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— EDITOR —
Prof. Dr. Selahattin BARDAK

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**INTERNATIONAL STUDIES
IN THE FIELD OF
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CHAPTER 1

THE ROLE, ESSENCE AND CONSEQUENCES OF COATINGS ON DISPOSABLE CUPS

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The Role, Essence and Consequences of Coatings on Disposable Cups

This chapter will talk about various types of coatings on water cups. Firstly, coating is a commonly used term defined by the Cambridge Dictionary as a layer of material that covers a surface. This concept applies across a wide range of industrial fields. Coatings are typically applied to enhance or add specific functional properties to a base material. For instance, when wood is coated, its resistance to moisture, ultraviolet radiation, and even fire can be significantly improved. In the graphic and printing industry, the coating process usually refers to applying an overprint coating or a primer onto the printing substrate in order to improve surface properties, print quality, and durability. Thus, it will be talked about different types of coatings, the roles of coatings on water cups, the materials used for the production of coatings, as well as various types of coatings on water cups. There will also be talk about why coatings as such are important and what their role is. Not only the aesthetic nature, but also how it improves the properties of the water cup itself, provides safety and hygienic requirements, and how it improves heat resistance in the case of using hot drinks. It will also be looked at the current legal regulations in the United States of America and Europe and make a comparison of them. Also, it will be looked at standards in production and safety testing. Some research results on the same topic that were created and whose research was carried out before the existence of this work will be shown. Finally, potential challenges and trends for the future will be listed and a valid conclusion will be drawn from the context of all of the above.

Coating

Surface coating, i.e. any mixture of materials that, with the addition of pigments, solvents and other additives, when applied to a previously dried surface of an object, create a thin layer of the so-called film, which can have a certain functional role and as such can serve exclusively for decorative purposes. Surface coatings contain paints, oils that promote drying, varnishes, synthetic transparent coatings and other products whose main function is to protect the surface of the object from the environment. In the event that surface coatings are used exclusively for aesthetic purposes, they can enhance the aesthetic appeal of an object by emphasizing its surface features or hiding them if necessary. Most of the surface coatings used by industry, as well as everyday consumers, are made of synthetic polymers. This means that industrially manufactured substances are made up of very large, often interconnected molecules, which form a solid, flexible and adhesive film when applied to the surface of an object. Surface coatings are manufactured from several key components, which are: pigments that give color, gloss, transparency, and other visual or functional characteristics; solvents or so-called carriers,

they form a liquid medium so that the coating can be more easily applied to the surface; and additives, which enhance specific performative properties. [1-3]

As mentioned before, cups are mostly coated with a thin layer of plastic, most often polyethylene or polypropylene, and less often with biodegradable materials such as polylactic acid (PLA). These types of coatings provide effective water resistance and mechanical strength and thus allow the cup to retain liquid without any leakage or potential damage to the walls of the cup itself. It is important to emphasize that the recycling of such cups is still a problem because the plastic inside the coating remains connected to the paper walls of the cup, making it difficult to separate the paper and plastic. Although some coatings are made of biodegradable and more easily recyclable materials, sometimes their complex structure makes it difficult to treat waste. The use of biodegradable materials is an attempt to reduce the environmental impact by choosing functional, purposeful materials instead of less sustainable alternatives. [1-3]

Coating types

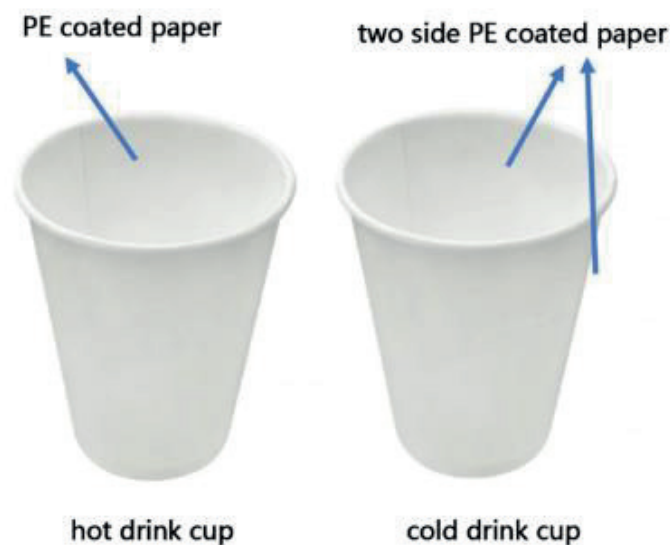
For optimal functionality, almost every paper cup needs an inner coating for an obvious reason, and that is that the paper would weaken very quickly in contact with water and the liquid would start to drop out of the glass. Due to, as already stated, the inability to recycle PE coatings, polylactic acid is increasingly used, because as a plant-based, compostable material it offers improved sustainability. Current market data suggests that the sustainable packaging sector will reach US\$441 billion by 2027, with a compound annual growth rate of 7.4% from 2020 to 2027. These types of technologies are receiving positive reviews around the world, especially in Europe, which is known for its very strict environmental regulations and growing consumer demand for green products. Research has shown that cups using next-generation coatings can achieve significant environmental impact benefits, including a reduction in carbon footprint of up to 50% by using biodegradable or water-based coatings. By integrating functional performance with environmental responsibility in mind, modern coating techniques are shaping the future of sustainable packaging. Coatings are very important for maintaining the durability as well as functionality of paper cups, thus making their application inevitable in industry. [3,4]

Currently, several coatings are used in practice: Polyethylene (PE), biodegradable polylactic acid (PLA), water-based coatings as well as wax-based coatings. PE coatings, although often used, are worrying due to the fact of very low biodegradability as well as dependence on fossil fuel raw materials. On the other hand, PLA coatings that are obtained from renewable sources such as corn, offer a better environmental effect through biodegradability, although they still

require a special waste management system for proper treatment. Water-based coatings are considered to have the lowest environmental footprint and show great potential for recycling and composting, with increasing adoption expected in the future. As for wax coatings, although they are known as eco-friendly and biodegradable, they are not so popular because their main and biggest drawback is very low resistance to liquids or in other words poor endurance. [3, 4]

Polyethylene (PE) coating

In the context of coating on plastic cups, double PE coating is an advanced option in the disposable cup market. Unlike single-sided coated cups, this option offers a coating on both sides, which ultimately means improved performance and reliability. The double coating provides significantly improved durability, thermal insulation and resistance to liquid absorption which ultimately allows the cups to retain their shape and strength while holding hot beverages such as coffee as well as cold beverages such as carbonated drinks. This design allows consistent performance and reduces the risk of liquid leakage or deformation of the cup walls during use. It is also very important to note that with improving the mechanical properties of the cups, double coating gives an opportunity for branding and visual customization. Branding on the outer layer of the cups brings the brand closer to the final costumer and increases the brands overall range. Also, double coating is considered very convenient because it maintains the temperature of the beverage and prevents moisture transfer to the hand, improving the handling and overall impression. With that being said, PE coatings successfully combine durability performance and marketing potential, which makes them an optimal solution in terms of improving the product quality and brand presentation. [5]



Picture 1. This picture shows the difference in coating depending on the beverage inside the cup [6]

Advantages of PE coating

Packaging quality plays a major role in customers' feedback as well as in brand image. PE coated cups are getting more and more attractive to many brands because of their usability and wide range of benefits. Compared to the standard paper cups, PE coating offers improved insulation which retains heat for longer periods of time and ensures a consistent temperature. Firstly, large printing surface allows brands to emphasize important features like logos, slogans or other promotional designs. Secondly, the glossy outer layer highlights visuals and makes them more noticeable which boosts brands recognition and customers loyalty. PE coated cups, as stated earlier, provide strength and durability which helps reducing product failures in everyday use. They can be used for both hot and cold beverages and provide good resistance to leaks. This makes them suitable for different types of drinks and everyday use. Their durability can also reduce the need to replace the cups as often, which can be beneficial from an economic point of view. Double-PE coated cups are also available in different sizes and designs. They can be printed with different graphics, allowing companies to use the cups as part of their branding. Because of these properties, double-PE coated paper cups are widely used when both practical performance and appearance are important. [5]

Applications of PE Coating

There are many industries that use PE coated paper cups. As you can see there are many applications that can benefit from using this type of cup. Below you will read more about what industries use PE coated cups. Food Industry PE coating is commonly found in the food industry. Not only are there many fast food restaurants that use these types of cups but also restaurants that offer top gastronomy. These cups can hold almost any type of food or drink which can benefit your business by having a trustworthy product and help speed up service. This is just one reason why PE coated paper cups are helpful in the food industry.

Many coffee shops around the world probably use PE coated cups. If you own a coffee shop or cafe that wants branding to be a priority you should look into using PE coated cups. Since these cups have a lot of space to print on them and are glossy they can create a nice picture on the cup. Having a logo or design printed on your cup will attract more eyes to your cup and allow it to stand out. Many catering companies that offer outside events will use PE coated paper cups. These cups are durable when traveling long distances and won't get damaged as easy. Another benefit to PE coated cups is that they won't leak. If your transporting drinks to an event you don't want to worry about any leaks happening.

Office/Institution Many offices will use PE coated paper cups because they are convenient and hygienic. As stated above they will not leak so if someone were to spill their drink in your office it would be less of a mess. They also allow people to have a hygienic drink.

As you can see there are many benefits that come with using PE coated paper cups in these situations. Whether it's for holding a drink, promoting your brand or allowing people to have a cleaner environment these cups can be very useful. [5]

Polylactic Acid (PLA) coating

PLA stands for Polylactic Acid. It is a biodegradable/compostable plastic that is made from renewable resources. Such as corn starch, sugar cane etc. PLA can be used as a coating on paper cups to replace the conventional plastic polyethylene (PE). It can act as a barrier to liquids and can be used with hot and cold drinks. Earlier we discussed how polyethylene coated paper cups are not biodegradable and hard to recycle. The paper itself will biodegrade but since there is plastic attached to it they will not break down at the same rate. There are some recycling facilities that can separate these products but most don't have the ability to do so. So what happens to all of these paper cups? Most end up in the trash or landfill. Because of these problems companies started looking for alternative ways to make paper cups. PLA coated paper cups can be used with most hot beverages. They are typically used with drinks that are around 60-70 degrees Celsius. If exposed to hotter temperatures such as boiling water (100 degrees Celsius) the cups may begin to lose shape. PLA coated cups are not recyclable. Similar to polyethylene coated cups they cannot be put in the recycling bin. They need to be placed in an industrial compost bin in order to biodegrade. Home composting bins will not provide the right amount of heat and humidity to break down the cups. Once in an industrial composting facility they can break down in as little as 2 months and as long as 6 months. Which is much quicker than normal plastic taking hundreds of years to biodegrade. [7]

PLA is created by using renewable plant material to make lactic acid. This lactic acid is then converted into a polymer which is known as PLA. Once created this polymer can be added to paper cups as a coating. It will resist water and some heat allowing it to hold your beverage. [7]

PE coating and PLA coating

There are many pros and cons when using polyethylene (PE) and polylactic acid (PLA) coated cups. As mentioned above PLA is created from renewable sources such as cornstarch. Not only

is it environmentally friendly but it is also created from less non-renewable resources. If you are looking for a more sustainable packaging option you should research the pros and cons of PE and PLA coated cups. A table showing the main properties of each coating can allow businesses to decide which is more beneficial for their business and the environment. [5, 7]

Table 1. Comparison of PE and PLA coatings

Attribute	PE Coating	PLA Coating
Material	Polyethylene (PE)	Polylactic Acid (PLA)
Origin	Derived from fossil fuels	Derived from renewable resources
Environmental Impact	Relies on fossil fuels; less eco-friendly	Biodegradable
Recycling Challenges	Cannot be recycled	Limited recycling facilities
Hot Beverages tolerance	Superior temperature resistance	Unreliable over 70°C
Costs	Affordable	Potentially higher production costs
Business Considerations	Balances cost-effectiveness and practicality	Weighs cost-effectiveness and eco-friendliness

Water-based (Aqueous) coating

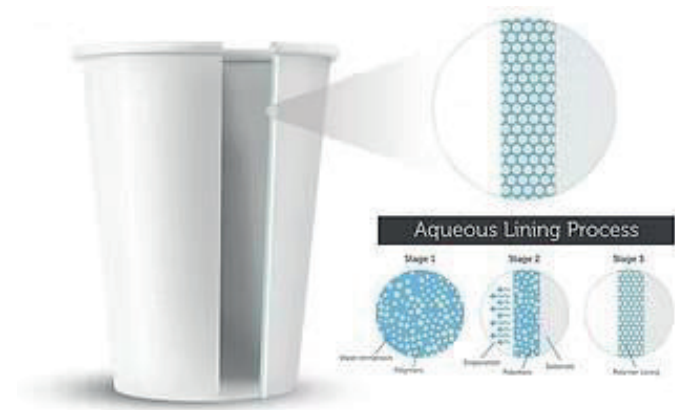
Water based coatings are a type of coating applied to many one time use paper products that we use in everyday life. Such as cups, trays and bowls. As the name suggests they use water as a carrier instead of using petro-chemical based solvents which are typically used when applying coatings such as PE. These coatings consist of water soluble resins and natural additives along with other ingredients. That can benefit our environment. These will create a light layer over the top of the paper that can withstand water and oil and have a smooth finish to allow better printability. Similar to many of the other plastic coatings water based coatings can provide similar features but have less of an impact on our environment. As there is no need for VOC's or chemicals such as PFAS. Which some coatings contain. Allowing these coatings to be healthier for us and our planet. [8, 10]

Composition of Water-Based Coatings

There are many different ingredients that go into making a water based coating each company will vary. But some of the main ingredients that you will find in a water based coating is water based resins. As mentioned above water based resins can be created from renewable materials such as plants or they can be synthesized. If the water based resin is made from plants it can have many environmental benefits compared to traditional resins found in plastic coatings.

Natural additives such as starch and cellulose can be found in water based coatings as well. Additives can also be used in water based coatings these include but are not limited to thickeners, stabilizers and dispersants. These can help increase the life span of the coating and make sure the coating is evenly spread over the paper and dries properly. You can also find surfactants and coalescent agents. These will help when applying the water based coating to the paper. Fillers such as calcium carbonate can also be used to improve some aspects of the coating and prevent streaks. Water is used as the carrier to apply all these ingredients to the paper. Additionally, synthetic polymers like acrylic and PLA are sometimes included to improve water resistance and overall durability. [8, 10]

The use of water-based coatings occurred due to their certain characteristics. As environmental awareness grows, consumers are actively looking for products that have as little impact on the environment as possible, and water-based coatings are biodegradable and recyclable, which makes them attractive to manufacturers looking to meet the demand for eco-friendly solutions. A certain level of safety also plays an important role in their increasingly ubiquitous appearance, as these coatings are manufactured from food-safe materials and comply with regulations set by bodies such as the FDA. Unlike conventional coatings, they do not release harmful chemicals or microplastics into beverages, thus offering greater protection to consumers. Water-based coatings also impose paper as a superior alternative to plastic, glass and aluminum for sustainable single-use packaging. These coatings bring higher water resistance and prevent liquid leakage. The application process typically involves a thin water-based layer applied to the cardboard so that it penetrates the fibers to reduce material consumption and preserve performance. Several application methods are used. Inverted roller coating is one of the more effective methods because it allows for accurate control of the coating thickness and consistency of coverage over the entire surface. This creates a durable barrier that protects against moisture and grease and makes the glasses suitable for both hot and cold drinks. Coated cardboard is laminated with a thin layer during production to further improve water resistance and ensure desired performance. Water-based coatings are becoming more widely accepted in the packaging industry as manufacturers try to be as environmentally sustainable as possible. [8, 10]



Picture 2. Aqueous Lining Process [9]

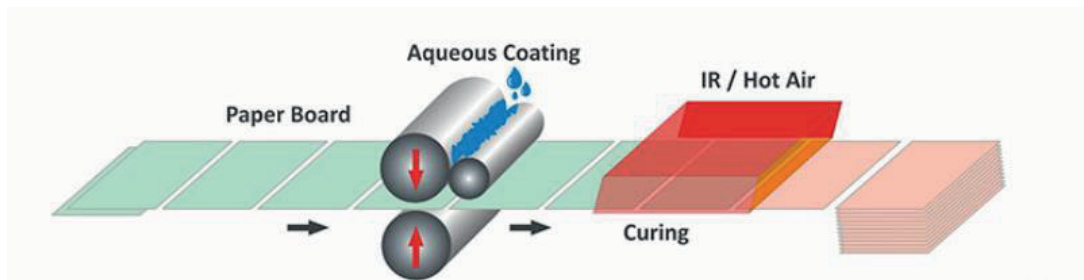
Description

A water-based coating is a dispersion that is used as a replacement for conventional plastic coatings in products such as disposable cups. Suspended plastic or latex particles which are being carried in water to the surface of the material is a process that can reduce the use of plastic by as much as two-thirds compared to standard cups with plastic coating. These coatings do not contain harmful chemicals, toxic substances, or intentionally added PFAS and that makes them eco-friendly, safe and more sustainable choice for consumers. [10]

How Water-Based Coatings Work

Water-based coatings function by creating a thin protective layer on the surface of paper materials. During the application, the coating sticks to the paper with the natural properties of resin binding. The water evaporates, the resin hardens and binds to the complex fibers, creating a durable and resistant barrier. The water-based surface layer protects the paper from moisture, oil and grease, which is essential for food packaging. The coating also creates a smoother surface ideal for printing, allowing high-quality visuals to be applied without the influence of plastic, allowing brands to keep their packaging striking and functional. Water-based coatings are biodegradable, in other words, they decompose naturally without leaving harmful substances, unlike plastic coatings that can remain in the environment for centuries. Also, they are non-toxic because they do not contain dangerous substances such as PFAS or BPA that can migrate into food, which carries a huge health risk. Many water-based coatings are compostable which allows them to decompose safely in composting systems and support sustainable disposal practices. Although they are plastic-free, water-based coatings provide resistance to moisture and oils, maintaining structural integrity when used with hot liquid or food. [8, 12]

