ACTA TECNOLOGÍA

electronic journal
ISSN 2453-675X
Volume 11
Issue 3
2025

International Scientific Journal about Technologies

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(SEPTEMBER 2025)

https://doi.org/10.22306/atec.v11i3.276 *Received: 24 Mar. 2025; Revised: 10 May 2025; Accepted: 22 July 2025*

Organoids as models for tissue engineering and biomedical applications

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Keywords: organoids, drug delivery, biomedical engineering.
Abstract: Collagen, the primary structural protein in the extracellular matrix, has gained significant attention as a surface modification agent for biomaterials due to its exceptional biocompatibility, bioactivity, and ability to promote cellular adhesion and proliferation. Collagen coatings enhance the integration of synthetic and natural biomaterials with biological tissues, making them highly relevant in biomedical engineering, regenerative medicine, and implantable medical devices. This review explores the mechanisms by which collagen coatings improve biomaterial properties, including their role in modulating surface chemistry, hydrophilicity, and cellular interactions. Furthermore, we discuss various coating techniques, such as adsorption, covalent binding, and electrospinning, and their implications for optimizing material performance in biomedical applications. The advantages of collagen coatings in orthopedic, dental, and cardiovascular implants, as well as wound healing and drug delivery systems, are also examined. By highlighting the potential of collagen-functionalized surfaces, this article provides insight into the future directions of biomaterial innovation aimed at improving patient outcomes and medical device efficacy.

1 Introduction

Organoids are three-dimensional (3D) cellular structures that mimic key functional and structural aspects of native organs. They are derived from stem cells, including pluripotent stem cells (PSCs) and adult stem cells (ASCs), which self-organize into complex tissue-like architectures through intrinsic developmental programs (Figure 1) [1,2]. Unlike traditional two-dimensional (2D) cell cultures, organoids provide a physiologically relevant microenvironment, allowing for the study of organogenesis, disease modeling, and regenerative medicine in a way that closely resembles in vivo conditions [3-5].

Organoid formation relies on the ability of stem cells to undergo self-assembly and differentiation in response to biochemical and biophysical cues. The process is typically initiated by embedding stem cells within a supportive extracellular matrix, such as Matrigel, which provides the necessary mechanical and biochemical signals for morphogenesis. Growth factors and signaling pathways, regulate cell fate determination, guiding the organization of cells into tissue-specific structures. This recapitulation of developmental processes enables organoids to exhibit functional properties similar to their corresponding organs, including tissue-specific cell types, spatial organization, and even rudimentary physiological activity [6,7].

Due to their remarkable ability to replicate organ complexity, organoids have become powerful tools in biomedical research. They are widely employed in disease modeling, where patient-derived organoids allow for personalized medicine approaches, including drug screening and toxicity testing [8,9]. Additionally, organoids provide an innovative platform for studying developmental biology, as they enable researchers to dissect the molecular and cellular mechanisms governing organ formation. In tissue engineering and regenerative medicine, organoids offer the potential to generate transplantable tissues and serve as building blocks for bioengineered organs. Their use in stem cell-based therapies further highlights their significance in advancing regenerative strategies for treating degenerative diseases and organ failure [3,10].

Despite their promise, several challenges remain, including scalability, vascularization, and functional maturation, which must be addressed before organoid-based therapies can be fully integrated into clinical practice. Nevertheless, ongoing advancements in biomaterials, bioprinting, and microfluidic systems continue to refine organoid technology, bringing it closer to real-world applications in tissue engineering and regenerative medicine [11,12].

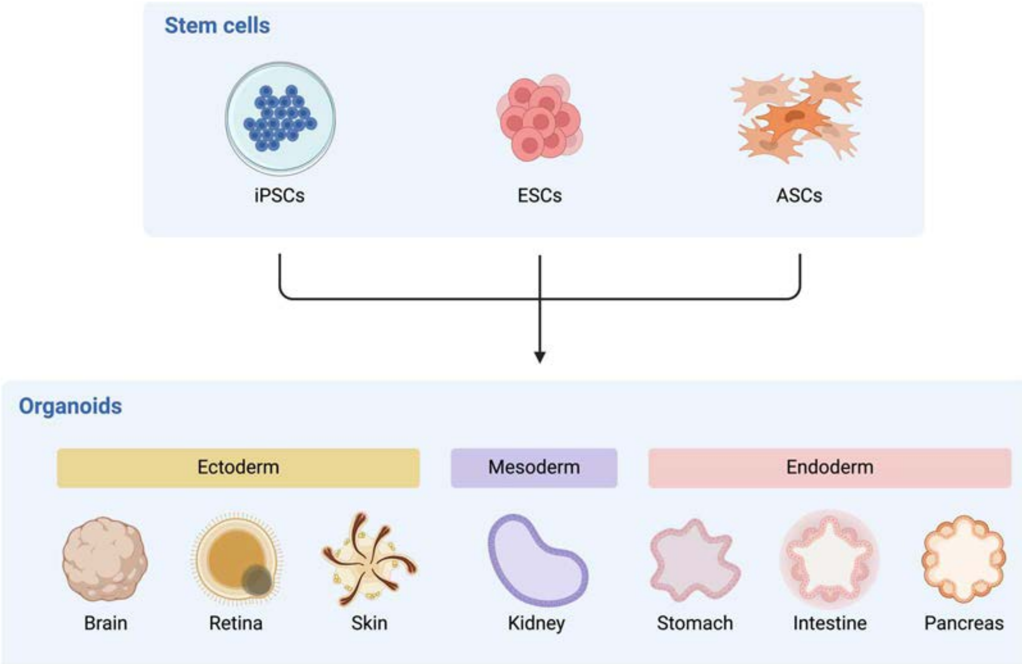

Figure 1 Differentiation of organoids from stem cells: A Visual representation of organoid development from Induced Pluripotent Stem Cells (iPSCs), Embryonic Stem Cells (ESCs), and Adult Stem Cells (ASCs), categorized by germ layer origin (Ectoderm, Mesoderm, Endoderm) (created with biorender.com)

2 Development of organoids

The development of organoids is a highly controlled process that mimics early organogenesis by guiding stem cells through self-organization and differentiation into functional tissue-like structures. This process involves key cellular mechanisms, including stem cell fate determination, spatial patterning, and microenvironmental regulation. The development of organoids can be broadly categorized into three stages: stem cell selection and initiation, directed differentiation and self-organization, and maturation and functional validation [13].

