et al.*, 2019).

Currently, there is a wide variety of processes for the thermal modification of wood. Table 2 lists the main commercial heat treatment processes used in Europe.

Table 2. Treatments used for thermal modification of timbers.

Process	Temperature (°C)	Duration (h)	Pressure (MPa)	Utilized atmosphere	References
FWD (*Feuchte-Wärme-Duck*)	120-180	≈15	0.5-0.6	Vapor	Sandberg *et al.* (2017)
	160-180		7-10 bar	Saturated vapor	Acosta-Acosta *et al.* (2021)

PLATO (Providing Lasting Advanced Timber Option)	150-180/ 170-190	4-5/ 70-120/ >2 weeks	(Partially) super-atmospheric	Saturated vapor/hot air	Sandberg *et al.* (2017)
	150-180/ 150-190			Saturated vapor	Gérardin (2016)
	160-190/ 170/190	4-5/3-5 days/ 14-16/2-3 days	Atmospheric	Saturated vapor	Acosta-Acosta *et al.* (2021)
	Over 190				Ormondroyd *et al.* (2015)
	150-190/	4-5/3 a 5 days/ 15-16 h/3 days	0.6-1	Water vapor/hot air	Reinprecht (2016)
ThermoWood	130/ 185-215/ 80-90	30-70	Atmospheric	Vapor	Sandberg *et al.* (2017)
	130/ 185-215	2-3		Overheated vapor	Gérardin (2016)
	100-130/ 185-215 a 230/ 80-90			Hot air or water vapor	Reinprecht (2016)
	185-215	2-15 h		Vapor	Acosta-Acosta *et al.* (2021)
	185-215				Ormondroyd *et al.* (2015)
Le Bois Perdure	200-230	12-36	Atmospheric	Vapor	Sandberg *et al.* (2017)
	200-230			Inert	Gérardin (2016)
	100-120/ 200-240/	Depends on the species			Acosta-Acosta *et al.* (2021)
	230			Nitrogen	Ormondroyd *et al.* (2015)
Rectification	160-240	8-24		Nitrogen or another gas	Sandberg *et al.* (2017)
	240			Nitrogen or CO_2	Gérardin (2016)
	210-260			Nitrogen with less than 2 % oxygen	Reinprecht (2016)
	210-240		Atmospheric <2.0 % oxygen	Inert gas	Acosta-Acosta *et al.* (2021)
OHT (Oil Heat Treatment)		24-36		Vegetable oils	Sandberg *et al.* (2017)
	180-220	2-4			Reinprecht (2016)
		18			Acosta-Acosta *et al.* (2021)
TVT (Thermo-	160-220	Over 25	Vacuum 150-350	Vacuum	Sandberg *et al.* (2017)

Vacuum Treatment)	100/ 160-220	Over 25	1 000 (mbar) Vacuum 150-350 1 000 (mbar)	Vacuum	Acosta-Acosta *et al.* (2021)
Westwood	204				Acosta-Acosta et al. (2021)

*The initial moisture content of all processes varies between 0 and 30 %. The stages of each process are separated by "/" and depend on the treatments and authors. Modified and expanded from Sandberg *et al.* (2017).

The choice of the best heat treatment is sometimes complicated, as all processes have some technical or economic limitations or disadvantages. The species and moisture content of the wood, as well as the intensity of the treatment, must be considered when making the selection. Pockrandt *et al.* (2018) compared different heat treatments of hardwoods and conclude that the TVT process is less destructive than ThermoWood; however, the durability of the wood is not significantly improved with the TVT process. Jebrane *et al.* (2018), for their part, cite that for softwoods both processes lead to similar results.

Thermogravimetric analysis has shown that hardwoods such as beech, poplar, ash, and eucalyptus are more susceptible to thermal degradation than softwoods such as pine and spruce (Candelier *et al.*, 2016). This is due to the hemicellulose content in hardwoods containing highly acetylated functional groups, compared to softwoods (Martínez-Abad *et al.*, 2018).

Traditional treatments of natural origin

Traditional treatments of natural origin are usually based on water or oily substances. Water-soluble preservatives are mainly used when the preservation of the color of the wood is an important factor, as is the odor of the preservative substance once applied to the wood. These preservatives have the disadvantage that they do not confer dimensional stability, while they may increase the corrosion rate of nails or metal fasteners (Reinprecht, 2016).

Oil-soluble wood preservative methods are a promising alternative as impregnators and binders in paints or in combination with other formulations (Cesprini *et al.*, 2022). They are preservatives that fill the cavities of the wood by capillary action, *i. e.*, they do not chemically bind to the cell walls; therefore, a high retention capacity must be ensured to achieve the desired protection (Woźniak, 2022).

There are other very effective preservatives such as creosote and PCP (pentachlorophenol); despite not being of natural origin, these were widely used in Europe and North America, but their use has been banned since 2018 due to health and environmental concerns (Khademibami and Bobadilha, 2022). Likewise, although the current acceptance of copper/chromate/arsenic salts (CCA), acid/copper/chromate (ACC), arsenate/cupric/ammonia (ACA), and arsenate/cupric/zinc/ammonia (ACZA) is limited by environmental concerns, they have played a crucial role in the conservation of timber (Tarmian *et al.*, 2020).