Of the various application techniques, roller coating is one of the most effective as it allows precise control of coating thickness and uniform coverage. In this way, it creates a strong protective barrier suitable for hot and cold drinks. During processing, the cardboard is laminated with a thin layer to further improve water resistance and ensure reliability. As companies increasingly adopt environmentally responsible practices, water-based coatings are becoming increasingly popular in a number of industries. One of the best examples is certainly the food service packaging industry, where the demand for sustainable, safe and recyclable materials continues to grow. Uses include paper cups and bowls, where the coating prevents leakage and soaking, trays and take-out containers that require protection from grease and moisture while remaining recyclable or compostable. Also, other food packaging applications such as cardboard and wrappers that need moisture barriers without relying on plastic coatings. The choice of coating plays a big role in the production of paper cups, functionality and environmental impact. This is why water-based coatings are emerging as a desirable alternative to conventional options such as polyethylene, polylactic acid or wax. [8, 12]



Picture 3. Aqueous Coating System [13]

Description

Water-based coatings have been widely used in commercial packaging for years. However, as the demand for these coatings continues to grow, there is also a need for more advanced printing technologies that can effectively support and optimize their application and on the picture above one of the application methods is being shown. [11]

Applying of water-based coatings

There are many steps that are taken when manufacturing paper cups and bowls that have a water based coating. Below will explain how they are made. First you need to select a paper that is good for making water based cups/bowls. This will be paper that can be pulped and dried to get the desired thickness. After your paper has been pulped, dried and made to your desired thickness. It is time to apply your water based coating. There are many ways to apply water based coatings but most common is using a Direct Gravure or Flexo coating method. These

methods will apply a thin layer of resin to the top of your paper. Using rollers and plates that will transfer the resin to your paper. Its important to apply your water based coating correctly so you dont create any flaws on the paper. Once again selecting the correct resin and additives/surfactants will help when applying the coating to your paper. Next the paper will be dried. Using an oven or conveyor belt with hot air that will dry the coating on your paper. If your water based coating is not dried correctly you can run into flaws on your paper such as cracks and bubbles. After your coating is fully dried you can start forming your cups and bowls. By cutting, rolling and sealing your paper. Or if you want to use a mold you can use heat and pressure to form your cups and bowls. You will need to make sure that your coating and paper stay intact during these processes. Your cups will then be inspected for any flaws.[11, 12]

Positive and negative sides of water-based coatings

Benefits of Water Based Coating There are many reasons why companies would want to use water based coatings. Some are compostable which means they will break down once thrown away and won't take up space in a landfill. Similar to most plastics some of these coatings can take many years to decompose. Some water based coatings can be created with no harmful chemicals which allows them to be used on food products if they meet those requirements. There are some that can be made without PFAS BPA or even some VOC's which can be found in your food and drink. Water based coatings are able to withstand water and oils just like plastic. Cups and bowls can contain liquid and food without compromising its strength. Water based coatings may cost a little more at first but could save money by decreasing waste. Meeting requirements for the environment and customer wants. [10, 12] As with all things there are negatives when using water based coating. When applying the coating to the paper you have to make sure that the paper is evenly coated. This can be hard when working with different textures and sizes of paper. Defects can occur from uneven surfaces on the paper causing streaking or holes. You also have to make sure the paper is dried properly. Drying too much or not enough can cause the paper to crack or peel and lose it's moisture resistance. Companies can use more advance coating equipment such as high speed gravure or flexo. Depending on what type of paper you're working with you can change your dry time to fit the paper. Also having employees trained on how to apply and dry coatings can help improve the quality of your product. [10, 12]

Water Based Coating vs. PE Coating PE Coating has been used for years because it's durable and water resistant. It is not biodegradable which is starting to become an issue. Water based coatings are made of natural and man made material so it can be composted and recycled. People are becoming more aware of there surroundings and using less plastic products. [10, 12]

On the other hand, like any manufacturing process, the use of water-based coatings presents certain challenges that need to be considered before production begins. One of the main difficulties is achieving consistent and uniform coverage across the paper surface, especially when using substrates with different textures or thicknesses. Surface irregularities can result in defects such as streaks, gaps, or uneven coating layers. Another important challenge is drying efficiency, as proper drying is necessary to achieve strong adhesion between the coating and the paper. Excessive drying times or poorly controlled temperatures can cause problems such as cracking, peeling, or reduced moisture resistance. To overcome these issues, manufacturers may use advanced coating equipment, including high-precision gravure or flexographic systems, and carefully adjust drying conditions for different types of paper. In addition, proper training of operators in coating application and drying techniques can help improve product consistency and overall production quality. [10, 12]

Water-Based Coating and PE Coating

PE coatings are still widely used due to their high durability and effective moisture resistance. They are not biodegradable, which is an increasing concern on their environmental impact. In comparison, water-based coatings are produced with a combination of natural and synthetic materials, which makes them compostable and recyclable and thus more environmentally friendly. This shift towards more environmentally responsible solutions is becoming very important as consumers become more aware of sustainability and environmental responsibility. [10, 12]

Table 2. Comparison of water-based and PE coatings

Attribute	Water-Based Coating	PE Coating
Material	Natural & synthetic blend	Petroleum plastic
Sustainability	Compostable & recyclable	Not compostable and not recyclable
Performance	Good for hot and cold drinks	Good for hot and cold drinks

Wax coatings

Wax coatings are derived from either natural or man-made substances. This is why they are classified as a more conventional method for providing better moisture protection for cups. They provide a light film that will help prevent your cup from leaking. They also provide better insulation properties. Since wax coatings provide good insulation this can allow for your drink to stay hot. There are some waxes that are biodegradable. So if you want to go with a more eco-

friendly product you can use wax coatings. The only down side to using wax is that they are not as durable as polymers. Therefore they do not provide the best barriers and you are more likely to experience leaking. Also you can have trouble getting an even coat of wax on your cups. If the wax is not evenly applied your cup may not perform as well. Wax coatings are typically found in cups that have wax coating. You can find disposable cups that use wax but they are not very popular. [14, 15]

Wax coatings are considered a natural alternative, but they are generally used for cold drinks and tend to perform poorly in high-humidity conditions. The wax layer strengthens the paper structure and helps prevent cold liquids from seeping through the cup. Wax-coated paper cups are also generally less expensive than plastic or ceramic alternatives, making them a cost-effective option for businesses purchasing large quantities. From a sustainability perspective, some wax-coated paper cups are produced using biodegradable or compostable materials, which can help reduce their environmental impact. However, water-based coatings can be used with both hot and cold liquids, making them a more versatile option. Although conventional coatings such as PE and wax have certain advantages, water-based coatings are increasingly being considered as an alternative due to their environmental characteristics and range of applications. As the packaging industry continues to develop, the demand for different coating solutions is likely to increase as businesses respond to sustainability requirements and consumer expectations. [14, 15]

Composite Coatings

Composite coatings are newer coating systems that combine several materials, including polymers, bioplastics, and various additives, to achieve a balance between performance, cost, and sustainability. They are designed to overcome some of the limitations of existing coating systems by combining different properties within a single coating solution. A key advantage is their flexibility, as different formulations can be adjusted to meet specific requirements, such as improved heat resistance, better barrier properties, or a lower environmental impact. They can therefore provide a balance between durability, affordability, and environmental performance. However, composite coatings also have certain drawbacks. Their formulation and application can be more complex, which may increase production costs and require specialized processing equipment. Furthermore, as the technology is still developing, some composite coatings are not yet widely available or fully standardized across the industry. In terms of application, advanced composite coatings are being explored for disposable coffee cups and

other specialized products, allowing manufacturers to develop products with specific performance characteristics while also addressing sustainability requirements. [16]

Importance of the coating

The inner coatings of disposable coffee cups are essential for their proper function, safety, and environmental performance. One of their main purposes is to create a moisture barrier that prevents liquids, such as hot coffee or cold beverages, from penetrating the paper. This helps prevent leaks and reduces unnecessary waste. Without a reliable coating, such as polyethylene or a water-based barrier, disposable cups would not be able to safely hold beverages. Coatings can also contribute to thermal insulation by adding an extra layer that slows heat transfer. This helps beverages remain hot or cold for longer. In addition, the inner coating acts as a barrier between the beverage and the paper, reducing the risk of unwanted chemical migration and contamination and helping the cup meet food-contact safety requirements. The coating can also improve the overall strength of the cup by increasing its rigidity and resistance to handling and transport. This is particularly important for takeaway and custom disposable cups. At the same time, coating materials are increasingly being developed with sustainability in mind. This has encouraged the use of alternatives such as PLA and advanced water-based coatings. When choosing a suitable disposable cup, companies need to consider several factors, including the environmental impact of the coating, production costs, the type of beverage being served, and applicable safety regulations. PLA and water-based coatings can provide alternatives to conventional PE coatings, while PE remains widely used because of its relatively low cost despite the recycling challenges associated with it. Hot beverages generally require greater heat resistance and leak protection, while cold beverages allow for a wider range of coating options. Overall, ensuring that coatings comply with relevant food-contact regulations and perform safely under the intended conditions is essential for consumer safety and product reliability. Factors such as leak resistance, heat retention, coating performance, and environmental impact can help manufacturers determine whether a particular coating is suitable for the intended application and target market. [17]

Comparison of all types of coatings

As mentioned several times throughout this chapter, the inner coating of a disposable cup is essential for preventing leaks and also contributes to insulation, user safety, and overall environmental performance. A more detailed overview of the most commonly used coatings in

disposable cups, including their materials, properties, advantages, limitations, and typical applications, is presented in the table below.

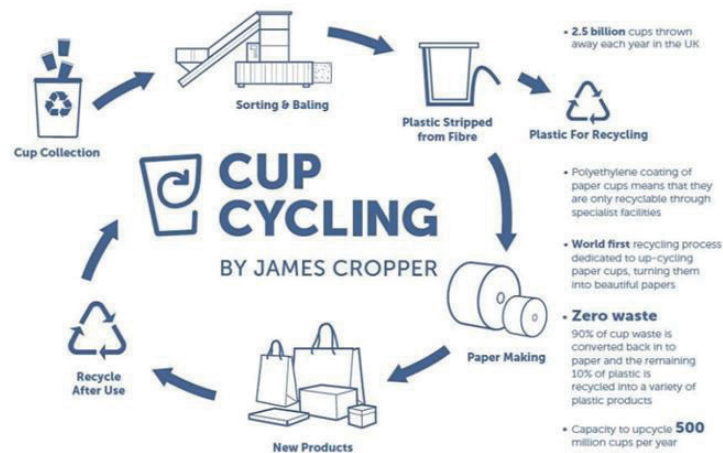
Table 3: Overview of Common Coatings Used in Disposable Cups

Type of coating	Environmental Impact	Cost	Performance	Regulations & Safety	Applications
Polyethylene (PE) Coating	High environmental impact; non-biodegradable, non-recyclable	Low	Excellent leak-proofing; high durability and insulation	Widely accepted but concerns over chemical migration	Disposable coffee cups, takeaway coffee cups, plastic lining
Polylactic Acid (PLA) Coating	Eco-friendly; biodegradable, compostable	Moderate to High	Good barrier properties; sensitive to very high temperatures	Compliant with eco-friendly standards; lower migration risks	Eco-friendly disposable cups, custom disposable coffee cups
Water-Based (Aqueous) Coating	Improved environmental profile; low VOC emissions	Moderate	Effective moisture barrier; variable performance under different conditions	Meets strict environmental standards; safe for food contact	Disposable tea cups, takeaway cups, sustainable beverage packaging
Wax Coating	Moderate; biodegradable options available	Low to Moderate	Provides insulation and moisture resistance; less robust than polymers	Generally safe but less consistent in performance	Wax paper cups, niche disposable cups with eco-friendly focus
Composite Coatings	Varies based on formulation; potential for highly sustainable options	Moderate to High	Customizable for optimal performance; balances durability and eco-friendliness	Can be engineered to exceed regulatory requirements	Custom disposable coffee cups, specialty applications

Environmental concerns

As regulatory pressure increases, consumer demand for more environmentally friendly products is also growing. People are becoming more aware of the environmental impact of packaging materials, and many consumers prefer products that are presented as more sustainable. By using paper cups and bowls with certified water-based coatings, companies can respond to this demand and demonstrate their focus on environmental responsibility. On the other hand, PE coatings raise environmental concerns because of their plastic content and the challenges they can create for recycling systems. With increasing efforts to reduce plastic consumption, companies using PE coatings may face greater pressure to consider alternative materials. PLA coatings can reduce dependence on fossil-based resources, making them an alternative for

companies looking to improve their environmental performance. However, their environmental benefits depend partly on access to suitable industrial composting facilities. Therefore, companies using PLA-coated products need to consider whether the necessary waste management infrastructure is available in their target market. Water-based coatings provide another alternative, particularly when they are designed to support recycling or composting processes. Their use can help companies reduce reliance on conventional plastic coatings while maintaining the required performance of disposable paper products. Overall, the choice of coating should take into account environmental impact, local waste management infrastructure, product performance, and applicable regulations. [17]



Picture 4. Cup Cycling [18]

Nowdays, where convenience influences everyday choices, disposable paper cups have become a common part of daily life. Billions are used worldwide each year, often for only a short period before being discarded. Although their paper exterior gives the impression of being environmentally friendly, the plastic coating used to prevent leaks can make recycling more difficult. For companies looking to improve their environmental performance, addressing this issue presents both a challenge and an opportunity. Most paper cups contain a polyethylene (PE) coating, a thin plastic layer that provides resistance to liquids but can complicate recycling. Conventional recycling facilities may have difficulty separating the paper fibers from the plastic layer, which means that many used cups are disposed of as general waste. One study reported that more than 2.5 billion cups were used annually in the UK, with less than one percent being successfully recycled. However, specialized recycling facilities are beginning to address this problem by using technologies that separate paper fibers from plastic. The recovered fibers can then be used in products such as packaging, tissues, and stationery, although access to these facilities remains limited. Businesses, including cafés, restaurants, and offices, can contribute to improving collection and recycling rates by providing dedicated collection containers,

cooperating with recycling partners, and educating staff and customers. Some major coffee chains have already introduced initiatives related to cup recycling and reuse. Costa Coffee, for example, has established collection points at selected locations, while Pret A Manger and Starbucks have promoted reusable cup schemes and incentives to encourage changes in consumer behavior. Public awareness of sustainable waste management is also increasing, although confusion about the recyclability of paper cups remains common. Their paper appearance can lead consumers to assume that they can be placed in standard paper recycling bins. Clear information through signs, digital platforms, QR codes, and public campaigns can help consumers understand how and where these cups should be disposed of. Access to suitable collection points in supermarkets, cafés, and selected municipal facilities can further encourage correct disposal, particularly when supported by clear information from local authorities. Technological development is also contributing to improvements in paper cup recycling. Newer pulp processing systems can improve the separation of paper fibers from plastic coatings and reduce contamination. At the same time, research into biodegradable and compostable alternatives is continuing, including coatings based on plant-derived materials. Circular economy initiatives are also introducing cup-return programs and reusable systems, some of which use mobile applications to allow customers to borrow and return cups.

Significant progress in this area requires cooperation between producers, retailers, consumers, and public authorities. Appropriate regulations, collection systems, and recycling infrastructure are all important for improving the management of disposable cups. Companies that adopt more sustainable materials, encourage reuse, and support effective waste collection can reduce the environmental impact of their products while responding to increasing consumer interest in sustainable packaging. By reconsidering the design, use, and disposal of single-use products, disposable cups can become part of more efficient resource-management systems rather than simply being treated as waste after one use. [18]

Health concerns

PE coatings are produced according to strict quality standards, and paper cups coated with PE are generally considered suitable for food and beverage contact when they meet the applicable safety requirements. Polyethylene is widely used in food packaging and is regulated by food safety authorities in many countries. It is chemically stable and has low reactivity, which means that it can provide an effective barrier between the paper and the beverage, including hot drinks. Potential safety concerns can arise when production standards are not properly followed or when unsuitable materials are used. For example, the use of recycled or low-quality

polyethylene that is not intended for food contact, as well as uneven coating application, can affect the protective properties of the cup and potentially increase the risk of unwanted substances migrating into the beverage. Proper manufacturing and quality control are therefore important for ensuring the safety and functionality of the final product. To reduce potential risks, PE-coated cups should be used according to the manufacturer's instructions. They are generally not intended for microwave heating unless specifically stated by the manufacturer, as uneven heating can affect the cup and its coating. Very hot or boiling liquids should also be handled carefully, particularly when the cup is not designed for high-temperature applications. Disposable cups should generally not be reused, especially if the coating or paper structure has been damaged. Washing can also affect the coating and the paper layer. Cups showing cracks, peeling, weak spots, or other visible damage should not be used. The safety and performance of the final product depend strongly on the manufacturing process. Modern paper cup production machines can provide accurate and uniform coating thickness, while precise thermal sealing of the side and bottom joints helps prevent leakage. Automated quality control systems can also detect defects and contamination during production. In addition, automated processes can reduce direct human contact with food-contact materials and improve overall production hygiene. Although PE remains one of the most widely used and established coating materials, concerns about plastic waste, fossil fuel dependence, and recycling difficulties have encouraged the development of alternatives. One example is PLA, which can be produced from renewable resources and is compostable under suitable industrial conditions, although it generally has lower heat resistance than PE. Water-based coatings are another alternative that can support recycling and composting, but they may still face challenges related to performance and production costs. Improved recycling systems for PE-coated cups and continued research into new biopolymers are therefore focused on finding a suitable balance between durability, heat resistance, and environmental performance. [17]

US & Europe legal regulations

Production of paper cups must comply with strict regulations on packaging that will come into contact with food, especially with regard to materials that come into direct contact with beverages. The U.S. Food and Drug Administration (FDA) has established regulations for inks, adhesives, and surface treatments used in food-contact packaging. These requirements help ensure that materials used in the production process are suitable for their intended application before products are placed on the market. In Europe, regulations are structured differently, but equally demanding. One of the important directives dates back to 2003. (Directive 2002/72/EC,

later Regulation (EU) No 10/2011), which requires manufacturers to establish protective barriers between packaging materials and food to prevent the migration of chemicals. Also, regulation (EC) No 1935/2004, which is considered the EU's general framework for contact with food. For companies operating internationally, meeting US and EU certification requirements has become common practice, as it allows access to global markets without the need for repeated product redesigns, but with longer production time and higher costs. Polyethylene (PE) coatings continue to be the dominant solution in paper cup machines, as they effectively retain liquids at temperatures close to 100°C without leakage. With environmental concerns growing, with studies suggesting that nearly two-thirds of microplastics from beverage containers come from PE-coated cups puts some pressure on manufacturers to develop more sustainable alternatives. Polylactic acid (PLA), produced from corn starch, offers industrial composability and supports the EU's 2025 Single-Use Plastics Directive. The features are similar to those of a PE coating for cold drinks, but with a lower heat resistance, usually only safe up to about 60°C, unless combined with additional layers of insulation. For paper-based materials in food packaging production, cleanliness is key, which is why most manufacturers avoid recycled fibers that may contain contaminants. Instead, manufacturers use raw pulp from FSC-certified sources. At the same time chlorine bleaching is eliminated to reduce environmental and health risks. The level of lamination is usually kept below five percent of the total weight of the cup to keep the strength for liquids close to 95°C while allowing for recycling, which is still difficult to achieve. The control of harmful substances is also crucial, as safety assessments from the BfR (Bundesinstitut für Risikobewertung, German Federal Institute for Risk Assessment) from 2022 showed that around 12% of non-compliant cups failed due to traces of fluorescent bleach. The resulting situation has prompted the integration of spectroscopic systems into modern cup machines capable of detecting optical brighteners at speeds of more than four hundred cups per minute for real-time quality control. Regulatory compliance is increasingly tied to market access in North America and Europe, with around forty percent of European food packaging examination units now requiring detailed digital traceability of production. Canadian regulations under the Consumer Packaging and Labelling Act require certain product information to be provided in both English and French. This has encouraged manufacturers to use precise printing and coding systems capable of applying the required information in a clear and consistent format. Non-compliance can also result in significant financial penalties, depending on the nature and severity of the violation.