2.1 Stem cell selection and initiation

Organoids are primarily derived from two main types of stem cells: pluripotent stem cells and adult stem cells. PSCs, including embryonic stem cells (ESCs) and induced pluripotent stem cells (iPSCs), possess the ability to differentiate into any cell type of the body, making them ideal for generating diverse organoid models [14]. ASCs, on the other hand, are tissue-resident stem cells capable of differentiating into specialized cell types within their respective tissues. While PSC-derived organoids are widely used for studying early organ development, ASC-derived organoids are particularly useful for modeling tissue homeostasis and disease [15]. The initiation phase involves embedding stem cells in a three-dimensional extracellular matrix (ECM), such as Matrigel, which provides the necessary mechanical support and biochemical signals for cell adhesion and morphogenesis. The presence of specific signaling factors plays a critical role in directing initial cell proliferation and fate determination. By manipulating these signaling pathways, researchers can guide stem cells toward specific lineage commitments, forming organoid structures that closely resemble native organs [16,17].

2.2 Directed differentiation and self-organisation

One of the defining features of organoids is their ability to undergo self-organization, a process in which cells autonomously arrange into complex structures that replicate in vivo tissue architecture. This phenomenon is driven by intrinsic developmental programs that regulate cellular differentiation, polarity, and spatial patterning [18].

The differentiation process relies on a combination of growth factors and small molecules that simulate the embryonic developmental cues of specific organs. For example, in brain organoids, dual inhibition of SMAD signaling (TGF-β and BMP inhibition) promotes neural induction, while in intestinal organoids, activation of Wnt and R-spondin signaling supports crypt formation and epithelial differentiation. The interplay between cell-cell adhesion, cytoskeletal dynamics, and ECM interactions further refines tissue organization, allowing for the emergence of distinct compartments resembling different anatomical regions of the organ [19,20].

As differentiation progresses, organoids begin to exhibit key features of their respective tissues, including the presence of multiple cell types, functional domains, and, in some cases, rudimentary physiological activity. This stage is crucial for ensuring that organoid development accurately recapitulates in vivo conditions, making them suitable for downstream applications in disease modeling and regenerative medicine [20].

2.3 Maturation and functional validation

While early-stage organoids exhibit structural and cellular similarities to their in vivo counterparts, further maturation is required to achieve full physiological functionality. Maturation involves extended culture periods, refinement of differentiation protocols, and integration of additional microenvironmental cues, such as mechanical forces and biochemical gradients. One of the major challenges in organoid maturation is vascularization, as most organoids lack functional blood vessels, limiting their size and metabolic activity [10,2]. Recent advances in co-culturing techniques, microfluidic systems, and bioengineering approaches have enabled the development of vascularized organoids that exhibit improved nutrient exchange and tissue survival. Additionally, incorporation of stromal and immune cell components has enhanced organoid complexity, bringing them closer to functional tissues found in the human body [21,17].

2.4 Applications in medicine and biomedical engineering

The continuous advancement of biomedical engineering is essential for improving medical treatments, enhancing the biocompatibility of materials, and driving innovation in personalized medicine [22]. Organoids offer an innovative platform for studying diseases at a more physiological level than traditional 2D cell cultures. Due to their complexity, they provide more accurate representations of human tissues and organs, enabling the study of disease mechanisms in a more relevant context [17]. For example, liver organoids have been used to model liver diseases such as hepatitis and cirrhosis, while brain organoids have become crucial in understanding neurodegenerative disorders like Alzheimer's and Parkinson's disease. Additionally, organoids are increasingly used in drug screening and toxicology. They can be exposed to various pharmaceutical compounds to test their effects on organ-specific functions, toxicity, and efficacy. This reduces the reliance on animal models and helps streamline the drug development process [23,24].

2.5 Drug delivery

Organoids are particularly valuable in drug delivery studies because they closely resemble the physiological characteristics of human tissues. For example, liver organoids can replicate hepatic metabolism, kidney organoids can model renal filtration and excretion, and intestinal organoids can simulate absorption and barrier functions. This allows for more realistic and predictive testing of how drugs behave within the human body, providing crucial insights into pharmacokinetics and the mechanisms of drug action. One of the primary uses of organoids in drug delivery is to study drug absorption, distribution, metabolism, and excretion (ADME) profiles. By mimicking the organs involved in drug metabolism and transport, such as the liver, intestine, and kidneys, organoids can be used to evaluate how drugs are absorbed through the gut, metabolized in the liver, or eliminated through the kidneys. This can help determine the bioavailability and effectiveness of oral drugs, as well as identify potential toxic effects or interactions with other medications. Intestinal organoids, in particular, are often used to study how drugs cross the intestinal barrier and are absorbed into the bloodstream. By incorporating human-derived cells, these models can better predict the absorption of drugs in humans compared to traditional animal models . Organoids also play a significant role in studying drug toxicity. Traditional in vitro cell cultures may fail to account for the complexity of human tissues, leading to inaccurate predictions of how a drug may affect the body.