Natural compounds, on the other hand, are renewable and easily obtainable substances with beneficial antimicrobial properties and less ecological impact than traditional chemical products (Broda, 2020). Wood protection research focuses on plant and animal compounds, such as essential oils, waxes, resins, and tannins from tree bark, as well as extracts and other related preservatives (Cesprini *et al.*, 2022; Ella *et al.*, 2022).

The heterogeneity from which the compounds are derived, their lower retention within the wood, their easy leaching, and their high susceptibility to degradation are some of the disadvantages of natural preservatives. Therefore, they are generally costly and not very cost-effective, and their use is limited.

Nanotechnological treatments

The main advantage of nanotechnologies in wood preservation is the high capacity of nanoparticles to penetrate wood structures completely and uniformly, resulting in a product with high physical and mechanical performance (Papadopoulos *et al.*, 2019). Therefore, they can improve wood bonding and durability, moisture resistance, UV absorption, structural performance, fire protection, and reduce excessive leaching (Jasmani *et al.*, 2020).

One of the applications of nanotechnology in wood protection is the use of polymeric nanocarriers, which act as a storage and transport medium for fungicides and bactericides to penetrate the wood, with the polymeric matrix controlling the release rate of the fungicides and bactericides (Teng *et al.*, 2018). However, there are certain limitations such as the need to maintain control of the size and stability of the nanoparticle suspension throughout the process, as well as to improve the surfactant system of the nanoparticles (Bi *et al.*, 2021).

Potential nanocarriers include carbon nanotubes (CNTs) and halloysite, a natural nanotubular material made of aluminosilicate clay, which is inexpensive and has no toxicity or negative environmental impact (Lisuzzo *et al.*, 2021).

Furthermore, certain nanometals can be synthesized by chemical methods in their gas and liquid states and used in mixtures with other nanometals or even in traditional heat treatments (Teng *et al.*, 2018). They improve the durability of wood in three ways: first, they interact with bacteria or deactivate the enzymes necessary for degradation reactions; second, they do not recognize fungus in the presence of nanometric metal and therefore prevent its development; and third, they generate reactive oxygen species in fungal cells (Bi *et al.*, 2021).

On the other hand, there are nanoadditives used in coatings to improve the durability of wood. Applied alone or with traditional coatings, they enhance the wood's mechanical properties, its fire resistance and protect against water and UV damage (Jasmani *et al.*, 2020). They can be applied by brushing, dipping, or *in situ* polymerization to achieve better adhesion (Bi *et al.*, 2021).

When these materials are used in a coating treatment, the slow and controlled release of the active ingredient is important due to its long-lasting effect and minimal environmental impact (Papadopoulos *et al.*, 2019). In this sense, the incorporation of bio-based nanoparticles could significantly improve the performance of existing compounds in traditional markets and promote the development of new types of biocomposites and markets (Pacheco-Torgal *et al.*, 2019).

Conclusions

The choice of the best wood protection treatment depends on the weighing of ecological, economic, and protection aspects.

To improve the dimensional stability of wood against moisture absorption, acetylation is suggested over furfurylation because it is more environmentally friendly, as it utilizes less aggressive compounds, and potentially more cost-effective in the long term. Both methods improve the effectiveness of the protection; acetylation stands out for its resistance to humidity and decomposition, and furfurylation for its improved stability and resistance, although the latter depends on the quality of the products and the precision of the process.

In the choice of heat treatment for wood, it is suggested to consider several options depending on the specific properties of the project. To minimize environmental impact, *FWD*, PLATO and ThermoWood all offer environmentally friendly alternatives, as they largely avoid the use of aggressive chemicals. If economic efficiency is crucial, ThermoWood could be a cost-effective selection in the long term, while *FWD* and *Le Bois Perdure* involve more substantial upfront investments. In terms of protection, all heat treatments provide significant improvements in wood strength and durability. However, it is important to consider that heat treatment leads to the deterioration of certain mechanical properties.

Natural, mostly environmentally friendly treatments, offer effective protection against insects, fungi, and decay. The economic feasibility depends on the specific substance and its availability; however, the possibility of reducing long-term maintenance costs should be considered. Therefore, it is recommended to use these treatments together with other methods.

If the application of advanced treatments for wood protection is desired, the cautious use of nanotechnology with a balanced approach is suggested. It is crucial to assess the sustainability of nanomaterials, minimizing environmental impacts. Despite the initial investment, nanotechnology promises long-term protection and potential cost savings. Its adoption requires addressing environmental considerations and must align with specific objectives to allow profiting from its innovative potential in a gradual and conscious manner.

The importance of adopting environmentally friendly practices is recognized; therefore, it is recommended to focus research on the generation of solutions for the protection of wood that minimize the ecological impact and prioritize treatments of natural origin. The treatment choice must meet the durability and resistance standards indicated in international quality standards. Finally, ways must be sought to optimize costs without compromising the environmental integrity or human health, as well as the effectiveness in protecting the environment.

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Conflict of interests

The authors declare that they have no conflicts of interest.

Contribution by author

Víctor Daniel Núñez-Retana: development of the idea and the manuscript; Marco Aurelio González-Tagle, Humberto González-Rodríguez and María Inés Yáñez-Díaz: revision of the manuscript; Wibke Himmelsbach: structuring and revision of the manuscript.

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