[19]

Conclusion

Applications of coatings to disposable cups were reviewed in this chapter. It was demonstrated that coatings play a significant role in ensuring disposables meet desired performance, safety and environmental requirements. Barrier properties that protect against liquid penetration influence thermal insulation performance, mechanical properties, printability, hygiene, as well as compliance with applicable regulations. Conventional polyethylene coatings continue to be popular due to their durability, heat resistance, and relatively low cost. However, PE is difficult to recycle with other plastics and is derived from fossil resources which has negative environmental implications. Polylactic acid coatings are an option that address some of these issues by being derived from renewable resources and potentially being compostable. However, PLA coatings have lower heat resistance and the availability of composting facilities can restrict the applicability of this option. Water-based coatings have also been developed that offer suitable performance while increasing recyclability compared to traditional plastic coatings and reducing the use of such plastics. Wax coatings and composite coatings were also discussed as examples of coatings that provide options between performance, cost and environmental factors. Regulatory landscapes in the US and Europe were compared. Regulatory requirements for food safety, restricting chemical migration, and ensuring traceability of packaging production were identified. Environmental concerns and changing policies also serve as drivers for further improvement of coating materials and processes. Moving forward, coating systems will have to balance performance, user safety, and environmental impact. Further research and development of coatings as well as collaboration between industry and regulators will be key to developing new coatings that can enable more sustainable use of resources.

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CHAPTER 2

INFORMATION SECURITY IN DIGITAL FORESTRY: RISKS, TECHNOLOGIES, AND SECURITY APPROACHES

Erol İMREN¹

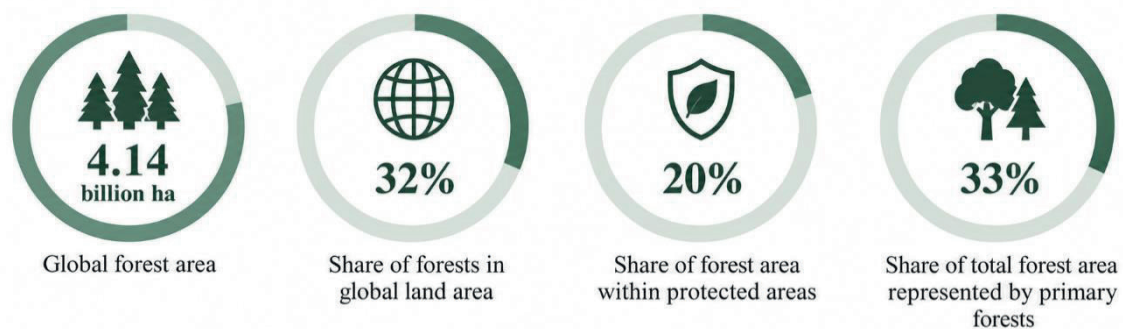
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1. Introduction

Forest management has historically relied on field observations, management plans, maps, sample-plot measurements, and administrative records. Increasingly, however, decisions are mediated by digital sensor networks, high-resolution satellite imagery, LiDAR point clouds, mobile field applications, cloud-based GIS, and AI models. FAO notes that national forest monitoring systems increasingly use remote sensing and cloud computing, while SEPAL and Open Foris support digital workflows for land-cover assessment, forest-change monitoring, inventory, and climate reporting (FAO, 2026a; FAO, 2026b).

This transformation is commonly described as “Forest 4.0” or “smart forestry.” Forest 4.0 integrates IoT, AI, big data, robotics, cloud computing, blockchain, and digital twins into forest operations (Damaševičius et al., 2024; Arion et al., 2026). Digitalization improves operational efficiency and enables faster decision support for forest health, wildfire risk, carbon stocks, biodiversity, harvesting, and timber movements. Yet this growing dependence makes information accuracy and system continuity critical security concerns.

Figure 1. *Global forestry context indicators (FAO, 2025)*



Information security is conventionally framed by confidentiality, integrity, and availability (CIA). Forestry applications also require authenticity, accountability, data provenance, and cyber-physical safety. Loss of a wildfire sensor network, for example, may delay early warning; GNSS deception may misdirect a UAV mission, response team, or timber-transport record; and manipulation of a carbon MRV dataset may have financial and regulatory consequences. Information security in forestry is therefore integral to environmental governance and operational safety.

The digital-forestry literature extensively examines technological innovation but treats cybersecurity more fragmentarily. He and Turner (2021) noted that the increased data sharing and interoperability enabled by Industry 4.0 in forest supply chains may introduce data-

leakage and cybersecurity risks. Their review of blockchain applications likewise found data breaches and cyberattacks insufficiently studied (He & Turner, 2022). This gap supports the development of a forestry-specific information-security framework.

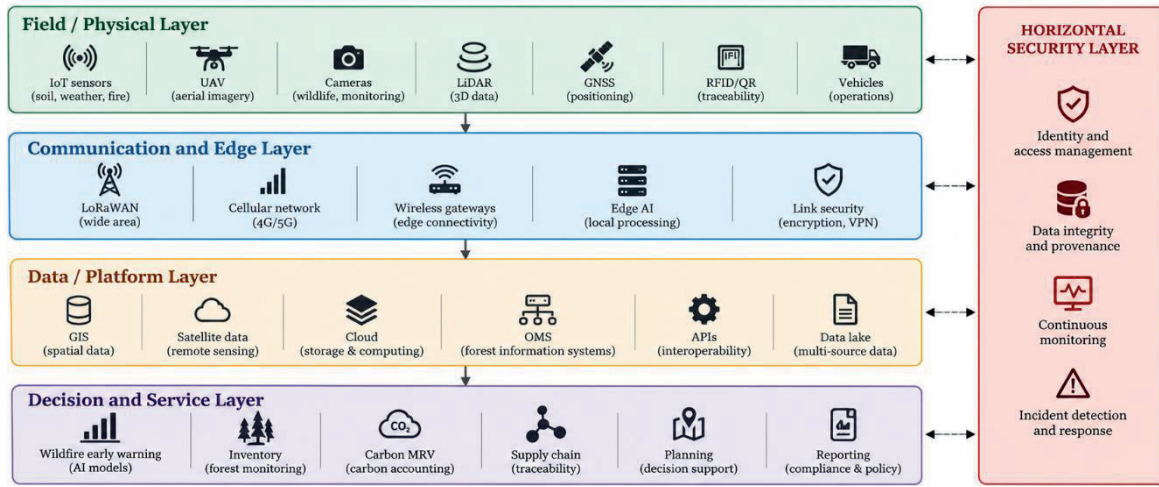
2. Conceptual Framework: Forest Information Assets and Security Requirements

In a forest enterprise or national forestry organization, an “information asset” extends beyond databases to sensors, mobile terminals, UAV ground-control stations, GIS layers, management data, user accounts, API keys, software models, training datasets, digital certificates, transport records, and wildfire communications. ISO/IEC 27001:2022 frames information security as an organization-wide, risk-based management system centered on confidentiality, integrity, and availability (ISO, 2022). NIST CSF 2.0 integrates governance, identification, protection, detection, response, and recovery within a single risk-management cycle (NIST, 2024a).

Table 1. *Digital forestry information assets and priority security requirements.*

Information/asset	Forestry example	Security priority	Primary threat	Potential impact
Spatial data	stand boundary, wildfire location, harvest parcel	Integrity + authenticity	coordinate manipulation, GNSS spoofing	misrouting; permit/planning error
IoT/WSN	temperature, humidity, smoke, soil, camera sensors	Availability + integrity	DoS, device compromise, physical sabotage	loss of early warning, false alarm
Remote sensing	satellite/UAV imagery; LiDAR	Integrity + provenance	file/metadata modification; fabricated imagery	classification/inventory errors
Artificial intelligence	wildfire classifier, tree detection, risk model	Integrity + reliability	data poisoning; backdoor; adversarial examples	incorrect risk/decision
Supply chain	RFID, QR, GPS, e-document, blockchain	Traceability + authenticity	identity cloning; fraudulent records	laundering illegal timber
Carbon MRV	biomass, carbon map, validation dataset	Integrity + auditability	data manipulation, version loss	incorrect crediting/reporting
Institutional system	ORBIS, file server, identity infrastructure	CIA + accountability	ransomware; privilege abuse	shutdown; data loss

Figure 2. *Digital forestry information architecture and horizontal security layer*
(Damaševičius et al.,2024; Arion et al.,2026; FAO, 2026a and NIST, 2024a).



3. Critical Technology Domains in Digital Forestry

3.1. Forest inventory, GIS, and geospatial data security

National forest inventories provide core data on the location, composition, structure, and change of forest resources. FAO notes that they can integrate field measurements with remote-sensing data to support sustainable forest management, policy, and climate reporting (FAO, 2026c). Inventory-data integrity is therefore critical to both technical accuracy and public decision-making.

LiDAR and AI are increasingly automating forest inventory. Rodrigues et al. (2024) found AI-LiDAR research concentrated on tree height, diameter, volume, and segmentation. Kulicki et al. (2025) reported substantial gains from deep learning on terrestrial point clouds but persistent problems with reference data, standardized metrics, and reproducibility. Xiang et al. (2024) demonstrated automated estimation of individual-tree and stand parameters from high-density airborne LiDAR using 3D deep learning.

Information security therefore extends beyond “accessing the correct file.” Changing the coordinate reference system, shifting geometries, manipulating attributes, or deleting source metadata can yield a visually plausible map that supports a wrong decision. ISO 19157-1:2023 provides a framework for geographic-data quality; secure forestry should complement it with cryptographic integrity, versioning, and access control (ISO, 2023). OGC security and API guidance likewise emphasize authentication, authorization, encryption, and HTTPS for geospatial services (OGC, 2023a; OGC, 2023b).

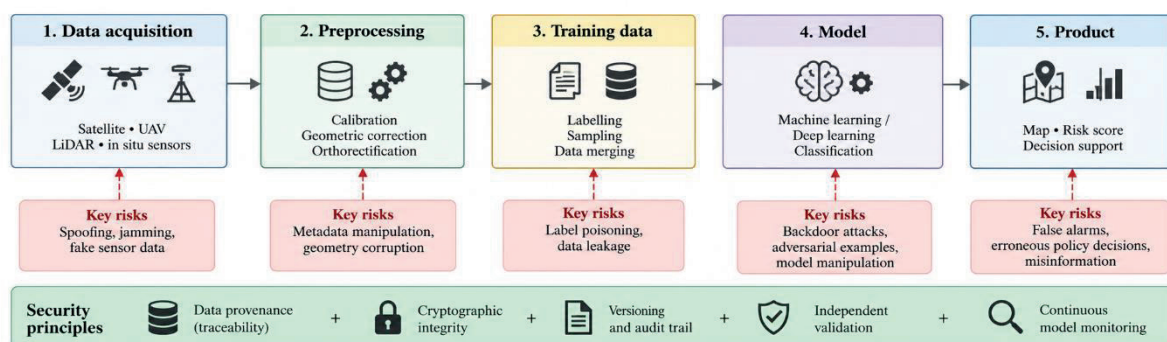
3.2. Remote sensing, satellite data, and UAV security

Satellite and UAV systems are increasingly central to monitoring deforestation, wildfires, insect damage, drought, harvested areas, canopy structure, and biomass. FAO's SEPAL supports high-resolution satellite-data access and analysis, while Open Foris links field collection, visual interpretation, and national reporting in an open-source ecosystem (FAO, 2026a; FAO, 2026b).

UAVs are cyber-physical systems. UAS security research identifies spoofing, jamming, denial of service, command injection, and malware across communication, software, payload, and control layers (Wang et al., 2023). GNSS is especially critical because spoofing can make a UAV position appear plausible while drifting from its true location. Multi-sensor validation, flight-log integrity, encrypted telemetry, and secure ground-control stations are therefore essential for UAVs used in wildfire response, inventory, or illegal-logging surveillance.

Remote-sensing workflows are sensitive to provenance risk because data undergo multiple transformations from sensor acquisition to final map products. Xu et al. (2023) identified adversarial and backdoor attacks, federated learning, uncertainty, and explainability as key AI-security topics in geoscience and remote sensing. Mei et al. (2024) documented the vulnerability of remote-sensing classification and object-detection models to adversarial perturbations. Treating model output as a direct “measurement” therefore creates substantial governance risk.

Figure 3. Data integrity risks across the remote sensing and AI lifecycle (Xu et al., 2023; Mei et al., 2024; ISO 19157-1:2023).



3.3. IoT, wireless sensor networks, and forest-fire early-warning systems

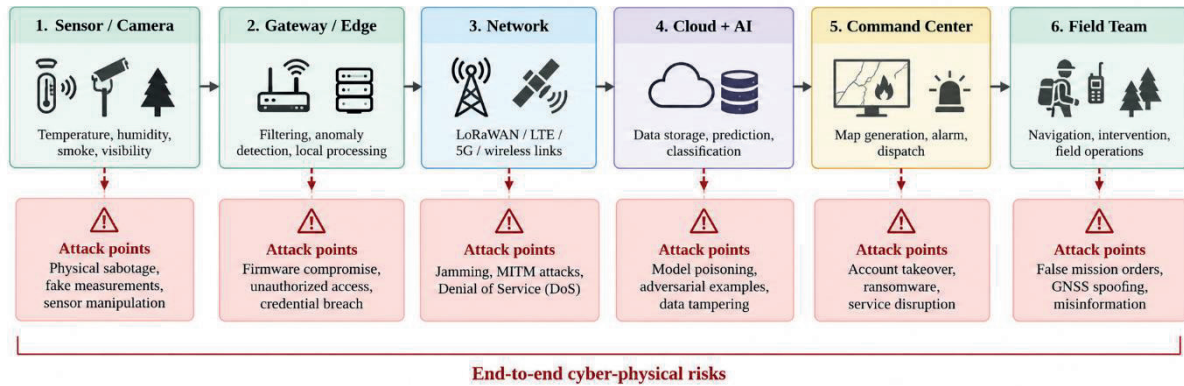
IoT-based smart-forestry systems continuously monitor temperature, humidity, smoke, gases, wind, and soil conditions, producing real-time data for wildfire, microclimate, and ecosystem-health monitoring. Reviewing the 2020–2025 literature, Arion et al. (2026) identified IoT-AI

integration, remote sensing, digital twins, and carbon accounting as major pillars of smart forestry.

Wildfire management is a prominent example of IoT-AI integration. Giannakidou et al. (2024) reviewed IoT and AI across prevention, detection, and restoration, while Ramadan et al. (2024) combined LoRaWAN IoT nodes with autonomous UAV image analysis in an early-detection architecture. Recent work also integrates edge computing, WSNs, multimedia sensors, and UAV validation in multilayer wildfire-detection systems (Radhi & Ibrahim, 2026).

In such systems, cyber risk becomes operational risk: an attacker may falsify sensor readings, jam communications to delay an alert, or compromise a cloud account and mislead the command center. NISTIR 8259A identifies foundational IoT capabilities including device identification, configuration, data protection, interface access, secure updates, and cybersecurity-state awareness; NISTIR 8259 Rev.1 further emphasizes security by design across the product lifecycle (NIST, 2020; NIST, 2026).

Figure 4. *Cyber-physical attack points in the forest-fire early-warning chain (Giannakidou et al., 2024; Ramadan et al., 2024).*



3.4. Artificial intelligence and model security

AI is rapidly being adopted for wildfire detection, tree-species classification, LiDAR segmentation, disease/stress detection, carbon estimation, and harvest planning (Jing et al., 2023; Wang et al., 2025). Unlike conventional software, AI systems expose distinct attack surfaces in data, model parameters, and inference behavior.

Data poisoning changes model behavior by introducing malicious or erroneous training samples; backdoors cause attacker-selected outputs when a trigger is present; and adversarial examples use subtle perturbations to alter predictions. Model extraction and membership inference also create intellectual-property and privacy risks. Because remote-sensing models

are vulnerable to these attacks, critical forestry decisions should not rely solely on automated model scores (Xu et al., 2023; Mei et al., 2024).