By using organoids to simulate human tissue responses, researchers can identify potential toxicities early in drug development. For example, liver organoids can be used to assess hepatotoxicity, and cardiac organoids can be employed to investigate cardiotoxicity. By understanding the toxicity profiles of drugs in more realistic human models, researchers can reduce the likelihood of harmful side effects when the drugs are tested in clinical trials.

Although organoids present significant advantages in drug delivery research, there are still challenges to overcome. One limitation is the size and complexity of organoids, which can make large-scale production and high-throughput screening difficult. As organoid culture techniques improve, the scalability of organoid models will likely increase, allowing for more widespread use in drug delivery studies. Additionally, while organoids replicate certain aspects of human tissue, they do not fully replicate the complexity of the entire organism, meaning their predictive value for drug responses may still be limited in certain cases. Advances in organoid technology, such as incorporating immune cells, vascular networks, and other components, will help address some of these limitations and provide more comprehensive models for drug delivery research [25].

2.6 Disease modeling

One of the primary advantages of organoids in disease modeling is their ability to mimic the architecture and function of human organs. Unlike 2D cultures, which consist of a single layer of cells, organoids are three-dimensional structures that resemble the organization and complexity of actual tissues [26]. This allows researchers to study diseases in a more physiologically relevant context. For instance, intestinal organoids replicate the villous structure of the human gut, enabling the modeling of gastrointestinal diseases such as Crohn’s disease, ulcerative colitis, and infections like Clostridium difficile. These organoids can also mimic the effects of environmental factors, such as diet or microbiome, on disease progression, providing valuable insights into the gut-brain axis and the role of the intestinal barrier in disease.

Authors Melzer et al. introduced the porcine urinary bladder (PUB) as an advanced organ culture model for creating an ex vivo pancreatic niche, which enables the study of pancreatic ductal adenocarcinoma (PDAC). This model allows pancreatic progenitor cells to develop into ductal and endocrine lineages, with pancreatic duct-like organoids (PDLOs) maturing into duct-like tissue. The PUB model supports the study of early pancreatic dysplasia and cancer [8].

Organoids have also proven crucial in modeling neurodegenerative diseases, such as Alzheimer's, Parkinson's, and Huntington's diseases. Brain organoids, derived from neural stem cells, can replicate the cellular diversity and complex structure of the human brain, allowing researchers to study neurodegenerative diseases in a way that was previously not possible. These organoids model the early stages of disease, including the accumulation of amyloid plaques in Alzheimer's or the loss of dopaminergic neurons in Parkinson's disease. Furthermore, they can be used to screen potential therapeutic compounds, providing a more effective method for identifying drugs that may slow disease progression (Figure 2) or alleviate symptoms.

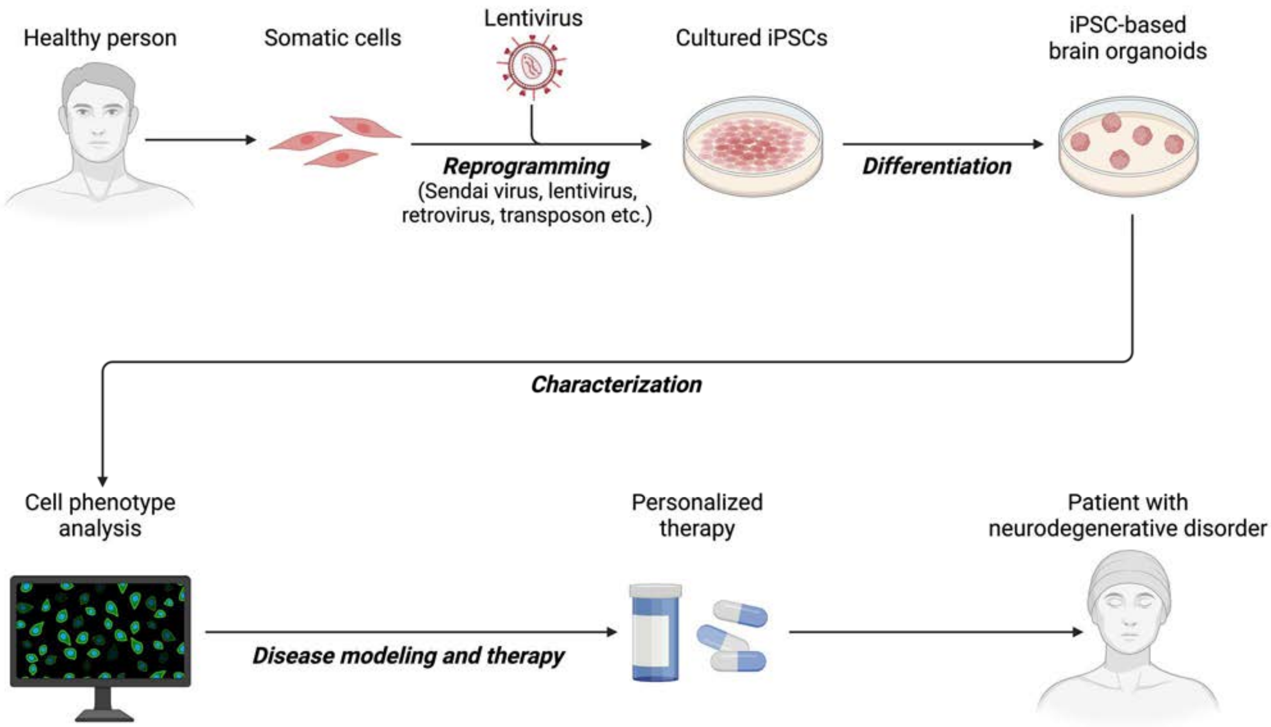

Figure 2 Disease modeling and personalized therapy using induced pluripotent stem cells (iPSCs) derived from healthy somatic cells via Lentivirus transduction (created with biorender.com)

Wang et al. explored the potential of bone organoids derived from stem cells for bone regeneration but faced challenges, such as the need for robust mechanical support through scaffolds and hybrid extracellular matrices (ECM). To overcome these obstacles, they developed a novel bioink made from gelatin methacrylate/alginate methacrylate/hydroxyapatite (GelMA/AlgMA/HAP), which was used in bioprinting to create intricate bone ECM analogs. The bioprinted scaffolds supported the long-term cultivation, maturation, and differentiation of bone organoids, mimicking the natural bone's self-mineralizing properties [9].