NIST AI RMF 1.0 organizes AI risk management around GOVERN, MAP, MEASURE, and MANAGE and treats validity, safety, resilience, transparency, explainability, and privacy as attributes of trustworthy AI (NIST, 2023). In forestry, implementation should include training-data provenance, model versioning, field drift monitoring, human validation for high-impact uses, and adversarial-robustness testing.

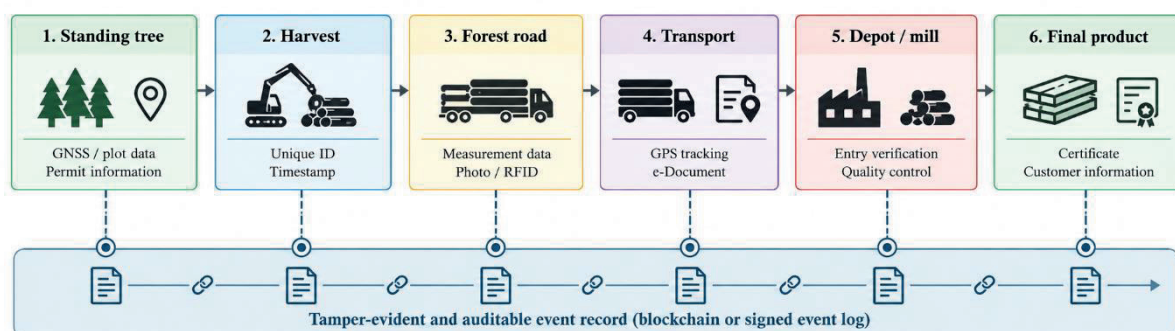
3.5. Timber supply chains, traceability, and blockchain security

The timber supply chain is a multi-actor information flow from standing trees through harvesting, roadside operations, transport, depots, mills, and final products. Kaulen et al. (2023) showed that QR/RFID, optical biometrics, geospatial tracking, and digital records are central to end-to-end traceability. Palander et al. (2024) identified digital data flows as a foundation for forest-to-mill supply-chain optimization.

Blockchain is often proposed for timber supply chains because it impedes retrospective record alteration and supports multi-stakeholder validation. He and Turner (2022) classified applications in forest management, timber traceability, and wildfire detection; Stopfer et al. (2024) highlighted potential benefits for illegal-timber control, certification, and chain-of-custody transparency. However, blockchain does not solve “garbage in, garbage out”: fraudulent permits, incorrect locations, or cloned RFID identities can become permanently recorded if input authentication is weak.

The EU Deforestation Regulation (EUDR; Regulation (EU) 2023/1115) requires geolocation and due-diligence data for relevant products. This requirement further elevates the importance of geospatial integrity and supply-chain information security in forestry and timber-product systems (European Union, 2023).

Figure 5. *Secure traceability and data-provenance model for the timber supply chain (He and Turner, 2022; Kaulen et al., 2023; Stopfer et al., 2024).*



3.6. Carbon MRV, digital twins, and trustworthy environmental data

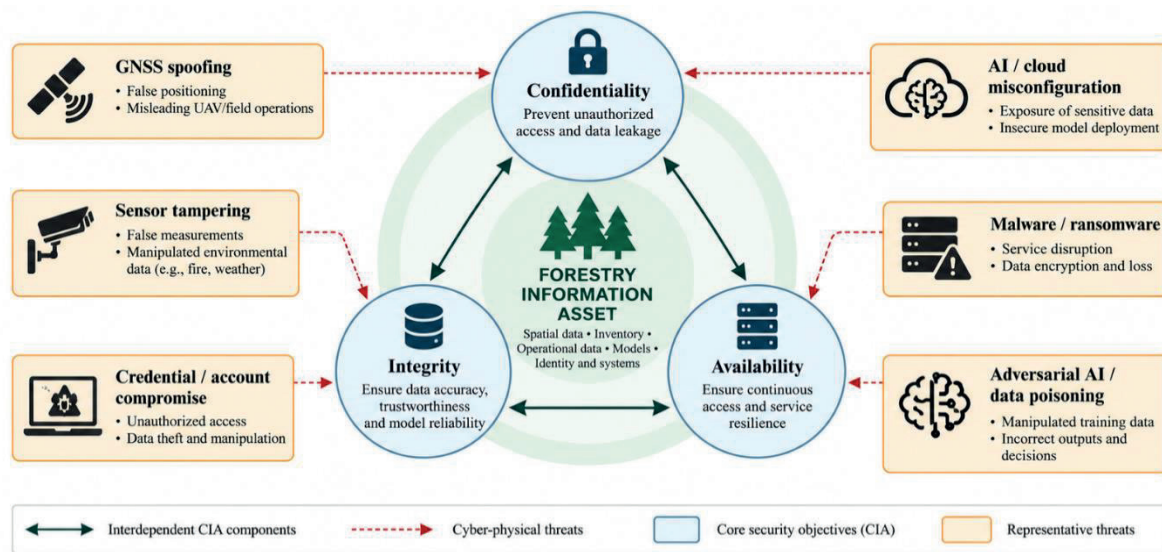
Climate policy is turning forest-carbon data into a high-value financial and regulatory asset. Digital MRV integrates field measurements, satellite/LiDAR data, models, and time series to monitor carbon stocks more frequently and at finer spatial resolution. Anderson et al. (2026) proposed a global digital-MRV approach for forest structure and aboveground carbon density that showed strong agreement with independent datasets.

A digital forest twin creates an updatable representation of forest condition rather than a one-time carbon estimate. The “digital forest carbon twin” proposed by Lopatin, Pitkänen, and Sikanen (2026) links tree-level monitoring with carbon MRV and climate-smart management, emphasizing data lineage, versioned state updates, uncertainty, and auditability. Information security and environmental verification therefore converge: a carbon claim is unreliable if its measurement source, algorithm version, transformations, and verification records cannot be traced.

Core carbon-data controls include immutable raw-data copies, verified sensor or satellite sources, versioned processing scripts, archived model parameters, hashes/electronic signatures, independent quality control, and segregation of duties. These controls also improve scientific reproducibility.

4. A Forestry-Specific Cyber Threat Model

A digital-forestry threat model should cover IT assets, field devices, geospatial accuracy, operational continuity, and ecological consequences. NIST SP 800-82 Rev. 3 notes that operational-technology systems may prioritize safety, reliability, and availability differently from conventional IT (NIST, 2023b). Wildfire communications, vehicle tracking, sensor networks, and automated routing should therefore be assessed as cyber-physical systems.

Figure 6. *Information-security threat surface in forestry: from CIA to cyber-physical impacts.***Table 2.** *Illustrative cyber threat-control matrix for digital forestry.*

Threat	Target	Security impact	Forestry scenario	Priority	Core control
Ransomware	server/GIS/backups	A + I	loss of wildfire, permit, or plan data	Very high	immutable offline backup; segmentation; EDR
GNSS spoofing / jamming	UAV / vehicle / field team	I + A	wrong wildfire location or route	Very high	multi-sensor validation; anti-spoofing; anomaly monitoring
IoT compromise	sensor/gateway	I + A + C	falsified sensor readings	High	device identity; secure boot; signed firmware
API/cloud breach	GIS/data platform	C + I + A	layer/data alteration; leakage	High	MFA; RBAC; secrets; logging
Data poisoning	AI training	I	biased AI model	High	provenance; data review; held-out validation
Adversarial example	AI inference	I	wildfire/illegal-logging evasion	Medium-high	robustness tests; ensembles; human approval
Insider/privilege abuse	institutional accounts	C + I	altered permit/harvest records	High	least privilege; duty separation; audit logs
Physical sabotage	field sensor/tower	A + I	lost/falsified data	Medium-high	tamper evidence; redundant sensing
Supply-chain software risk	firmware/library/service	C + I + A	mass device compromise	High	SBOM; signed updates; supplier risk management

4.1. Data-integrity attacks

In forestry, integrity breaches may be more operationally damaging than confidentiality breaches. Incorrect forest boundaries, wildfire coordinates, timber volumes, species classes, or carbon values can yield wrong decisions while systems appear normal. Geospatial changes should therefore use versioning, signed records, editor identity, timestamps, and rollback.

Recent research identifies unauthorized modification of geometry, attributes, topology, and GPS/IoT locations in cloud GIS as a distinct security problem (Kiedrowicz & Rozmus, 2026).

4.2. Availability and business continuity

Information-system availability is critical during wildfire seasons, storms, extreme heat, and large-scale harvesting or transport. Dependence on one data center or communication technology creates a common failure point. Critical forestry services should define RTO/RPO targets and maintain redundant communications, offline maps and task lists, local edge capability, and regular restoration exercises.

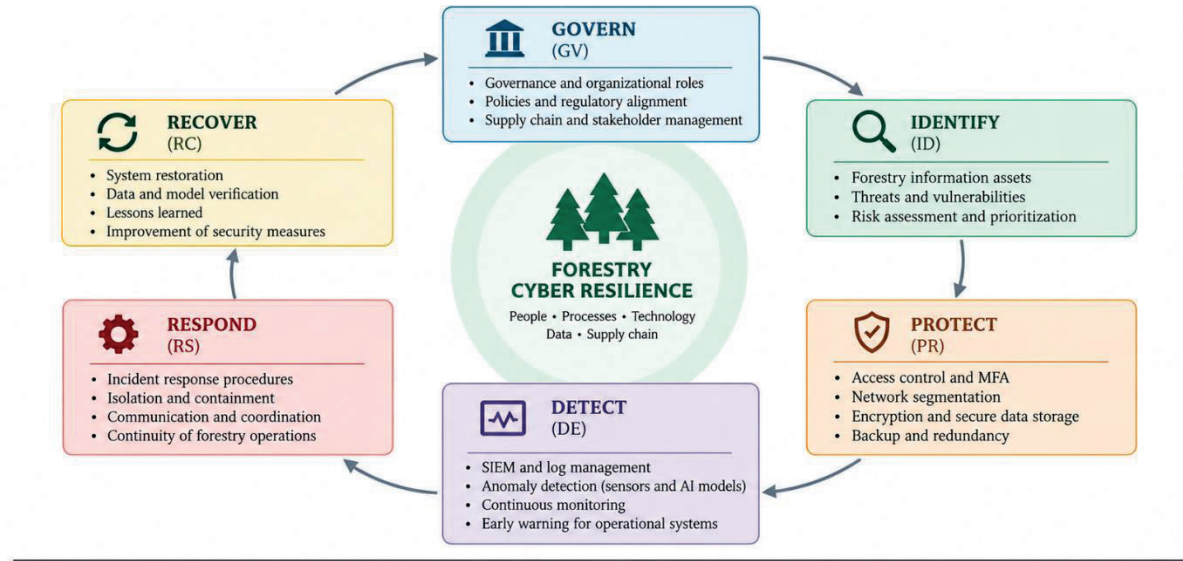
4.3. Identity, authorization, and the Zero Trust approach

Forestry organizations may connect field personnel, contractors, carriers, producers, laboratories, certification bodies, and central administration in one digital environment, weakening perimeter-based trust. Core controls should include identity-centric security, MFA, conditional access, role/attribute-based authorization, short-lived tokens, device identity, and privileged-access management. OGC guidance on HTTPS, authentication, and authorization is directly applicable to API-based data sharing (OGC, 2023b).

5. International Standards and Regulatory Frameworks

Table 3. *International frameworks relevant to information security in digital forestry.*

Framework/standard	Primary focus	Forestry relevance	Example application
ISO/IEC 27001:2022	ISMS, risk management, CIA	institutional forest information systems	asset inventory, risk register, ISMS
NIST CSF 2.0	Govern-Identify-Protect-Detect-Respond-Recover	national/institutional cyber resilience	forestry cyber-risk profile
NISTIR 8259A / 8259 Rev.1	IoT device security	field sensors, gateways, cameras	device identity, secure updates
NIST SP 800-82 Rev.3	OT/ICS security	wildfire, vehicle, and field operations	segmentation, secure remote access
NIST AI RMF 1.0	AI risk management	wildfire/mapping/prediction models	model validation, drift, human oversight
ISO 19157-1:2023	geographic data quality	GIS, inventory, EUDR geolocation	quality metrics + metadata
OGC API / Security	geospatial-service interoperability and security	web maps/APIs	HTTPS, authn/authz, OAuth/OpenID
EU 2023/1115 (EUDR)	deforestation-free products and geolocation due diligence	timber and related product supply chains	plot geolocation + traceability

Figure 7. *Adaptation of NIST CSF 2.0 (2024) functions to digital forestry .*

6. The Turkish Context: ORBİS, Wildfire Management, and Security in Digital Forestry

Türkiye's General Directorate of Forestry (Orman Genel Müdürlüğü; OGM) has long developed digital-forestry infrastructure. ORBİS (Orman Bilgi Sistemi; Forest Information System) centralizes electronic monitoring, reporting, and integration of institutional map and data layers. A TULIP monitoring system introduced in 2025 also tracks financial and physical progress through ORBİS layers and web-based processes (OGM, 2025). ORBİS therefore functions as infrastructure for both administration and institutional accountability.

OGM's forest-fire infrastructure combines UAVs, unmanned surveillance towers, decision support, vehicle tracking, Yangın-Cell, mobile applications, and headquarters-field communications (OGM, 2021a; OGM, 2021b). In 2026, OGM reported AI-supported risk maps using temperature, wind, humidity, topography, fuel type, and drought to forecast wildfire risk up to seven days ahead, while work continued to integrate software under a single Forest Fire Management System (OGM, 2026).

Integration creates both opportunity and risk. A common platform can improve visibility and incident management, but weak identity infrastructure, segmentation, API security, or backups can turn it into a single point of failure or compromise. For Türkiye, ORBİS and wildfire infrastructure should be classified as critical assets; field IoT and communication devices should use device-identity and secure-firmware policies; geospatial changes should be recorded in signed audit logs; and cyber-incident and restoration exercises should precede the wildfire season.

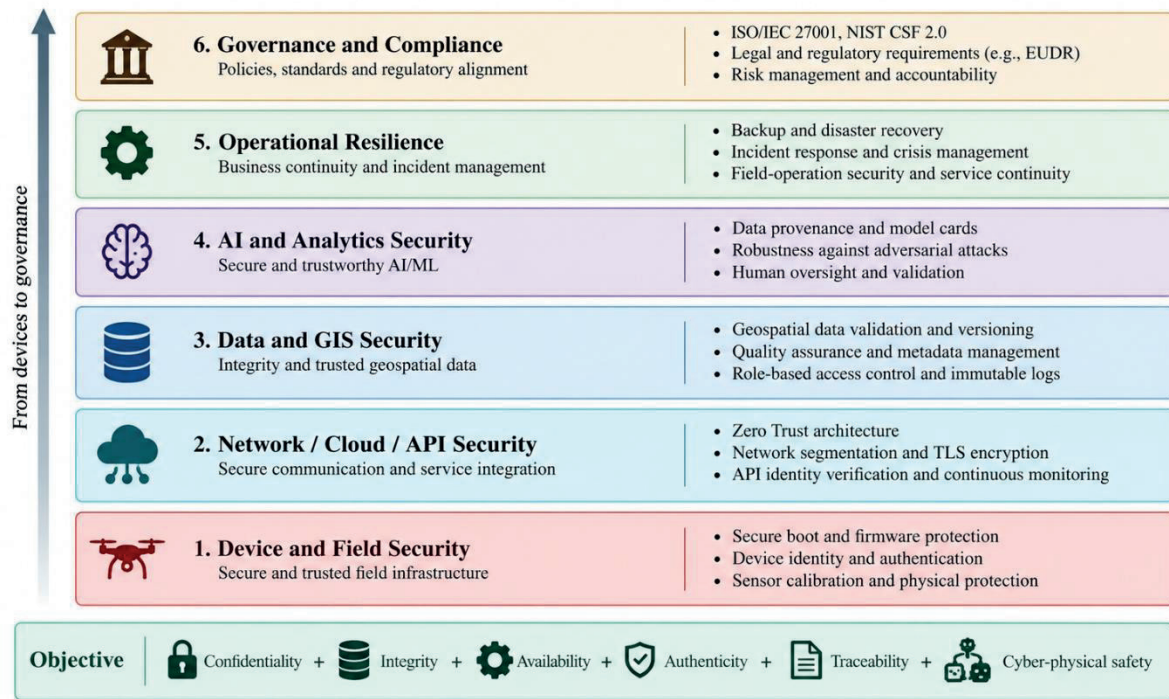
OGM privacy notices also indicate that vehicle and product-movement data are processed in shared digital repositories. Personal, commercial/operational, and geospatial data should

therefore be classified within one security architecture, with data minimization, purpose limitation, and access authorization embedded by design.

7. Proposed Model: Secure Forest 4.0

The proposed Secure Forest 4.0 model organizes forestry digitalization into six security layers. Its premise is that security is not a separate IT layer but a security-by-design requirement extending from sensors to governance.

Figure 8. *Secure Forest 4.0: A six-layer information-security model for digital forestry.*



7.1. Device and field security

Sensors, cameras, gateways, RFID readers, and UAVs should use unique identities, secure boot, signed firmware, secure updates, tamper indicators, calibration histories, and least-privilege local services. Because field connectivity is often intermittent, device security must not depend on continuous cloud access.

7.2. Network, cloud, and API security

Wildfire, inventory, and supply-chain traffic should be logically separated from user office networks. API access should use HTTPS/TLS, strong authentication, token-lifetime controls, rate limiting, and centralized logging; cloud storage should include public-exposure checks and automated secret management.

7.3. Data and GIS integrity

Critical geospatial datasets should retain source, production date, coordinate reference system, transformation steps, responsible actor/system, and quality metrics as metadata. Critical layers should also use hashes/signatures, version control, WORM/immutable archives, and authorized change workflows.

7.4. AI and analytics security

Controls should include model cards, training-dataset inventories, code/model versioning, independent test sets, drift monitoring, data-poisoning controls, adversarial testing, and uncertainty reporting. Human approval should be retained for high-impact decisions such as wildfire alerts, enforcement, or permitting.