Organoids are also instrumental in studying rare genetic disorders. Diseases that affect specific tissues or organs, such as cystic fibrosis or Duchenne muscular dystrophy, can be modeled using patient-derived organoids. For example, organoids derived from cystic fibrosis patients can mimic the defective epithelial cell function seen in the disease, providing a platform for drug screening and studying the underlying pathophysiology. These models can also be used to explore how genetic mutations affect organ development and function, helping to identify novel therapeutic targets for rare diseases that currently lack effective treatments.

Revah et al. transplanted human stem cell-derived cortical organoids into the somatosensory cortex of newborn athymic rats, where the organoids matured and integrated into sensory and motivation-related circuits.

MRI and single-nucleus profiling showed organoid growth, corticogenesis, and activity-dependent transcriptional programs. Transplanted neurons exhibited more complex properties than in vitro counterparts, enabling the discovery of defects in neurons from Timothy syndrome patients [27].

2.7 Cancer treatment

Organoids derived from cancerous tissues offer a more accurate representation of tumors compared to traditional 2D cell cultures. They maintain the architecture, cellular diversity, and genetic features of the original tumor, which is crucial for understanding the complexity of cancer. Tumor organoids can be generated from different types of cancer, such as colorectal, breast, lung, pancreatic, and ovarian cancer, allowing for the study of tumor progression, metastasis, and the molecular mechanisms underlying cancer development. These models also provide a better means of recapitulating the tumor microenvironment (TME), which plays a critical role in cancer behavior, including immune cell infiltration, hypoxia, and extracellular matrix composition. By mimicking these factors, organoids serve as valuable platforms for exploring how tumors interact with surrounding tissue and how the TME affects tumor growth and therapy resistance.

Choi et al. developed a vascularized lung cancer model incorporating patient-derived lung cancer organoids, lung fibroblasts, and perfusable vessels using 3D bioprinting. They utilized a porcine lung-derived decellularized extracellular matrix hydrogel to mimic the biochemical composition of native lung tissue, providing physical and biochemical cues for the cells within the LC microenvironment [28].

One of the most promising applications of organoids in cancer treatment is their role in personalized medicine. Organoids derived from a patient's own tumor cells offer a unique opportunity to test a range of chemotherapies, targeted therapies, and immunotherapies before deciding on a treatment plan. This personalized approach helps determine which drug or combination of therapies will be most effective for the individual, reducing the risk of adverse side effects and improving overall treatment outcomes. Organoid-based drug screening platforms have been used in clinical settings to identify the most effective treatment options for patients. For example, patient-derived organoids (PDOs) from colorectal cancer can be exposed to various chemotherapy agents, and the response can be monitored in real-time to predict how the patient will respond to the same drugs in vivo. This helps clinicians select the best course of action for each patient, tailoring treatment to the specific molecular and genetic characteristics of their cancer.

Yuan et al. established organoid lines from human gallbladder carcinoma (GBC), normal gallbladder, and benign gallbladder adenoma tissues. These organoids accurately reflected the histopathology, genetic features, and heterogeneity of primary tissues. The study suggests that patient-derived organoids can be a valuable tool for exploring gallbladder tumor pathogenesis and developing personalized treatments [29].

Immunotherapy, which utilizes the body's immune system to fight cancer, has shown promise in treating a variety of cancers. However, the effectiveness of immunotherapies can vary greatly between patients. Organoids derived from patient tumors provide a unique platform for testing the efficacy of different immunotherapies, such as immune checkpoint inhibitors, CAR-T cell therapies, and cytokine therapies. Cancer organoids can be co-cultured with immune cells to study how the immune system interacts with the tumor. This allows researchers to evaluate how immune cells infiltrate the tumor, recognize cancerous cells, and whether the tumor can evade immune detection. By using patient-derived organoids in immuno-oncology studies, it is possible to identify factors that predict responses to immunotherapy and improve the selection of patients who are most likely to benefit from these treatments.

3 Discussion

Organoids represent a transformative advancement in the field of disease modeling, bridging the gap between traditional 2D cell cultures and whole animal models. Their ability to mimic human tissues more accurately, both structurally and functionally, has significantly enhanced our understanding of complex diseases. As demonstrated throughout this article, organoids offer a more physiologically relevant model for studying a wide range of diseases, including genetic disorders, neurodegenerative diseases, infectious diseases, and cancer, among others. They allow for the replication of human tissue architecture, cellular diversity, and microenvironments, which are critical for understanding disease mechanisms that cannot be fully captured by animal models or traditional cell cultures.

Patient-derived organoids (PDOs) are particularly valuable in the context of personalized medicine. By using organoids derived from individual patients, researchers can create models that closely mimic the specific genetic, molecular, and environmental factors influencing disease development in that patient. This personalized approach allows for the evaluation of therapeutic strategies tailored to the patient's unique disease profile, potentially leading to more effective and targeted treatments. For example, organoid models of cancer have shown promise in identifying the most effective therapies for specific tumor types, enabling the testing of drug combinations in a patient-specific context. Similarly, organoids derived from patients with genetic diseases, such as cystic fibrosis or Duchenne muscular dystrophy, can be used to test potential gene therapies or drug candidates tailored to the patient’s specific mutation.

Despite their significant advantages, the use of organoids in disease modeling is not without its challenges.

One of the key limitations of organoid models is their inability to fully replicate the complexity of entire organs or the interactions between different organ systems. While organoids capture the cellular diversity and architectural features of individual tissues, they do not mimic the full range of physiological processes that occur in a whole organism [30].

Despite these limitations, organoids remain a powerful tool in disease modeling, offering a more accurate and relevant model for understanding human diseases. They provide a unique opportunity to study disease mechanisms in ways that were previously not possible, especially in the context of rare genetic disorders and complex multi-system diseases. Furthermore, organoids are being used to test drug candidates, identify biomarkers, and explore novel therapeutic strategies, contributing to the development of more effective treatments for a wide range of diseases.

4 Conclusion

This article provided a comprehensive review of organoids as innovative 3D biological models with significant applications in tissue engineering, disease modeling, and personalized medicine. It outlined the fundamental processes involved in organoid development—from stem cell selection and differentiation to maturation and functional validation. The article highlighted the diverse biomedical applications of organoids, including their roles in drug delivery studies, disease modeling for neurodegenerative and genetic disorders, and the development of personalized cancer therapies. Specific examples were discussed to demonstrate how organoid systems have been engineered to replicate organ-specific functions, improve drug testing accuracy, and reduce reliance on animal models. Challenges such as vascularization, scalability, and incomplete tissue maturation were acknowledged, alongside emerging solutions involving advanced bioinks, co-culture systems, and microfluidics. By compiling recent advancements and practical applications, this review underscores the transformative potential of organoid technology in advancing biomedical research and clinical therapies.

Acknowledgement
The state grant agency supported this article with projects KEGA 018/TUKE-4/2023 and VEGA 1/0403/25.

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Review process
Single-blind peer review process.

Acta Tecnología - International Scientific Journal about Technologies
Volume: 11 2025 Issue: 3 Pages: 121-126 ISSN 2453-675X

https://doi.org/10.22306/atec.v11i3.289 *Received: 12 May 2025; Revised: 16 July 2025; Accepted: 31 July 2025*

Analytical solution for optimizing pollution load capacity in river segments

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Keywords: pollution load, loading capacity, decay coefficient, dispersion, analytical solution.
Abstract: The problem of determining the pollution load capacity for a river section has an important meaning in protecting the water environment for the purpose of sustainable development. This is a complex optimization problem that only has an analytic solution in simple cases. This paper presents a method for obtaining an analytical solution for a river section in the case of dispersed waste sources distributed along the river, taking into account the influence of decay and dispersion processes. The results show a quantitative relationship between the decay coefficient, the dispersion coefficient and the load capacity of the river. The obtained results can be applied to more complex real-world problems.

1 Introduction

The determination of pollution load capacity in river systems plays a crucial role in water quality management and sustainable environmental development. As the pressures from urbanization, industrialization, and agricultural activities increase, rivers are becoming more vulnerable to pollution, necessitating effective methods to quantify and control pollutant discharge. Regulatory approaches such as the Total Maximum Daily Load (TMDL) [1,2] framework have been adopted in various countries to ensure that pollutant inputs do not exceed the assimilative capacity of water bodies, maintaining water quality standards for aquatic life and human use [3,4].

Analytical and mathematical models have long been used to simulate and optimize pollutant transport and transformation in riverine systems. These models account for critical processes such as advection, dispersion, and degradation [5,6]. However, many optimization problems regarding load capacity lack general analytical solutions and often require numerical approaches, especially when dealing with spatially distributed pollution sources [7,8]. Despite this complexity, analytical solutions—where obtainable—provide valuable insight and computational efficiency for water quality planning.

Previous studies have provided guidance and technical frameworks for implementing pollution control strategies, including Japan's Total Pollutant Load Control System (TPLCS), and comprehensive TMDL reports from states such as Maryland, USA [9-11]. These efforts highlight the importance of incorporating hydrodynamic and biochemical processes into load estimation and management decisions.

This paper presents an analytical solution for optimizing the pollution load capacity of a river segment with distributed waste sources. The model incorporates the effects of pollutant decay and dispersion, enabling a more accurate estimation of load capacities under constrained environmental conditions. By deriving closed-form solutions under specific assumptions, the study contributes a novel theoretical framework that can support more effective and efficient pollutant management strategies in river systems. The findings also provide a foundation for extending these methods to more complex scenarios and integrating them into practical water quality control programs.

2 Materials and methods

2.1 Problem

In order to solve the problem analytically, we selected a 1D model with a river segment of length L, cross-section A, and a constant discharge Q. Concentration of influent waste in the river section is c_0, the reduction coefficient is λ (including decomposition and deposition). Discharge load distribution on both sides of the river is ρ(x). Find ρ(x) such that the total load on both sides of the river into the river is the maximum. The constrain conditions are as follows:

(1) Concentration of pollutants in the river section does not exceed the allowable standard C_{max}

(2) Density of discharge load in the river does not exceed the limit ρ_{max}

2.2 Mathematical model

The river segment is shown on the x coordinate axis from coordinates a, b (section L= [a,b]). In the case of constant flow rate Q, the problem considered is stationary.

The distribution of pollutant concentrations is determined by the following differential equation:

$$v\frac{dc}{dx} = \alpha\frac{d^2c}{dx^2} - \lambda c + \varrho(x) \qquad (1)$$

Where c(x) [mg/L] pollutant concentration; v=Q/A [m/s] average flow velocity; α [m²/s] eddy diffusion coefficient; λ [1/s] the degradation coefficient of the pollutant; ρ(x) [mg/L.s] discharge rate density along the river.