7.5. Operational resilience

Critical functions require business-impact analysis, RTO/RPO targets, offline capability, alternative communications, backup command locations, and restoration exercises. Cyber-response plans can be aligned with wildfire incident-command structures so technical and field teams share a common crisis-management framework.

7.6. Governance, compliance, and supplier risk

The institutional ISMS should cover device manufacturers, cloud providers, software contractors, data providers, and research partners. Contracts should address security updates, vulnerability-notification periods, incident reporting, data ownership, data deletion/return, and software-component transparency such as SBOMs.

8. Research Gaps and Future Directions

- Forestry-specific cyber-incident datasets and benchmarks remain scarce. Although threat models transferred from smart agriculture and UAS security are useful, sector-specific characteristics—including wildfires, remote-field connectivity, and public forest data—require dedicated test environments.
- Cryptographic data provenance and scientific provenance should be considered jointly for remote-sensing products. Verification should extend beyond the file hash of satellite or UAV imagery to include the processing chain and model version.
- Adversarial-robustness testing should be incorporated into standard evaluation metrics for AI-based wildfire detection and forest-inventory models. Accuracy and F1 scores alone do not represent operational reliability.

- The trade-off between energy constraints and security overhead in IoT sensor networks should be measured empirically under forestry field conditions. Key management, updates, and anomaly detection should be adapted to low-power environments.
- The relationship between geolocation accuracy and information security should be investigated in the context of the EUDR and similar regulations. Compliance systems should be resilient to falsified coordinates, identity cloning, and data manipulation.
- For carbon MRV, data integrity, model uncertainty, and cyber risk should be addressed within a common assurance framework. Neither a system that is cybersecure but scientifically weak nor one that is scientifically sound but cyber-insecure can support a trustworthy carbon claim.
- For Türkiye, a sector-specific NIST CSF profile or ISO/IEC 27001 implementation guide could be developed to jointly address ORBİS, the Forest Fire Management System, UAVs, vehicle and sensor infrastructure, and e-document processes.
- As digital twins and autonomous forestry systems expand, the human-machine boundary of authority, explainability, safety, and cybersecurity will increasingly become a shared design problem.

9. Phased Roadmap for Institutional Implementation

Table 4. *Illustrative maturity roadmap for information security in digital forestry.*

Stage	0–3 months	3–9 months	9–18 months	18+ months
Governance	responsibilities; critical assets	risk register/policy segmentation;	supplier security terms	sector CSF profile; continuous metrics
Technical	MFA; backup checks; logging	EDR; API security	IoT identity; immutable logs	Zero Trust; automated policies
Data/GIS	critical-layer classes	versioning; metadata; hashing	provenance; quality dashboard	cryptographically verifiable chain
AI	model inventory	test set; model card	adversarial/drift tests	AI assurance; independent audit
Incident response	contacts; backup procedure	tabletop exercise	joint field/cyber exercise	regular cross-agency exercises

10. Conclusion

Forestry digitalization expands measurement and decision capacity for sustainable management while increasing dependence on reliable information systems. Forest inventory, wildfire early warning, supply chains, carbon MRV, and regulatory reporting are no longer isolated data silos but a cyber-physical ecosystem connected through sensors, networks, cloud platforms, GIS, and AI.

Accordingly, forestry information security extends beyond “Who can see the data?” It also asks whether data are correct, locations manipulated, devices trustworthy, models attack-resistant, systems available during wildfires, timber identities matched to physical products, and carbon claims retrospectively verifiable. These questions belong to the same security framework.

Forest 4.0 will continue to evolve through IoT, AI, remote sensing, and digital supply chains. Sustainable and trustworthy adoption requires security to be embedded within this architecture. The proposed Secure Forest 4.0 model provides a six-layer foundation from devices to governance. Future forestry informatics should therefore be judged not only by its ability to generate and analyze data, but also by whether those data remain verifiable, resilient, and trustworthy under cyber threat.

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CHAPTER 3

GNSS POSITIONING ACCURACY IN FORESTED AREAS: A COMPARATIVE LITERATURE REVIEW BASED ON ENVIRONMENTAL CONDITIONS, GNSS SIGNAL CHARACTERISTICS, AND MEASUREMENT PARAMETERS

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1. Use of GNSS in Forestry

Global Navigation Satellite Systems (GNSS) have significantly improved positioning accuracy in recent years, largely due to advances in hardware and signal technologies. Modern receivers are now capable of simultaneously processing multi-constellation and multi-frequency data without relying on a single satellite constellation. In particular, the transition from single-frequency to multi-frequency receivers provides significant advantages in terms of reducing ionospheric delays and improving positioning accuracy (Uradziński & Bakula, 2023). In addition to enhancing positioning accuracy, these technological developments have also led to the exploration of alternative solutions for challenging environments, such as forests, where signal reception is often impeded.

Forest resource management requires continuous and systematic collection of spatial data across extensive and often difficult-to-access terrains. GNSS technology has rapidly become widespread in forestry applications to meet this need and has evolved into an indispensable tool across a broad range of applications, including tree inventory, boundary delineation, forest road planning, and harvesting operations. However, the unique physical structure of forested environments presents a major challenge to the accurate and reliable reception of GNSS signals. In particular, operational activities within forests often require centimeter- to decimeter-level positioning accuracy for real-time navigation; however, achieving this level of accuracy becomes considerably more difficult under dense forest canopy (Blum et al., 2016). Similarly, precision forestry applications, such as positioning individual trees and accurately targeting selective interventions (e.g., thinning), depend on high positioning accuracy (Cho et al., 2024). In GNSS measurements conducted in forested areas, signal attenuation and multipath effects caused by dense vegetation can adversely affect positioning accuracy. The Continuously Operating Reference Station (CORS) technique, developed to improve positioning accuracy, enables more reliable positioning by providing differential correction data (Pirtı & Eren, 2025). In forest inventory studies, GNSS is widely used as a fundamental tool for the geospatial positioning of sample plots, tree groups, and stand boundaries. However, because inventory points are often located beneath forest canopy, canopy cover can directly affect measurement accuracy. Short-duration static measurements conducted using smartphone-based low-cost receivers have been shown to achieve centimeter-level accuracy in open areas; however, their positioning performance decreases markedly under forest canopy (Tomašík & Varga, 2021). This situation highlights the need to carefully select the receiver type, observation duration, and processing method according to forest conditions when planning forest inventory surveys.

Determining the positions of individual trees forms the basis of precision forestry applications, including growth monitoring, selective harvesting, and precision thinning operations. Studies conducted using the Global Navigation Satellite System–Real-Time Kinematic (GNSS-RTK) method have reported mean horizontal positioning errors ranging from 0.26 to 0.48 m across different forest types, indicating that RTK technology can be practically applied to precision thinning operations (Cho et al., 2024). On the other hand, it has been suggested that the attenuation and scattering experienced by GNSS signals as they propagate through forest canopy should not be considered solely as sources of positioning error but may also serve as a source of information on forest structure (Guerriero et al., 2020). This approach indicates that GNSS has potential applications beyond tree positioning, particularly for the remote sensing of forest structural characteristics.

The determination of forest property boundaries and parcel corner points is of critical importance for cadastral surveys and resource management planning. In such boundary delineation studies, RTK and static surveying methods, which provide high positioning accuracy, are generally preferred. However, RTK applications using low-cost receivers have been reported to experience difficulties in maintaining a continuous fixed solution in forest environments, frequently switching to a float solution due to signal attenuation and multipath effects (Mahato et al., 2020). This finding highlights the need to consider forest density when selecting equipment and surveying methods for boundary delineation studies.

The planning of forest road and extraction trail networks requires accurate spatial information to ensure both harvesting efficiency and the protection of soil and water resources. It has been reported that the target accuracy levels for real-time navigation cannot be consistently achieved under dense forest canopy when determining extraction trail routes, thereby necessitating additional correction strategies for road and trail planning (Blum et al., 2016). In this context, it is recommended that road planning studies be supported not only by GNSS data but also by complementary information, such as terrain slope and soil characteristics.

Precision forestry is a holistic approach that involves the integrated use of spatial data with harvesting machinery, thinning operations, and growth monitoring systems. Within this framework, GNSS-RTK systems enable the centimeter- to decimeter-level tracking of harvesting machines and harvester heads, allowing the precise recording of the location of each felled tree (Cho et al., 2024). However, factors such as signal attenuation, multipath effects, and reduced satellite visibility remain among the primary factors limiting GNSS performance in precision forestry applications (Mahato et al., 2020; Xu et al., 2024).

GNSS data are commonly integrated with LiDAR (Light Detection and Ranging) and Geographic Information Systems (GIS) to overcome the accuracy limitations encountered in forested areas when GNSS is used alone. A comprehensive review evaluating the accuracy of global canopy height models demonstrated that LiDAR-based data, particularly airborne laser scanning (ALS), provide the most reliable source for the validation of ground control points and model calibration, whereas satellite-based data offer broader spatial coverage but generally provide lower levels of accuracy (Lencinas, 2025). These findings indicate that ground control points obtained using GNSS can play a complementary role in improving the accuracy of LiDAR- and GIS-based analyses. In addition, sky-view-based modeling studies have provided approaches that can be used to quantify canopy density within GIS environments and to predict GNSS performance in advance (Wright et al., 2017).

GNSS positioning accuracy in forested areas is influenced by multiple factors rather than being determined by a single variable. In addition to environmental effects, such as forest canopy density and structure, signal attenuation, and multipath propagation, the characteristics of the GNSS receiver, satellite geometry, observation duration, number of frequencies, and positioning method also play a determining role in the resulting accuracy. Therefore, the evaluation of GNSS performance in forested areas should not be limited to comparisons of different receivers or positioning techniques; rather, environmental conditions, GNSS signal characteristics, and measurement parameters should be considered collectively.

Furthermore, evaluating GNSS performance solely in terms of horizontal positioning error is insufficient. The effects of variables such as satellite constellation and frequency combination, canopy density, observation duration, solution type, satellite geometry, and the correction service employed should be examined collectively in terms of their impacts on positioning accuracy, solution continuity, and the success of obtaining a fixed solution. Accordingly, this study evaluates the effects of these variables on GNSS positioning accuracy and solution continuity.

2. Effects of Forest Environmental Conditions on GNSS Positioning Accuracy

In forested areas, GNSS positioning accuracy is influenced not only by the technical characteristics of the receiver and the positioning method employed, but also to a considerable extent by the physical and structural characteristics of the environment in which the measurements are conducted.

In particular, canopy closure, reduced sky visibility, signal attenuation, and multipath propagation can alter the conditions under which satellite signals reach the receiver, thereby affecting the stability and accuracy of the positioning solution. Forest canopy, consisting of tree

trunks, branches, and leaves, can attenuate satellite signals, reduce satellite visibility, and cause reflected signals to reach the receiver. These effects may result in degraded signal quality, increased difficulty in carrier-phase ambiguity resolution, increased positioning errors, and transitions of RTK solutions from a fixed to a float status. A study comparing GPS–GLONASS signals under forest canopy and in open areas demonstrated that, although the use of multiple constellations can increase the number of available satellites, it does not completely eliminate signal attenuation and multipath propagation problems under dense canopy conditions (Blum et al., 2016; Moore et al., 2023; Guerriero et al., 2020).

Canopy Closure and Sky Visibility

Canopy closure is one of the primary environmental variables directly affecting the reception of GNSS signals in forested areas. The canopy structure, consisting of tree trunks, branches, and leaves, can restrict the direct line of sight to satellites and reduce the number of satellites observable by the receiver. As a result, satellite visibility may decrease, while signal reflections can give rise to multipath effects. These effects may lead to reduced positioning accuracy, particularly under dense canopy conditions. Measurements conducted in open areas and beneath forest canopy have been compared, and reductions in signal quality and positioning accuracy, along with decreases in the number of visible satellites and difficulties in carrier-phase ambiguity resolution, have been reported under forest canopy (Blum et al., 2016).

The effect of canopy closure on GNSS performance can be addressed not only qualitatively but also quantitatively through sky visibility. Ghosh et al. (2024) demonstrated that the effect of canopy closure on GNSS signals should not be considered solely as a source of error that reduces positioning accuracy; rather, the degree of signal attenuation experienced as the signal passes through the canopy can also be used to map the structural and biophysical characteristics of forest cover. In their study, vegetation optical depth was estimated by comparing a reference GNSS signal measured in an open area with the signal measured beneath the canopy using an unmanned ground vehicle (UGV).

Wright et al. (2017) investigated the relationship between forest canopy and GPS signal loss using sky photographs and metrics representing sky visibility. Greater sky obstruction was associated with increased signal loss; therefore, sky visibility can serve as an environmental indicator for evaluating GNSS performance (Wright et al., 2017). Similarly, a study aimed at predicting GPS performance in densely forested areas evaluated variables such as canopy density, sky visibility, PDOP, and signal strength collectively. The findings indicate that canopy closure is an important environmental variable affecting GNSS performance; however, performance should not be determined solely by canopy density, but rather in conjunction with

satellite geometry and signal characteristics. While canopy density emerged as an important explanatory variable, increased sky visibility was associated with more favorable GPS performance (Moore et al., 2023). These findings demonstrate that the effect of forest environments on GNSS positioning accuracy cannot be adequately explained solely by considering the number of visible satellites.

Leaf Area Index (LAI)

Leaf Area Index (LAI) is an important ecological metric used to characterize the structural density of vegetation. In forested areas, an increase in LAI theoretically indicates an increase in the amount of vegetation material along the propagation path of satellite signals. Rather than focusing directly on LAI, existing studies have generally focused on more directly observable variables, such as canopy closure, sky visibility, signal loss, and signal quality (Blum et al., 2016; Moore et al., 2023; Wright et al., 2017). Current studies have primarily focused on the relationships among canopy density, sky visibility, canopy height, and signal loss.

Tree Species and Forest Structural Characteristics

Forest structure is shaped by the combined effects of several components, including tree species, crown architecture, foliage density, branching characteristics, and canopy closure. Therefore, the conditions under which GNSS signals reach the receiver are not expected to be identical across different forest types. These characteristics can alter the way the canopy obstructs the sky and influence signal propagation within the forest environment.

GNSS-T measurements were conducted across three different forest zones: medium-sized oak trees, medium-sized mixed deciduous trees, and large pine trees, and the VOD values were compared among these zones. The results indicated that the effects of different tree species on signal attenuation and scattering were not identical. In comparisons conducted in May, VOD values were higher in the oak zone than in the pine and mixed-tree zones, which was associated with denser canopy and a higher expected vegetation water content. In the pine zone, the greater tree height and higher needle density were associated with higher VOD values compared with the mixed forest. These findings suggest that tree species can influence GNSS signal propagation through their effects on canopy density, tree height, leaf/needle geometry, and vegetation water content (Ghosh et al., 2024).

A study examining the accuracy of global canopy height models also indicated that heterogeneity in forest structure, differences among tree species, and the data source used can affect the accuracy of canopy modeling. This finding highlights the importance of accurately characterizing canopy structure for environmental analyses; however, it does not demonstrate that tree species directly alter GNSS positioning accuracy. Therefore, tree species should not

be considered a direct indicator of GNSS positioning accuracy, but rather as an environmental factor that contributes to canopy structure and warrants further investigation (Lencinas, 2025).

Seasonal Variation

Seasonal variation can alter canopy permeability and sky visibility, particularly in deciduous forests. During leaf-on and leaf-off periods, satellite visibility at a measurement location, the signal attenuation capacity of vegetation, and signal reflection conditions may differ. A sky photography study conducted in a deciduous forest demonstrated that leaf-on and leaf-off conditions should be considered when evaluating canopy openness and GPS signal loss. This finding indicates that seasonal variation is an environmental condition that should be controlled for when assessing GNSS performance (Wright et al., 2017).

The study by Ghosh et al. (2024) also reported that VOD values generally increased with the transition from the leaf-off to the leaf-on period, showing an increasing trend from March to June. However, this change was not linear; different tree species responded to seasonal variation at different times and with different magnitudes. For example, VOD values increased in the oak zone as foliage density increased throughout spring, whereas higher values were observed at an earlier stage in the pine zone.

Terrain Slope and Aspect

Terrain slope and aspect are topographic variables that can indirectly influence satellite visibility geometry and the directions of open sky in forest environments. They can affect the horizon openness at a measurement location, satellite visibility geometry, and the position of surrounding reflective surfaces. Particularly in areas characterized by steep terrain and dense vegetation, sky visibility may be constrained not only by tree canopies but also by the geometric configuration of the terrain.

Romero et al. (2025) evaluated the accuracy of GNSS and UAV-LiDAR in a small study area with an approximate slope of 5%; however, this information does not imply that the effect of slope on positioning accuracy was specifically investigated. In particular, evaluating satellite geometry indicators, such as PDOP, together with terrain conditions may contribute to a clearer understanding of this relationship (Moore et al., 2023).

Multipath Propagation and Signal Attenuation

One of the primary mechanisms underlying the degradation of GNSS positioning accuracy in forested areas is signal attenuation and multipath propagation. Multipath occurs when, in addition to the direct reception of a satellite signal by the receiver, the signal is reflected from tree trunks, branches, leaves, the ground, or other surfaces and reaches the receiver through different paths. The simultaneous reception of direct and reflected signals can cause distortions

in signal measurements and instability in carrier-phase ambiguity resolution. In addition to reductions in signal quality and satellite visibility under forest canopy, multipath effects have been reported to complicate ambiguity resolution and increase positioning errors (Blum et al., 2016).

A study investigating the RTK performance of low-cost GNSS receivers also reported that, although high positioning accuracy was achieved in open areas, signal attenuation and multipath effects under forest canopy reduced the continuity of the fixed solution and increased the frequency of fixed–float transitions (Mahato et al., 2020). This finding demonstrates that forest canopy can affect not only measurement accuracy but also the stability of the RTK solution.

Antenna technologies and multi-GNSS systems used to mitigate multipath effects may provide certain improvements. However, although approaches such as choke-ring antennas can reduce multipath effects, they cannot completely eliminate the signal attenuation caused by dense forest canopy (Blum et al., 2016). Similarly, although machine learning-based multipath/NLOS mitigation methods are promising, their applications in forest environments remain limited, and concerns have been raised regarding their environmental generalizability (Xu et al., 2024).

Atmospheric and Environmental Effects

Although the accuracy of GNSS signals can also be affected by atmospheric conditions, in forest environments, particular attention should be given to the effects of forest canopy on physical signal obstruction, signal attenuation, reflection, and satellite visibility. A study investigating the use of multi-frequency GNSS indicated that the use of different frequencies can contribute to the mitigation of ionospheric effects and the improvement of carrier-phase ambiguity resolution (Cole et al., 2020). This finding suggests that multi-frequency observations can provide benefits in terms of reducing atmospheric effects and improving ambiguity resolution; however, they cannot by themselves resolve physical signal obstruction. The study by Romero et al. (2025) demonstrates the importance of using static GNSS, RTK, CORS-based corrections, and total station references together for accuracy assessment. However, because the study was conducted under open-sky conditions in a small study area, its results should not be directly generalized to GNSS performance under forest canopy.

The conditions that most directly affect GNSS performance in forest environments appear to be reduced satellite visibility associated with canopy closure, signal attenuation, and multipath propagation. Although multi-constellation systems, multi-frequency receivers, RTK corrections, and multipath-mitigating antenna designs can improve performance, physical signal obstruction persists under dense canopy. Therefore, GNSS performance should not be

evaluated solely on the basis of horizontal positioning error; signal quality, the number of available satellites, carrier-phase ambiguity resolution, fixed/float solution continuity, and sky visibility should also be considered. Nevertheless, because the physical obstruction and multipath effects caused by dense forest canopy persist, these approaches cannot be considered to completely eliminate environmental effects. In addition, short-duration smartphone-based GNSS measurements have been reported to have limited accuracy under tree canopy, while post-processing can only partially mitigate this limitation (Tomašík & Varga, 2021).

It has been suggested that GNSS signal degradation can be evaluated not only as a source of positioning error but also as an environmental observation source containing information about forest structure (Guerriero et al., 2020).

3. Effects of GNSS Signal Characteristics and Measurement Parameters on Positioning Accuracy

GNSS positioning accuracy depends not only on the environment in which measurements are conducted but also on the satellite system used, signal frequency, satellite geometry, signal quality, and observation design. In forest environments, these variables should be evaluated in conjunction with environmental effects such as canopy closure and multipath propagation. Therefore, explaining the accuracy of a GNSS solution requires more than considering only the nominal technical specifications of the receiver or the total number of available satellites; the quality of satellite signals, their geometric distribution, observation duration, and the positioning method employed should be considered collectively.

GNSS Systems

Global Navigation Satellite Systems consist of different satellite constellations and enable receivers to simultaneously use signals from multiple constellations. Measurements have been conducted under both open-sky and forest-canopy conditions, and signal quality, the number of satellites, positioning accuracy, and carrier-phase ambiguity resolution have been compared. Although the combined use of GPS and GLONASS can increase the number of available satellites and geometric diversity, this contribution may remain limited under dense canopy due to signal attenuation and reflection (Blum et al., 2016). GNSS signal quality may decrease under forest canopy compared with open-sky conditions, while satellite visibility may be reduced and the positioning solution may become less stable. The multi-constellation approach can improve the number of available satellites and satellite geometry under open-sky conditions. However, under forest canopy, an increase in the number of satellites alone does not guarantee the expected improvement in positioning accuracy if signal quality is insufficient (Blum et al., 2016).

The frequency characteristics of GNSS signals are important for modeling ionospheric delays, carrier-phase ambiguity resolution, and reducing error components in measurements. However, although multi-frequency observations can mitigate atmospheric and some measurement-related errors, they cannot completely eliminate physical signal obstruction caused by tree trunks, branches, and leaves. Therefore, the number of frequencies should be evaluated together with the environmental conditions that determine GNSS performance in forest environments (Cole et al., 2020). The study by Munoz-Martin et al. (2022), which considered L1 and L5 frequencies together, investigated vegetation height estimation using airborne GNSS reflectometry (GNSS-R). The objective of the study was not to assess conventional GNSS positioning accuracy but to derive information on canopy height from reflections of L1 and L5 signals. Therefore, the study supports the applicability of L1 and L5 for GNSS-R-based environmental remote sensing; however, it does not directly demonstrate that L5 provides higher positioning accuracy than L1 in conventional positioning applications (Munoz-Martin et al., 2022).

One of the important developments in GNSS technology has been the transition from single-frequency to multi-frequency receivers. In particular, the L5 signal, owing to its higher transmission power, wider bandwidth, and advanced signal design, offers greater resistance to multipath effects and noise compared with the L1 signal. Therefore, multi-frequency GNSS receivers provide important advantages in reducing ionospheric errors and obtaining more reliable positioning solutions (Uradziński & Bakula, 2023).

A study investigating the use of multi-frequency GNSS under dense tree canopy reported that multi-frequency solutions can improve positioning accuracy compared with single-frequency solutions; however, signal attenuation and multipath effects caused by the canopy persisted (Cole et al., 2020). This finding indicates that multi-frequency observations can provide a useful improvement in forest environments but cannot, by themselves, eliminate the effects of environmental obstruction.

The use of multiple constellations can contribute to improved satellite geometry by providing access to a greater number of satellites simultaneously. In the forest study using GPS and GLONASS together, this approach increased the number of available satellites; however, the resulting accuracy gain remained limited when signal quality decreased under canopy (Blum et al., 2016). Accordingly, multi-constellation positioning represents a useful supporting capability in forest environments but is not, by itself, a solution to signal attenuation and multipath effects.

In interpreting GNSS measurement results, the number of satellites, satellite geometry, signal-to-noise ratio, mask angle, and observation duration are fundamental parameters. These parameters are not independent of one another. For example, an increase in the number of satellites does not always imply an improvement in positioning accuracy; the distribution of satellites across the sky and signal quality also determine the reliability of the positioning solution. Forest canopy can limit satellite visibility and thereby reduce the number of available satellites. The study using GPS and GLONASS together demonstrated that although multi-constellation positioning increased the number of available satellites, signal quality could remain low under dense canopy conditions (Blum et al., 2016). Therefore, the number of satellites is not a sufficient indicator of positioning accuracy on its own and should be evaluated together with signal strength and satellite geometry.

A study aimed at predicting GPS accuracy in dense forests jointly considered canopy density, sky visibility, signal strength, and geometric variables such as PDOP. This approach demonstrates that GNSS performance can be predicted using environmental and geometric indicators prior to measurement planning (Moore et al., 2023).

PDOP, HDOP, and VDOP are geometric indicators representing the effects of satellite geometry on three-dimensional, horizontal, and vertical positioning solutions, respectively. PDOP has been reported to be used for predicting positioning accuracy in dense forests. However, PDOP alone is not considered sufficient; it should be evaluated together with canopy density and signal quality (Moore et al., 2023).

Signal-to-noise ratio and overall signal quality are important observation indicators for evaluating the effects of forest canopy on GNSS measurements. Because canopy can attenuate signals and generate reflected signals, a decrease in SNR may be accompanied by degradation in carrier-phase ambiguity resolution and positioning continuity. The study by Guerriero et al. (2020) demonstrated that GNSS signal characteristics, such as signal strength, signal loss, multipath, and satellite visibility, can carry information about canopy structure.

Observation duration is important for the stability of the positioning solution, particularly in static and short-duration measurements. A study investigating raw GNSS data obtained from smartphones using short-duration static measurements reported that short observation periods limited positioning accuracy under tree canopy. Although post-processing could improve performance, limitations associated with the device antenna and observation duration persisted (Tomašík & Varga, 2021). This finding demonstrates that observation duration cannot be evaluated independently of receiver type and environmental conditions.

The GNSS positioning method determines how raw observations are collected, corrected, and converted into coordinates. Static, rapid-static, RTK, PPP, and DGPS/SBAS methods differ in terms of accuracy, solution continuity, and field operational requirements. In static surveying, the receiver is kept stationary at a specific point, and observations are collected over a defined period. The smartphone-based study investigated short-duration static measurements and reported that they can provide limited positioning accuracy under tree canopy (Tomašík & Varga, 2021). In the study by Romero et al. (2025), static GNSS observations, RINEX data recording, and CORS-based post-processing procedures were used for GNSS–LiDAR accuracy assessment.

The RTK method aims to provide high-accuracy positioning using real-time correction information. A study investigating the RTK performance of low-cost GNSS receivers in forest environments reported that, although high accuracy was achieved in open areas, the continuity of the fixed solution deteriorated under forest canopy and the solution could transition to a float status (Mahato et al., 2020). This finding demonstrates that although RTK is useful in forest environments, positioning accuracy cannot be guaranteed because of canopy-induced signal attenuation and multipath effects.

Romero et al. (2025) used RTK and static GNSS methods together with total station references and CORS-based corrections for GNSS measurements. However, because the study was conducted under open-sky conditions in a small study area, it should not be considered direct evidence of RTK performance under forest canopy.

PPP is a positioning method that generates a position solution using precise satellite orbit and clock products without directly relying on a base station. PPP has been considered particularly in the context of UAV and GNSS/INS/LiDAR integration. Pilarska et al. (2016) discussed GNSS, INS, and LiDAR components in UAV laser scanning systems together with GNSS processing approaches such as DGPS, RTK, and PPP.

DGPS aims to improve positioning accuracy through corrections provided by reference stations. In the study by Romero et al. (2025), static GNSS data were processed using differential corrections based on CORS stations, and the resulting coordinates were compared with reference measurements. Such corrections may contribute to reducing atmospheric- and orbit-related error components; however, they are not expected to completely eliminate signal obstruction and multipath effects caused by forest canopy.

The findings demonstrate that GNSS positioning accuracy results from the interaction among the satellite system, frequency characteristics, satellite geometry, signal quality, observation duration, and positioning method. Multi-constellation positioning can increase the number of

available satellites and the range of geometric configurations; multi-frequency observations can contribute to reducing certain error components; and RTK, static, and differential correction methods can improve positioning accuracy under suitable conditions. However, in forest environments, canopy-induced signal attenuation and multipath effects can limit these technical benefits. Therefore, when evaluating GNSS performance in forested areas, it is important not to report only the receiver or positioning method used; the constellations and frequencies employed, number of satellites, PDOP and signal quality, observation duration, solution type, and correction method should be reported collectively.

4. Comparative Evaluation of the Studies

The studies demonstrate that GNSS accuracy in forest environments cannot be explained by a single technical characteristic. The direct comparison between forest-canopy and open-sky conditions reveals the effects of canopy on signal quality, satellite visibility, and carrier-phase ambiguity resolution. The low-cost RTK study, in turn, demonstrates that this environmental effect is reflected not only in positioning error but also in the continuity of the solution type. When these two studies are considered together, GNSS reliability under forest canopy should be characterized not only by the magnitude of the average error but also by the rate at which the fixed solution is maintained and by measurement continuity (Blum et al., 2016; Mahato et al., 2020).

The measurement platform and observation duration are also important components of the comparison. The smartphone-based study demonstrates that short-duration static measurements can provide limited accuracy under tree canopy. This finding indicates that, under the same environmental conditions, the receiver antenna and observation duration can influence measurement performance (Tomaščík & Varga, 2021).

Comparisons of frequency and satellite constellations demonstrate that technological improvements should be evaluated together with environmental effects. Although the multi-frequency GNSS study reported improvements compared with single-frequency solutions, signal attenuation and multipath effects caused by the canopy were not completely eliminated. Similarly, the combined use of GPS and GLONASS increased the number of available satellite options; however, this advantage remained limited under forest conditions where signal quality was low (Blum et al., 2016; Cole et al., 2020).

Some studies focus on environmental indicators that explain GNSS performance rather than directly measuring positioning errors. The study by Wright et al. (2017) used the Sky View Factor to predict GPS signal loss, whereas Moore et al. (2023) jointly modeled canopy density, sky visibility, PDOP, and signal strength. These studies demonstrate that GNSS performance

is not merely an outcome to be evaluated after measurements have been conducted but can also be predicted prior to measurement using environmental and geometric variables.

Table 1. Comparative Synthesis of the Reviewed Literature

Paper	Forest Type / Environment	GNSS	Survey Method	Key Findings
Blum et al. (2016)	Black Forest; under-canopy and open-sky conditions	GPS + GLONASS	Open-sky–canopy comparison; choke-ring antenna; assessment of signal quality, number of satellites, and carrier-phase ambiguity resolution	Signal quality and positioning accuracy decreased under canopy. Multi-constellation positioning provided some benefits; however, it did not eliminate signal attenuation and multipath effects.
Mahato et al. (2020)	Forested area; dense canopy	Low-cost GNSS receiver; RTK	Open-sky–under-canopy comparison; fixed/float solution rate; positioning error	Fixed-solution continuity deteriorated under forest canopy, while float solutions and positioning errors increased.
Tomašík & Varga (2021)	Under tree canopy and open-sky conditions	Raw GNSS data from a smartphone	Short-duration static measurements; raw-data post-processing	Short observation duration, lower-quality antenna characteristics, and canopy effects jointly limited performance. Post-processing provided improvements but did not completely resolve the limitations.
Cole et al. (2020)	Dense tree canopy	Single- and multi-frequency GNSS; summarized as L1/L2/L5	Single-frequency–multi-frequency comparison; assessment of signal quality, carrier-phase ambiguity resolution, and positioning error	Multi-frequency observations improved positioning accuracy; however, canopy-induced signal attenuation and multipath effects persisted.
Wright et al. (2017)	Natural deciduous forest; leaf-on/leaf-off conditions	GPS	Comparison of hemispherical photographs, Sky View Factor, and GPS signal data	Sky visibility was identified as a useful indicator for estimating canopy effects and GPS signal loss.
Moore et al. (2023)	Dense forest	GPS	Modeling using canopy density, sky visibility, PDOP, and signal strength	GPS accuracy could be predicted in advance using environmental and geometric variables; canopy density was reported as one of the dominant explanatory variables.
Qian et al. (2016)	Forested area; forest stem mapping	GNSS/INS/LiDAR-SLAM	Integration of GNSS, INS, and LiDAR-SLAM for forest stem mapping	LiDAR-SLAM and INS support were used to mitigate the effects of weak and intermittent GNSS signals under canopy.
Romero et al. (2025)	Open site; approximately 800 m ² training area; not a forest environment	CHCNAV i50 GNSS; RTK and static; CORS corrections	17 GCPs; total station reference; GNSS–LiDAR comparison	GNSS and LiDAR achieved sub-decimeter-level accuracy; however, the results are limited to open-site conditions and should not be directly generalized to forest canopy environments.

The role of sensor integration is particularly important in forest environments where GNSS alone may be insufficient. The GNSS/INS/LiDAR-SLAM approach supports positioning continuity by utilizing LiDAR and INS data when GNSS signals are weakened or interrupted. This approach demonstrates that, when high positioning accuracy is targeted in forested areas,

the integration of GNSS with complementary sensors should also be considered rather than relying solely on efforts to obtain stronger GNSS signals (Qian et al., 2016).

The centimeter-level GNSS RMS values reported in the study by Romero et al. (2025) provide a methodological reference for the accuracy that modern GNSS systems can achieve under suitable open-sky and controlled measurement conditions. However, these values should not be directly compared with those obtained from forest studies because the study was conducted in a small and open training area, and canopy-induced signal attenuation and multipath conditions were not tested.

GNSS accuracy in forest environments is determined by the combined effects of canopy structure, signal quality, satellite geometry, receiver characteristics, observation duration, and positioning method. Techniques such as multi-constellation and multi-frequency receivers, RTK, and post-processing can improve performance; however, their effectiveness may be limited by forest canopy density and multipath conditions.

5. Future Research Trends and Conclusion

The studies reviewed on GNSS positioning accuracy in forested areas demonstrate that existing methods have achieved significant improvements; however, challenges associated with dense canopy, signal attenuation, multipath, and solution continuity have not been completely eliminated. Future research should focus not only on identifying receivers that provide higher accuracy but also on integrated approaches that jointly consider environmental conditions, signal characteristics, measurement parameters, and complementary sensors.

The accuracy metrics and experimental conditions used in different studies vary considerably. While some studies directly evaluate positioning error or RMSE, others focus on signal quality, sky visibility, satellite geometry, or fixed/float solution continuity. This situation makes direct numerical comparisons among studies difficult. In future research, the use of standardized measurement protocols across different forest types and canopy densities would be beneficial for standardizing observation duration, satellite constellation, frequency combinations, and error metrics.

Multi-frequency GNSS receivers represent an important research direction in terms of modeling ionospheric delays and improving carrier-phase ambiguity resolution. It has been reported that multi-frequency GNSS can improve positioning accuracy compared with single-frequency solutions under dense tree canopy; however, canopy-induced signal attenuation and multipath effects persist (Cole et al., 2020). Therefore, future studies should focus not only on increasing the number of frequencies but also on how different frequencies perform under varying canopy densities and signal quality conditions.

The study using L1 and L5 frequencies within a GNSS-R approach demonstrates that frequency information can also be utilized in environmental remote sensing applications beyond conventional positioning. However, this study addresses canopy height estimation rather than conventional GNSS positioning accuracy; therefore, the superiority of L5 for positioning within forest environments should be tested separately and directly (Munoz-Martin et al., 2022). In future research, controlled experiments comparing L1, L2, and L5 under the same receiver and field conditions could provide a clearer understanding of the effects of frequency selection on positioning accuracy and solution continuity.

However, the study using GPS and GLONASS together demonstrated that an increase in the number of satellites alone is insufficient when signal quality is low (Blum et al., 2016). Therefore, future studies should evaluate integrated GPS, GLONASS, Galileo, and BeiDou systems in conjunction with the number of satellites, PDOP, SNR, multipath, and the fixed-solution rate.

Machine learning studies aimed at mitigating multipath and NLOS errors have demonstrated that erroneous or unreliable observations can be identified using signal characteristics and that positioning solutions can consequently be improved. However, a substantial proportion of these studies has focused on urban canyon environments, while their applicability in forest environments has been investigated to a more limited extent (Xu et al., 2024).