Constrain conditions:

(1) $0<c(x)<c_{max}$; $x \in [a,b]$

(2) $0<\rho(x)<\rho_{max}$; $x \in [a,b]$

Boundary conditions (given the input concentration of the river section):

(1) $c(a)=c_0$ (taking into account the concentration of pollutants from upstream)

Determining the total load of the river section is objective function:

Find ρ(x) with x ∈ [a,b] to $TL = \int_a^b \varrho(x)dx$ max.

Then the load capacity (LC) of the river section (including upstream load) is

$$LC = \int_a^b \varrho(x)dx + c_0 Q \quad (2)$$

also reached its maximum.

For the convenience of finding analytical solutions, the above equations are reduced to dimensionless form, with dimensionless variables as follows:

$$\tilde{x} = \frac{(x-a)}{L}; \quad \tilde{c} = \frac{(c-c_0)}{(c_{max}-c_0)}; \quad \tilde{\rho}(\tilde{x}) = \rho(x) \quad (3)$$

Equation 2 (2) is rewritten by substituting Equation 3 (3) into equation 2:

$$vL\frac{d\tilde{c}}{d\tilde{x}} = \alpha\frac{d^2\tilde{c}}{d\tilde{x}^2} - \lambda L^2\tilde{c} - \frac{\lambda L^2}{(c_{max}-c_0)}c_0 + \frac{L}{(c_{max}-c_0)}\tilde{\rho}$$

Divide both sides by vL, remove the "~" sign of the variables, we get:

$$\frac{dc}{dx} = A\frac{d^2c}{dx^2} - \Lambda c + R(x) \quad (4)$$

where

$$A = \frac{\alpha}{vL}; \quad \Lambda = \frac{\lambda L}{v}; \quad \tilde{c}_0 = \frac{c_0}{(c_{max}-c_0)};$$

$$R(x) = \frac{L}{v(c_{max}-c_0)}\rho(x) - \Lambda\tilde{c}_0$$

With constrain conditions:

$$-\Lambda\tilde{c}_0 = R_0 \le R(x) \le R_{max} = \frac{L\rho_{max}}{v(c_{max}-c_0)} - \Lambda\tilde{c}_0$$

$$-\tilde{c}_0 \le c(x) \le 1$$

With the boundary condition:

$c(x=0) = 0$.

The objective function becomes:

$$TL = \int_a^b \rho(x)dx = v(c_{max}-c_0)\int_0^1 R(x)dx + L\lambda c_0$$

The objective function becomes finding maximum of R(x) where x belongs to the following interval [0,1] for the integral (5):

$$\int_0^1 R(x)dx \quad (5)$$

With the conditions (6):

$$R_0 \le R(x) \le R_{max} \quad (6)$$

And with c(x) being the solution of the differential equation (7):

$$\frac{dc}{dx} = A\frac{d^2c}{dx^2} - \Lambda c + R(x) \quad (7)$$

Satisfy the boundary conditions (8):

$$c(x=0)=0 \quad (8)$$

then (9):

$$-\tilde{c}_0 \le c(x) \le 1 \quad (9)$$

3 Results

3.1 *Results of determination of waste source distribution in case A=0*

In the absence of the influence of dispersion processes (molecular diffusion and turbulent diffusion) corresponding to A=0, equation (7) is rewritten as:

$$\frac{dc}{dx} = -\Lambda c + R(x) \quad (10)$$

This equation with condition (5) has a unique solution:

$$c(x) = e^{-\Lambda x}\int_0^x R(s)e^{\Lambda s}ds$$

When R_{max} is very small, c(x) may not reach $c_{max}=1$ in [0,1], in this case, in order to maximum the integral, we set $R(x)=R_{max}$ over the whole interval [0,1]. We have:

$$c(x) = e^{-\Lambda x}\int_0^x R(s)e^{\Lambda s}ds \le R_{max}(1-e^{-\Lambda x})/\Lambda$$

At x = 1, the right-hand side is only maximized and the value of c(x) = 1.

Therefore, the critical value R_c of R_{max} is determined by:

$$\frac{R_c(1-e^{-\Lambda})}{\Lambda} = 1 \quad \rightarrow R_c = \frac{\Lambda}{(1-e^{-\Lambda})}$$

From here there is always the inequality $R_c > \Lambda$.

With $R_{max} \le R_c$

We have: $R(x)=R_{max}$ with $0 \le x \le 1$.

and

$$c(x) = e^{-\Lambda x}\int_0^x R_{max}e^{\Lambda s}ds$$

or

$$c(x) = R_{max}(1-e^{-\Lambda x})/\Lambda \quad (11)$$

so:

$$TL = \int_a^b \rho(x)dx = v(c_{max}-c_0)\int_0^1 R(x)dx + L\lambda c_0$$

Thus, the total load of the river will be:

$$TL = v(c_{max}-c_0)R_{max} + L\lambda c_0$$

The total load capacity of the river section will be:

Volume: 11 2025 Issue: 3 Pages: 121-126 ISSN 2453-675X

$$LC = v(c_{max} - c_0)R_{max} + L\lambda c_0 + c_0 Q$$

In this case $R_{max}>R_c$,

We have:

$$\int_0^1 R(x)dx = \int_0^1 \left(\frac{dc}{dx} + \Lambda c\right) dx = c(1) + \Lambda \int_0^1 c(x)dx \quad (12)$$

So the solution where c(1)=1 and the integral c(x) over [0,1] is maximized will be the optimal solution. This integral is maximal when c(x) soon reaches its maximum value. So the function R(x) needs to have the maximum value from the point x=0, that is, $R=R_{max}$ in the interval $[0,x_0]$ so that at $x_0=1$, c(x)=1 we have (13):

$$1 = \frac{R_{max}(1-e^{-\Lambda x_0})}{\Lambda} \rightarrow x_0 = -\frac{1}{\Lambda}\ln\left(1 - \frac{\Lambda}{R_{max}}\right) \quad (13)$$

On the segment $[x_0,1]$ to maximize the integral (10), we need to maintain c(x)=1, which means dc/dx=0. From equation 10 we have R=Λ because $R>R_c>\Lambda$.

So with $R>R_c$ we have:

$R=R_{max}$ with $0 \le x < x_0$

R=Λ với $x_0 \le x \le 1$.

So:

$$c(x) = R_{max}e^{-\Lambda x}(e^{\Lambda x} - 1)/\Lambda \qquad 0 \le x < x_0$$

$$c(x) = 1 \qquad x_0 \le x < 1$$

Thus:

$$\int_0^1 R(x)dx = R_{max}x_0 + \Lambda(1 - x_0) = \Lambda + \left(1 - \frac{R_{max}}{\Lambda}\right)\ln\left(1 - \frac{\Lambda}{R_{max}}\right)$$

$$TL = \int_a^b \rho(x)dx = v(c_{max} - c_0)\int_0^1 R(x)dx + L\lambda c_0$$

Thus, the total load will be:

$$TL = v(c_{max} - c_0)\left[\Lambda + \left(1 - \frac{R_{max}}{\Lambda}\right)\ln\left(1 - \frac{\Lambda}{R_{max}}\right)\right] + L\lambda c_0 \quad (14)$$

The total load capacity of the river section will be:

$$LC = v(c_{max} - c_0)\left[\Lambda + \left(1 - \frac{R_{max}}{\Lambda}\right)\ln\left(1 - \frac{\Lambda}{R_{max}}\right)\right] + L\lambda c_0 + c_0 Q \quad (15)$$

3.2 Results of determination of waste source distribution in case A≠0

In the case, the influence of the dispersion process (molecular diffusion and turbulent diffusion) are considered in equation 4, we have A≠0.

Similar to the case A=0, there exists a value of R_c so that when $R_{max}<R_c$, the concentration value c(x) does not exceed the value 1. So:

a. With $R_{max}<R_c$

We have

$R=R_{max}$

General solution of the equation:

$$\frac{dc}{dx} = A\frac{d^2c}{dx^2} - \Lambda c + R(x)$$

satisfy the boundary conditions:

$$c(x=0) = 0$$

With 0<=x<=1 have the form:

$$c(x) = C_1 e^{\lambda_1 x} + C_2 e^{\lambda_2 x} + Rmax/\Lambda \quad (16)$$

Where: $\lambda_{1,2} = \frac{1 \pm \sqrt{1+4A\Lambda}}{2A}$, with $\lambda_1<0<\lambda_2$; C_1, C_2 are the coefficient which are obtained from boundary conditions below:

- At x=0: $c(x=0)=0$
- At x=1: c(x) and its derivative satisfy the continuity condition with d(x) is the solution of equation (7) with R=0, in the interval [1,+∞)
- At x=+∞, d(x) is limited, so d(x) has a general solution of

$$d(x) = D_1 e^{\lambda_1 x}$$

From the above boundary conditions, we have a linear system equations for the coefficients C_1, C_2 and D_1

$$\begin{cases} C_1 + C_2 = -\frac{R_{max}}{\Lambda} \\ e^{\lambda_1}C_1 + e^{\lambda_2}C_2 - e^{\lambda_1}D_1 = -\frac{R_{max}}{\Lambda} \\ \lambda_1 e^{\lambda_1}C_1 + \lambda_2 e^{\lambda_2}C_2 - \lambda_1 e^{\lambda_1}D_1 = 0 \end{cases} \quad (17)$$

Solving the equations (17), we have:

$$C_1 = \frac{R_{max}(\lambda_1 - \lambda_1 e^{\lambda_2} + \lambda_2 e^{\lambda_2})}{\Lambda(\lambda_1 e^{\lambda_2} - \lambda_2 e^{\lambda_2})} \quad (18)$$

$$C_2 = -\frac{R_{max}\lambda_1}{\Lambda(\lambda_1 e^{\lambda_2} - \lambda_2 e^{\lambda_2})} \quad (19)$$

$$C_3 = \frac{e^{-\lambda_1}R_{max}[\lambda_1 e^{\lambda_1} - \lambda_2 e^{\lambda_2} - (\lambda_1 - \lambda_2)e^{1/2A}]}{\Lambda(\lambda_1 e^{\lambda_2} - \lambda_2 e^{\lambda_2})} \quad (20)$$

Substitute the coefficients in (15), since c(x) increases in the interval (0,1) thus reaching a maximum at 1 and R_c is found from the condition c(1)=1. We have:

$$R_c = \frac{\Lambda}{(1 - e^{\lambda_1}) + \frac{\lambda_1(e^{\lambda_1 - \lambda_2 - 1})}{\lambda_1 - \lambda_2}} \quad (21)$$

b. $R_{max}>R_c$:

$$\int_0^1 R(x)dx = \int_0^1 \left(\frac{dc}{dx} + \Lambda c - A\frac{\partial^2 c}{\partial x^2}\right)dx = \Lambda\int_0^1 c(x)dx + [c(1) - c(0)] - A\left[\frac{dc}{dx}(1) - \frac{dc}{dx}(0)\right] \quad (22)$$

with c(0)=0 and $\frac{dc}{dx}(1) = \lambda_1 c(1)$ we have:

$$\int_0^1 R(x)dx = \Lambda\int_0^1 c(x)dx + c(1)(1 - \lambda_2 A) + A\frac{dc}{dx}(0) \quad (23)$$