For AI-assisted positioning enhancement in forest environments, environment-specific datasets are needed in which variables such as canopy density, sky visibility, SNR, satellite elevation, azimuth, PDOP, observation duration, and solution type are considered jointly. Rather than training future models using data from a single forest, these models should be tested across different tree species, seasons, canopy densities, and receiver types. In addition, model performance should be evaluated not only in terms of mean positioning error but also according to the fixed-solution rate, solution continuity, generalization capability, and real-time processing capacity.

When GNSS signals are weakened or interrupted in forest environments, LiDAR and INS data can support the positioning solution. Qian et al. (2016) presented an integrated approach for mapping forest stems by combining GNSS/INS/LiDAR-SLAM components. This approach demonstrates that, under canopy conditions where GNSS alone is not sufficiently reliable, LiDAR can contribute geometric information, while INS can provide short-term motion information, thereby supporting positioning continuity (Qian et al., 2016).

Romero et al. (2025) demonstrated that GNSS and UAV-LiDAR data can be compared with total station references; however, the study was conducted under open-sky conditions.

Therefore, future research should evaluate LiDAR–GNSS integration in dense forests by jointly considering the visibility of ground points beneath the canopy, GNSS/IMU trajectory accuracy, and LiDAR point-cloud alignment (Romero et al., 2025). In addition, the contribution of integration should be reported separately for different applications, such as forest stem mapping, canopy height estimation, and ground model generation.

Low-cost GNSS receivers have the potential to increase accessibility and portability in field surveys. However, the study investigating RTK performance in forest environments demonstrated that, although low-cost receivers can provide high accuracy in open areas, they may have difficulty maintaining fixed-solution continuity under canopy and may be more susceptible to multipath effects (Mahato et al., 2020). In future studies, low-cost receivers should be compared with professional receivers not only in terms of open-sky accuracy but also across different canopy densities, considering SNR, number of satellites, fixed/float ratio, observation duration, energy consumption, and data-processing requirements. The smartphone-based study also demonstrated the importance of short observation duration and antenna limitations in low-cost platforms (Tomaščík & Varga, 2021). Therefore, the applicability of low-cost systems in forested areas should be determined by jointly evaluating accuracy and reliability components rather than relying on a single RMSE value.

The reviewed studies demonstrate that GNSS positioning accuracy in forested areas is determined by the interaction among canopy density, sky visibility, signal attenuation, multipath, satellite geometry, observation duration, receiver characteristics, and positioning method. Multi-constellation and multi-frequency GNSS can increase the range of available satellites and the capacity for error modeling, while RTK, static surveying, and differential correction methods can improve positioning accuracy under suitable conditions. However, these techniques do not completely eliminate the physical signal obstruction and reflection-related errors caused by dense forest canopy.

Future research should employ common and standardized measurement protocols, compare different GNSS constellations, frequencies, and positioning methods under the same forest conditions, and incorporate environmental variables such as canopy density, LAI, season, and topography into the measurement design. Artificial intelligence, LiDAR–GNSS–INS integration, and low-cost receivers represent promising directions for improving GNSS performance; however, the effectiveness of these approaches should be independently validated under different forest conditions.

In conclusion, reliable GNSS positioning in forested areas is not a simple problem that can be addressed using a single receiver or a single correction technique. The most appropriate

approach involves measuring environmental conditions, monitoring signal characteristics and satellite geometry, selecting observation parameters according to the intended application, and, when necessary, integrating GNSS with LiDAR, INS, or artificial intelligence-based methods. Such a framework would enable not only improvements in positioning accuracy but also a comprehensive assessment of measurement reliability and applicability in forestry applications.

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CHAPTER 4

TECHNICAL AND ECONOMIC ANALYSIS OF CONVERSION TO ENERGY-EFFICIENT LUMINAIRES IN AN EDUCATIONAL BUILDING

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1. INTRODUCTION

Meeting the increasing energy demand largely from fossil sources leads to a rise in greenhouse gas emissions and to problems related to the security of energy supply. For this reason, the efficient use of energy is among the priority issues both in national energy policies and in building-scale applications. It is stated that buildings constitute a significant part of the final energy consumption in developed countries and that the consumption trends in the building sector are effective in shaping energy policies (Pérez-Lombard et al., 2008). Within the energy consumed in buildings, lighting has a considerable share, especially in commercial and public buildings. It has been reported that the share of lighting in the energy consumption of commercial buildings is 25% in the United States of America, while this share is at the level of 14% in the commercial sector of the European Union (Halonen et al., 2010). In Türkiye, it is stated that approximately 20% of the total electricity consumption is used for lighting purposes (Demir et al., 2020). In an evaluation carried out for a sample public building in different degree-day regions of Türkiye, it was determined that the improvements made in the building envelope significantly reduced the heating energy demand (Kavun, 2026).

In Türkiye, the legal framework for energy efficiency was established with the Energy Efficiency Law No. 5627 (Energy Efficiency Law No. 5627, 2007). With the Regulation on Energy Performance in Buildings, which was prepared based on this law, the procedures related to the evaluation of the energy performance of lighting systems in buildings were determined (Regulation on Energy Performance in Buildings, 2008). The Regulation on Increasing Efficiency in the Use of Energy Resources and Energy, on the other hand, regulates the procedures and principles regarding energy audits, energy management practices and the preparation and support of efficiency improvement projects (Regulation on Increasing Efficiency in the Use of Energy Resources and Energy, 2011). Efficiency improvement projects prepared within this scope enable the evaluation of the savings potential determined on the basis of measurements in an existing system from technical and economic perspectives.

Energy efficiency in lighting systems does not depend only on the efficacy of the light source, it is considered as a quantity that should be evaluated together with the installed power density, luminaire efficiency and control strategies (Ryckaert et al., 2010). It is stated that LED technology has started to replace fluorescent and incandescent light sources in general lighting due to its high luminous efficacy and long lifetime (Pimputkar et al., 2009). It has been reported that a significant reduction in lighting energy can be achieved when efficient light sources are

applied together with daylight-dependent and occupancy-dependent control systems (Dubois & Blomsterberg, 2011; Halonen et al., 2010).

In the literature, there are various studies on the replacement of fluorescent lighting systems with LED lighting systems in educational and public buildings. Gan et al. (2013) compared the electrical and photometric performances of fluorescent lamps and LED tubes in a faculty building of a university in Malaysia. In the study, different lighting energy saving strategies were also evaluated from an economic point of view. As a result of the study, the authors stated that LED tubes have a high potential to replace fluorescent lamps, especially due to the cost savings they provide. Ghisi et al. (2019) investigated the electricity saving potential of replacing fluorescent lamps with LEDs in the classrooms of the Federal University of Santa Catarina in Brazil. In the study, it was determined that daytime lighting conditions were adequate in 65% of the classrooms, while adequate lighting could not be provided in any classroom under night conditions. The authors found that the installed power was reduced by 45.5% with the LED lighting system designed using the DIALux software and that the investment paid back in 8.6 years. Hussin et al. (2021) evaluated the use of T8 type LED tubes in an academic building in Malaysia within the scope of the national energy efficiency action plan. As a result of the study, the authors determined that the power factor of LED tubes was higher than that of fluorescent lamps, that approximately 50% energy savings were achieved in indoor lighting and that the investment paid back within six months.

Various studies on the subject have also been carried out in Türkiye. Yılmaz and Sungur (2020) investigated the energy efficiency of lighting elements used in public buildings on a pilot building. In the study, it was determined that replacing the existing 40 W lighting elements with 24 W LED luminaires provided an approximately 40% reduction in annual electricity consumption. Demir et al. (2020) evaluated the energy efficiency in lighting in the building of the Faculty of Engineering of Yalova University. As a result of the study, the authors revealed that approximately 1.95 million TL savings could be achieved over the economic lifetime by replacing the existing luminaires with LED luminaires. Bayram et al. (2020) carried out illuminance measurements with a luxmeter between 2015 and 2017 in 14 indoor spaces, including classrooms, a conference hall, a computer laboratory and corridors, in the building of the Department of Civil Engineering of Ege University. In the study, the measurement results obtained under natural, artificial and combined lighting conditions were compared with the TS EN 12464-1 standard, and suggestions were presented for eliminating the identified deficiencies.

In this study, the conversion of the existing fluorescent lighting system into an LED lighting system in an educational building belonging to Osmaniye Korkut Ata University was investigated from technical and economic perspectives. Within the scope of the study, firstly the condition of the existing lighting system was determined by on-site illuminance measurements in the building, and then the illuminance levels after the conversion were calculated with the lumen method and DIALux simulation. Finally, the conversion was evaluated in terms of energy savings, simple payback period and net present value. The economic analysis was carried out based on the current electricity unit price and exchange rate. It is aimed that the study will provide a reference for researchers and practitioners in studies on improving the lighting systems of public educational buildings.

2. MATERIAL AND METHOD

2.1. Study Area and Existing Lighting System

The study was carried out in an educational building located in the province of Osmaniye. The building, which has a total usage area of 4,500 m², consists of classrooms, administrative offices, a conference hall, an entrance hall, corridors and wet areas. Only daytime education is carried out in the building and there is no evening education. The architectural plan of the basement floor of the building is given in Figure 1.

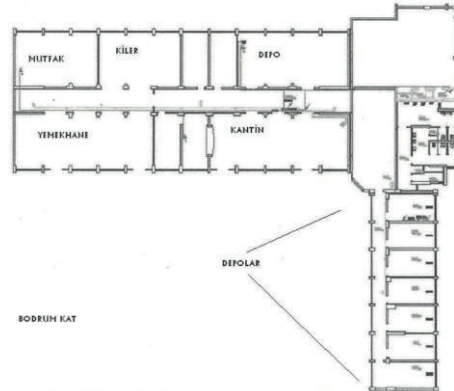


Figure 1. Basement floor plan of the educational building

As a result of the inspection carried out in the general use areas of the building, it was determined that the existing lighting system consists of 199 T8 fluorescent luminaires with a power of 4×18 W and light colour code 840 (colour temperature of 4000 K, Ra ≥ 80), and 50 lamps of 21 W used in the wet areas. The distribution of the existing lighting system according to the spaces and its installed power are given in Table 1.

Table 1. Distribution of the existing lighting system according to spaces and installed power

Space	Lighting element	Quantity	Unit power (W)	Installed power (W)
Conference hall	4×18 W T8 fluorescent luminaire	50	72	3,600
Corridors	4×18 W T8 fluorescent luminaire	51	72	3,672
Classrooms (8 units)	4×18 W T8 fluorescent luminaire	72	72	5,184
Administrative offices (8 units)	4×18 W T8 fluorescent luminaire	16	72	1,152
Entrance hall	4×18 W T8 fluorescent luminaire	10	72	720
Wet areas	21 W lamp	50	21	1,050
Total		249		15,378

In the calculation of the installed power, the lamp powers of the fluorescent luminaires were taken as the basis and the ballast losses were not included in the calculation. Since the consumption of the existing system and accordingly the amount of savings are calculated lower than they actually are with this approach, the results obtained were evaluated as conservative values. Considering that the building, in which daytime education is carried out, is used 9 hours a day and 230 days a year, the annual operating time of the lighting system was taken as $9 \text{ h/day} \times 230 \text{ days/year} = 2,070 \text{ h/year}$.

2.2. Illuminance Measurements

In order to determine the performance of the existing lighting system, illuminance measurements were carried out in the spaces with a Testo 435 model measuring device. The measurements were made between 14:00 and 16:00 while the artificial lighting system was on. The measurements were carried out in two classrooms, one administrative office, the lower corridor and the corridor. The number of measurement points was determined according to the size of the spaces; measurements were taken at 15 points in the classrooms and the administrative office, at 25 points in the lower corridor and at 40 points in the corridor. The measurement points were selected to represent the edge and middle regions of the spaces. The images of the measurement studies are given in Figure 2.



Figure 2. Images of the illuminance measurements carried out in the classrooms and corridors

Simultaneously with the measurements, the general condition of the corridors was recorded with visible and thermal images. The thermal images were obtained with a Testo 881 model thermal camera, and the visible and thermal images of the corridors are presented in Figure 3.



Figure 3. Visible and thermal images of the corridors

For each space, the average (E_{ave}), minimum (E_{min}) and maximum (E_{max}) illuminance values were determined, and the uniformity ratio was calculated with Equation (1) in order to express the distribution of illuminance within the space (European Committee for Standardization, 2021).

$$U_o = E_{min} / E_{ave} \quad (1)$$

2.3. LED Conversion and Lighting Calculation

In the conversion, it was planned to replace the existing 199 fluorescent luminaires with 199 LED luminaires at the same positions, and to replace the 50 lamps of 21 W in the wet areas with 10 W LED lamps by keeping the existing lamp holders. The technical specifications of the LED luminaire used in the application are given in Table 2.

Table 2. Technical specifications of the LED luminaire

Specification	Value
Luminaire type	Surface-mounted waterproof LED luminaire
Power consumption	28 W
Luminaire luminous flux	3,674.8 lm
Luminaire efficacy	130.9 lm/W
Colour temperature / Colour rendering index	4000 K / Ra > 80
Power factor	> 0.9
Protection class	IP65
LED lifetime (L70)	> 72,000 hours

The average illuminance to be obtained in the spaces after the conversion was calculated with the lumen (utilization factor) method. In this method, the room index (k), which represents the geometry of the space, was determined with Equation (2) (Özkaya, 1994).

$$k = (a \cdot b) / [h \cdot (a + b)] \quad (2)$$

In the equation, a and b represent the width and length of the space (m), respectively, and h represents the height between the luminaire and the working plane (m). The height of the spaces is 3.5 m and the luminaires were considered to be mounted on the ceiling. The working plane was taken at a height of 0.85 m above the floor ($h = 2.65$ m) in the classrooms,

administrative offices and conference hall, and at floor level ($h = 3.50$ m) in the entrance hall and corridors. The reflectance values of the ceiling, walls and floor were determined as 0.80, 0.50 and 0.30, respectively, and the utilization factor (η) values corresponding to these reflectances were obtained from Table 3 by linear interpolation. For the administrative office, in which the room index remains below the range of the table, the utilization factor was determined by linear extrapolation using the first two values of the table.

Table 3. Utilization factor values for ceiling/wall/floor reflectances of 0.80/0.50/0.30

k	0.60	0.80	1.00	1.25	1.50	2.00	2.50	3.00	4.00	5.00
η	0.24	0.31	0.36	0.41	0.45	0.51	0.56	0.59	0.63	0.66

The average illuminance to be obtained in the space (E_h) was calculated with Equation (3) (Özkaya, 1994).

$$E_h = (N \cdot \Phi \cdot \eta) / (a \cdot b \cdot d) \quad (3)$$

Here, N represents the number of luminaires in the space, Φ the luminous flux of the luminaire (lm) and d the depreciation factor of the installation. The depreciation factor was taken as 1.25 (maintenance factor of 0.80). The calculated illuminance values were compared with the maintained illuminance values given for the relevant spaces in the EN 12464-1 standard. In the standard, maintained illuminance values of 300 lx for classrooms, 500 lx for offices in which reading and writing tasks are performed and for lecture halls, 200 lx for entrance halls and 100 lx for corridors and circulation areas are defined (European Committee for Standardization, 2021). Since only daytime education is carried out in the building, the value of 300 lx was taken as the basis for the classrooms, while the value defined for lecture halls was applied for the conference hall. The dimensions of the spaces and the required illuminance values are given in Table 4.

Table 4. Dimensions of the spaces, number of spaces and required illuminance values

Space	a (m)	b (m)	Number of spaces	Luminaires per space	h (m)	Required E (lx)
Administrative office	2.5	2.0	8	2	2.65	500
Entrance hall	9.0	15.0	1	10	3.50	200
Conference hall	20.0	20.0	1	50	2.65	500
Classroom	6.0	10.0	8	9	2.65	300
Corridor	8.0	40.0	1	51	3.50	100

2.4. Luminaire Layout and Lighting Simulation

In order to determine the effect of the luminaire layout after the conversion on the illuminance distribution within the space, a simulation was carried out for the classroom with the DIALux lighting calculation software. In the simulation, the existing luminaire positions in the classroom with dimensions of 6.0 m × 10.0 m were taken as the basis; 9 LED luminaires were placed in 3 rows with 3 luminaires in each row, with their long axes parallel to the long side of the classroom. In this way, the illuminance distribution to be obtained without any change in the number and positions of the luminaires in the conversion was determined. The simulation results were obtained at a scale of 1:75 in the form of iso-illuminance curves and illuminance distribution together with the luminaire layout. Similarly, Ghisi et al. (2019) used the DIALux software in the redesign of classroom lighting for LED conversion.

2.5. Energy Consumption and Savings Calculation

The annual energy consumption for the existing and converted lighting systems was calculated with Equation (4).

$$E_{year} = P_i \cdot t_o / 1000 \quad (4)$$

In the equation, E_{year} represents the annual energy consumption (kWh/year), P_i the total installed power (W) and t_o the annual operating time (h/year). The annual energy saving (ΔE) was determined as the difference between the annual consumptions of the existing and converted systems. The tonne of oil equivalent (TOE) of the energy saving was calculated with the conversion factor of 0.086 TOE/MWh based on the equivalence of 1 TOE = 11.63 MWh.

2.6. Economic Analysis

In the economic analysis, the electricity unit price was taken as 4.80 TL/kWh. As the exchange rate, the indicative US dollar selling rate (49.2353 TL/\$) announced by the Central Bank of the Republic of Türkiye on 6 October 2026 was applied (Central Bank of the Republic of Türkiye, 2026). The unit price of the LED luminaire was evaluated as 30 \$ according to the price offer received from the company, and the unit price of the LED lamp was evaluated as 16.95 \$. All prices exclude VAT, and the installation labour was not included in the investment cost.

The annual benefit (S) was defined as the reduction in the annual electricity cost, and the simple payback period (SPP) was calculated with Equation (5) (Blank & Tarquin, 2012; Demir et al., 2020).

$$SPP = I / S \quad (5)$$

Here, I represents the total investment cost (TL). The net present value (NPV) of the investment was calculated with Equation (6) and Equation (7) by subtracting the investment cost from the present value of the annual benefits (Blank & Tarquin, 2012).

$$F = S \cdot [(1 + i)^n - 1] / [i \cdot (1 + i)^n] \quad (6)$$

$$NPV = F - I \quad (7)$$

In the equations, F represents the present value of the benefits (TL), i the discount rate and n the analysis period (year). The expression $[(1 + i)^n - 1] / [i \cdot (1 + i)^n]$ in Equation (6) represents the present worth factor (PWF). The discount rate was taken as 10% (real interest rate) and the analysis period as 10 years.

3. RESULTS AND DISCUSSION

3.1. Illuminance Measurement Results

In this part of the study, the measurement results of the existing lighting system were evaluated first. The illuminance values obtained at the measurement points in the spaces are given in Table 5, and the statistical values of these measurements are given in Table 6.

Table 5. Illuminance values according to the measurement points in the spaces (lx)

Point	Classroom 1	Classroom 2	Adm. office	Lower corridor	Corridor	Point	Lower corridor	Corridor
1	184	165	397	10	63	21	21	102
2	194	179	389	8	73	22	13	81
3	202	241	371	7	72	23	7	44
4	216	259	281	8	33	24	5	23
5	227	191	165	11	22	25	4	32
6	264	141	98	16	14	26	–	58
7	298	153	86	18	23	27	–	75
8	327	176	78	11	43	28	–	94
9	331	205	79	13	71	29	–	99
10	336	227	74	15	77	30	–	83
11	311	209	83	22	69	31	–	60
12	301	174	95	29	32	32	–	50
13	266	164	103	35	23	33	–	42
14	211	163	140	43	18	34	–	62
15	201	148	214	52	33	35	–	118
16	–	–	–	61	61	36	–	140
17	–	–	–	43	89	37	–	125
18	–	–	–	38	93	38	–	156
19	–	–	–	34	76	39	–	186
20	–	–	–	29	96	40	–	246

Table 6. Statistical values of the illuminance measurements

Space	Number of points	E_{min} (lx)	E_{max} (lx)	E_{ave} (lx)	U_o	Required E (lx)
Classroom 1	15	184	336	257.9	0.71	300
Classroom 2	15	141	259	186.3	0.76	300
Administrative office	15	74	397	176.9	0.42	500
Lower corridor	25	4	61	22.1	0.18	100
Corridor	40	14	246	73.9	0.19	100

In Classroom 1, the average illuminance was measured as 257.9 lx, and the value of 300 lx was reached only at 5 of the 15 measurement points. In Classroom 2, the average illuminance is 186.3 lx and the value of 300 lx could not be provided at any measurement point. The uniformity ratios in the classrooms were calculated as 0.71 and 0.76. The values measured in the administrative office vary between 74 and 397 lx, and the average illuminance and uniformity ratio were determined as 176.9 lx and 0.42, respectively. It was found that while

values above 370 lx were measured in one part of the office, the illuminance dropped below 100 lx in the other regions.

It was determined that the illuminance in the corridors is insufficient in terms of both the average value and the distribution. The average illuminance in the lower corridor is 22.1 lx and all measurement points remained below the value of 100 lx. The average illuminance in the corridor was measured as 73.9 lx, and the value of 100 lx was exceeded only at 7 of the 40 measurement points. It was found that the illuminance increased significantly at the last measurement points of the corridor and reached the value of 246 lx. It was determined that the uniformity ratio remained below 0.20 in both corridors and that the existing system does not provide a balanced lighting in the circulation areas. According to the measurement results, it was determined that the existing system operates below the required average illuminance values in all measured spaces. Similarly, Bayram et al. (2020) found lighting deficiencies in various spaces in the measurements they carried out in an educational building.

3.2. Illuminance Levels after the Conversion

The average illuminance values to be obtained in the spaces after the conversion with the lumen method are given in Table 7.

Table 7. Average illuminance values calculated in the spaces after the conversion

Space	k	η	Luminaires per space	Calculated E_h (lx)	Measured E_{ave} (lx)	Required E (lx)
Administrative office	0.42	0.177	2	208	176.9	500
Entrance hall	1.61	0.463	10	101	–	200
Conference hall	3.77	0.621	50	228	–	500
Classroom	1.42	0.436	9	192	186.3–257.9	300
Corridor	1.90	0.499	51	234	22.1–73.9	100

As an example of the calculation steps, the room index for the classroom was calculated with Equation (2), the utilization factor by linear interpolation from Table 3 and the average illuminance with Equation (3) as follows. The same steps were applied for the other spaces.

$$k = (6.0 \cdot 10.0) / [2.65 \cdot (6.0 + 10.0)] = 1.415 \approx 1.42$$

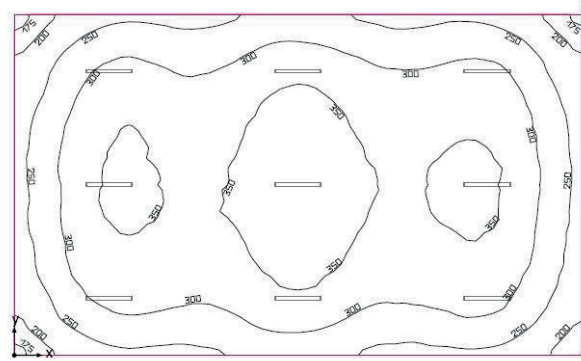
$$\eta = 0.41 + (1.415 - 1.25) \cdot (0.45 - 0.41) / (1.50 - 1.25) = 0.436$$

$$E_h = (9 \cdot 3,674.8 \cdot 0.436) / (6.0 \cdot 10.0 \cdot 1.25) = 192 \text{ lx}$$

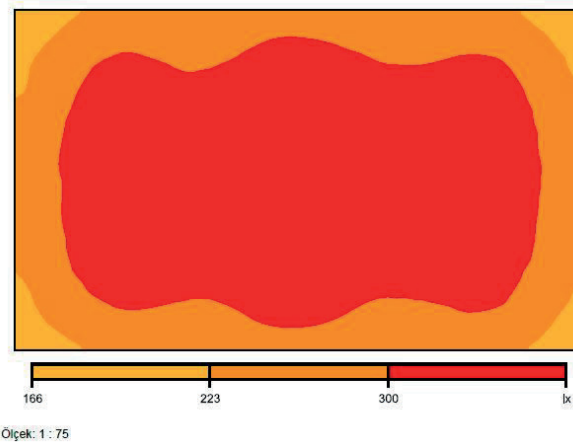
It was calculated that the average illuminance in the corridor increased to 234 lx after the conversion and that the required value of 100 lx was clearly exceeded. Considering the average values in the range of 22.1–73.9 lx measured in the corridors, it was evaluated that a significant improvement will be provided in the visual conditions of the circulation areas with the conversion. It was determined that the value of 208 lx calculated for the administrative office is above the measured average value. It was found that the value of 192 lx calculated for the classrooms is in the same order as the measured values. This value represents the maintained illuminance calculated by applying the maintenance factor, and the illuminance at the initial installation stage was calculated as approximately 240 lx. According to the lumen method, it was determined that the average illuminance values calculated for the classroom, administrative office, conference hall and entrance hall remain below the values given in the standard. Since the lumen method is an average approach based on generalized utilization factor values, the simulation results obtained by considering the luminaire layout for the classroom were also evaluated separately.

3.3. Luminaire Layout and Lighting Simulation Results for the Classroom

The luminaire layout and iso-illuminance curves created for the classroom are given in Figure 4a, and the illuminance distribution within the space is given in Figure 4b.



(a)



(b)

Figure 4. (a) Luminaire layout and iso-illuminance curves, (b) illuminance distribution created for the classroom (scale 1:75)

When Figure 4a is examined, it was determined that the iso-illuminance curves start from the value of 175 lx at the corners of the classroom and reach 250 lx in the regions parallel to the walls, 300 lx around the luminaire rows and 350 lx in the middle region. It was found that the highest illuminance values occur around the luminaires in the middle row and in the region between the luminaire rows. In the distribution given in Figure 4b, it was determined that an illuminance above 300 lx was obtained in most of the space, while values in the range of 223–300 lx occur in the peripheral region close to the walls and values in the range of 166–223 lx occur only in the corner regions.

According to the simulation results, it was determined that with the conversion carried out by keeping the existing luminaire positions, the value of 300 lx given in the standard is

provided in most of the usage area where the student desks are located in the classrooms. Considering that the value of 300 lx was reached at only 5 of the 15 points in Classroom 1 and at none of the points in Classroom 2 in the measurements, it was evaluated that the conversion will improve the visual conditions in the classrooms. It was evaluated that the values obtained by the simulation being higher than the value of 192 lx calculated with the lumen method results from the calculation of the space average with generalized utilization factor values and the maintenance factor of 0.80 in the lumen method, while the light distribution of the luminaire and the reflections between the room surfaces are taken into account point by point in the simulation. It was evaluated that the decrease to the level of 175–200 lx in the corner regions results from the distance between the luminaire rows and the walls, and that it would be appropriate to support these regions with local lighting in case visual task areas such as the lecturer desk or the board are located in these regions.

3.4. Energy Consumption and Savings Results

The installed power, annual energy consumption and annual energy cost values of the existing and converted lighting systems are given in Table 8.

Table 8. Energy consumption and savings values of the existing and converted systems

Parameter	Existing system	Converted system
Luminaire	199 × 72 W	199 × 28 W
Wet area lamp	50 × 21 W	50 × 10 W
Total installed power (W)	15,378	6,072
Annual energy consumption (kWh/year)	31,832.46	12,569.04
Annual energy cost (TL/year)	152,795.81	60,331.39
Annual energy saving (kWh/year)	19,263.42	
Saving rate (%)	60.5	
Annual energy saving (TOE/year)	1.66	
Annual energy cost saving (TL/year)	92,464.42	

In the calculations, firstly the total installed powers of the existing and converted systems were determined, and then the annual energy consumptions were calculated using Equation (4). The calculation steps are given below.

$$P_{i,existing} = 199 \cdot 72 + 50 \cdot 21 = 15,378 \text{ W}$$

$$E_{year,existing} = 15,378 \cdot 2,070 / 1000 = 31,832.46 \text{ kWh/year}$$

$$P_{i,LED} = 199 \cdot 28 + 50 \cdot 10 = 6,072 \text{ W}$$

$$E_{year,LED} = 6,072 \cdot 2,070 / 1000 = 12,569.04 \text{ kWh/year}$$

$$\Delta E = 31,832.46 - 12,569.04 = 19,263.42 \text{ kWh/year}$$

$$\Delta E_{TOE} = 19.263 \text{ MWh/year} \cdot 0.086 \text{ TOE/MWh} = 1.66 \text{ TOE/year}$$

$$S = 19,263.42 \text{ kWh/year} \cdot 4.80 \text{ TL/kWh} = 92,464.42 \text{ TL/year}$$

As a result of the calculations, it was determined that the total installed power of the existing lighting system is 15,378 W and its annual energy consumption is 31,832.46 kWh. It was calculated that after the conversion the installed power decreased to 6,072 W and the annual energy consumption decreased to 12,569.04 kWh. Therefore, it was determined that an annual energy saving of 19,263.42 kWh (60.5%) was achieved with the conversion and that this value corresponds to a primary energy saving of 1.66 TOE/year. It was found that with an electricity unit price of 4.80 TL/kWh, the annual energy cost decreased from 152,795.81 TL to 60,331.39 TL and an annual cost saving of 92,464.42 TL was obtained. It was determined that the obtained saving rate of 60.5% is higher than the saving rates at the level of 40–50% reported by Ghisi et al. (2019), Hussin et al. (2021) and Yılmaz and Sungur (2020). It was evaluated that this difference results from the high installed power per luminaire due to the four-lamp structure of the existing luminaires and from the high luminous efficacy of the LED luminaire used.

3.5. Economic Analysis Results

The investment cost, annual benefit and economic indicators of the conversion are given in Table 9.

Table 9. Economic analysis results of the conversion

Parameter	Value
LED luminaire investment ($199 \times 30 \$ \times 49.2353 \text{ TL}/\$$)	293,934.74 TL
LED lamp investment ($50 \times 16.95 \$ \times 49.2353 \text{ TL}/\$$)	41,726.92 TL
Total investment cost, I	335,661.66 TL
Annual benefit, S	92,464.42 TL/year
Simple payback period, SPP	3.63 years
Present value of benefits, F	568,156.88 TL
Net present value, NPV	232,495.22 TL

In the economic analysis, firstly the total investment cost was determined and the simple payback period was calculated with Equation (5). Then, the net present value of the investment was calculated using Equation (6) and Equation (7). The calculation steps are given below.

$$I = 199 \cdot 30 \cdot 49.2353 + 50 \cdot 16.95 \cdot 49.2353 = 293,934.74 + 41,726.92 = 335,661.66 \text{ TL}$$

$$SPP = 335,661.66 / 92,464.42 = 3.63 \text{ years}$$

$$PWF = [(1 + 0.10)^{10} - 1] / [0.10 \cdot (1 + 0.10)^{10}] = 6.1446$$

$$F = 92,464.42 \cdot 6.1446 = 568,156.88 \text{ TL}$$

$$NPV = 568,156.88 - 335,661.66 = 232,495.22 \text{ TL}$$

As a result of the calculations, it was determined that the total investment cost for the conversion is 335,661.66 TL and the simple payback period is 3.63 years. In the net present value calculation, the present value of the annual benefits for the analysis period of 10 years was calculated as 568,156.88 TL, and it was determined that the net present value of the investment is 232,495.22 TL. The distribution of the investment and benefits by years is given in Table 10.

Table 10. Distribution of the investment and benefits by years (TL)

Year	Investment	Energy cost saving (annual benefit)
0	335,661.66	–
1–10	–	92,464.42

It was determined that the obtained simple payback period is short when compared with the L70 lifetime of the LED luminaires exceeding 72,000 hours and the corresponding usage period of approximately 35 years. Considering that the net present value is positive, it was determined that the conversion is economically feasible under the conditions of a 10% discount rate and a 10-year analysis period. Since the ballast losses were not taken into account in the analysis, it was evaluated that the actual energy saving and the related economic indicators will be higher than the calculated values.

3.6. Discussion

According to the results obtained, it was determined that replacing the existing fluorescent luminaires with LED luminaires has a high energy saving potential in the investigated building. It was found that the electricity consumption caused by lighting decreased significantly with the 60.5% reduction of the installed power by the conversion. It was evaluated that the electricity unit price is the main parameter that directly determines the payback period of the investment.

On the other hand, it was determined from the illuminance calculations after the conversion that the luminaire layout should be rearranged in accordance with the requirements of the spaces. It was determined that while an illuminance higher than required was obtained in

the corridors, the values given in the standard could not be reached in the administrative office, conference hall and entrance hall. In the classrooms, according to the simulation results, it was found that the value of 300 lx was provided in most of the usage area, while the illuminance decreased below this value in the corner regions. It was evaluated that reducing the number of luminaires in the corridors and transferring them to the administrative offices and the conference hall will contribute to the improvement of the visual conditions without requiring an additional investment. In addition, it is stated in the literature that applying daylight-dependent control for the luminaire rows near the windows and occupancy-dependent control for the classrooms, wet areas and circulation areas can further reduce the lighting energy (Dubois & Blomsterberg, 2011; Halonen et al., 2010).

There are some limitations in the study. The illuminance measurements were carried out on a single day, the daylight contribution was not separated in the measured values, and no measurements were made in the entrance hall and conference hall. The point-by-point lighting simulation based on the luminaire layout was carried out only for the classroom, and the other spaces were evaluated over average values with the lumen method. In the economic analysis, the unit prices of the luminaires and lamps determined in US dollars were converted into Turkish lira with the current exchange rate, and the installation labour was not included in the investment cost.

4. CONCLUSIONS AND RECOMMENDATIONS

Lighting has a significant share in the electricity consumption of public educational buildings due to their long usage periods. In this study, the condition of the existing lighting system in an educational building belonging to Osmaniye Korkut Ata University was determined by on-site illuminance measurements, and the replacement of the existing fluorescent luminaires with LED luminaires was evaluated from technical and economic perspectives.

As a result of the measurements, it was determined that the average illuminance remained below the values given in the standard in all measured spaces. The average illuminance was measured in the range of 186.3–257.9 lx in the classrooms, as 176.9 lx in the administrative office and in the range of 22.1–73.9 lx in the corridors.

It was determined that the total installed power decreased from 15,378 W to 6,072 W by replacing the existing 199 fluorescent luminaires of 4×18 W with 28 W LED luminaires and the 50 lamps of 21 W with 10 W LED lamps. It was found that an annual energy saving of

19,263.42 kWh (60.5%; 1.66 TOE) and, with an electricity unit price of 4.80 TL/kWh, an annual cost saving of 92,464.42 TL were achieved with the conversion. The simple payback period of the investment of 335,661.66 TL in total was calculated as 3.63 years, and its net present value for the 10-year analysis period was calculated as 232,495.22 TL. Therefore, it was determined that the conversion is economically feasible for the investigated building.

It was calculated that the illuminance in the corridors increased to 234 lx after the conversion. In the simulation carried out for the classroom, it was determined that with the existing 3×3 luminaire layout the value of 300 lx was provided in most of the usage area, while the illuminance decreased to the level of 175–200 lx in the corner regions. In the administrative office, conference hall and entrance hall, it was determined that the values given in the standard could not be reached according to the lumen method. According to these results, it was evaluated that energy savings and visual comfort can be improved together by rearranging the luminaire layout according to the requirements of the spaces and by including daylight-dependent and occupancy-dependent lighting control systems in the conversion. Considering that the simple payback period of the conversion is 3.63 years and that this period remains short compared with the usage period of approximately 35 years of the LED luminaires, it was evaluated that the proposed improvements are also economically applicable. In addition, it was evaluated that repeated measurements in different seasons and at different times of the day and point-by-point lighting simulations for all spaces are important for the generalizability of the results to be obtained in public educational buildings with a similar structure.

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