The above integral reaches its maximum when there exists a condition for all three terms to simultaneously attain their maxima. The first term reaches its maximum when $c(x)$ increases as rapidly as possible to 1 and maintains the value 1 until x=1. This condition is entirely consistent with the conditions for the second and third terms to also reach their maxima, with c(1) =1 (since $\lambda_2<0$ we have 1- λ_2A>0) and $\frac{dc}{dx}$ attaining its maximum. The optimization problem is thus reduced to the following problem:

Determine x_0 such that c(x) increases as rapidly as possible to 1 on the interval $[0,x_0)$, and then, c(x) reaches its maximum value c(x)=1 (from x_0 to 1). To make c(x) increase as rapidly as possible, we set $R=R_{max}$. For c(x)=const=1, we have $\frac{dc}{dx} = 0$ and $\frac{d^2c}{dx^2} = 0$, then from equation 4 deduce R=Λ. The problem now is determining x_0.

In the interval $[0,x_0]$ the solution has the form (since $R(x)=const=R_{max}$):

$$c(x) = C_1 e^{\lambda_1 x} + C_2 e^{\lambda_2 x} + Rmax/\Lambda \qquad (24)$$

With the condition c(0)=0; $c(x_0)=1$ and $dc/dx(x0)=0$, we obtain a system equations to find C_1,C_2 and x_0:

$$\begin{cases} C_1 + C_2 + \frac{R_{max}}{\Lambda} = 0 \\ C_1 e^{\lambda_1 x_0} + C_2 e^{\lambda_2 x_0} + \frac{R_{max}}{\Lambda} = 1 \\ C_1 \lambda_1 e^{\lambda_1 x_0} + C_2 \lambda_2 e^{\lambda_2 x_0} = 0 \end{cases} \qquad (25)$$

Solving the system equations with the condition $x_0 \in [0,1]$, we get the values of the constants C_1,C_2 and x_0.

The total load of the river will be:

$$TL = \int_a^b \rho(x)dx = v(c_{max} - c_0)\int_0^1 R(x)dx + L\lambda c_0 \quad (26)$$

in which

$$\int_0^1 R(x)dx = x_0 Rmax + (1 - x_0)\Lambda$$

The load capacity of the river section including the load from upstream will be:

$$LC = v(c_{max} - c_0)[x_0 Rmax + (1 - x_0)\Lambda] + L\lambda c_0 + c_0 Q \quad (27)$$

4 Applies to specific river sections

Consider the river section with the following characteristics (Figure 1):

- Length L=1000 (m)
- Discharge Q=200 m^3/s
- Cross-section A_s=300 m2
- Velocity $v=Q/A_s=0.67$ (m/s)
- Pollutants c (eg BOD, COD): affected by degradation and dispersion
- Decomposition coefficient (decay, deposition...): λ=0.2/day
- Partition coefficient (molecular and turbulent diffusion): α= 1 (m^2/s)
- Concentration of C at upstream inlet: c_0=4 mg/L
- Permissible concentration: c_{max}=15 mg/L
- Maximum allowable discharge density near the riverbank: ρ_{max}=0.1 mg/L.s (equivalent to 8.64 $kg/m/day/m^2$

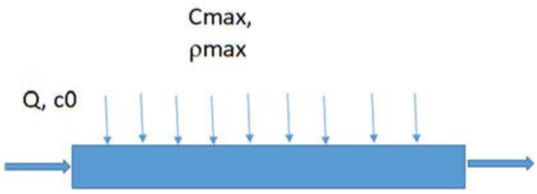

Figure 1 The illustration of a specific river section

In case of dispersion coefficient (molecular and turbulent diffusion): α = 0 (m^2/s)

Calculation results of load capacity and distance x_0 according to the formulas (14),(15) and (13) are presented below (Teble 1):

Table 1 The calculation results of load capacity and distance x0

Total Load Capacity (kg/day)	Load Capacity along river (kg/day)	Upstream (kg/day)	x_0 (m)
260076	190956	69120	73.35

The distribution of concentration c along the river and the load along the river is shown in Table 2, and Figures 2, 3 below:

Table 2 The distribution of concentration c along the river and the load along the river with α= 0 (m^2/s)

x (m)	c(x) (mg/l)	ρ(x)	
		$kg/m/day/m^2$	kg/m/day
0	4	8.64	2592
10	5.50	8.64	2592
20	7.00	8.64	2592
30	8.50	8.64	2592
40	10.00	8.64	2592
50	11.50	8.64	2592
60	13.00	8.64	2592
73.3	14.99	8.64	2592
75	15	0.003	0.9
100	15	0.003	0.9
200	15	0.003	0.9
300	15	0.003	0.9
400	15	0.003	0.9
500	15	0.003	0.9
600	15	0.003	0.9
700	15	0.003	0.9
800	15	0.003	0.9
900	15	0.003	0.9
1000	15	0.003	0.9

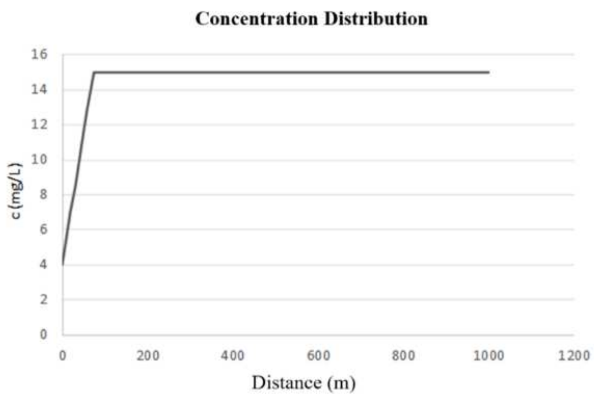

Figure 2 The distribution of concentration along the river

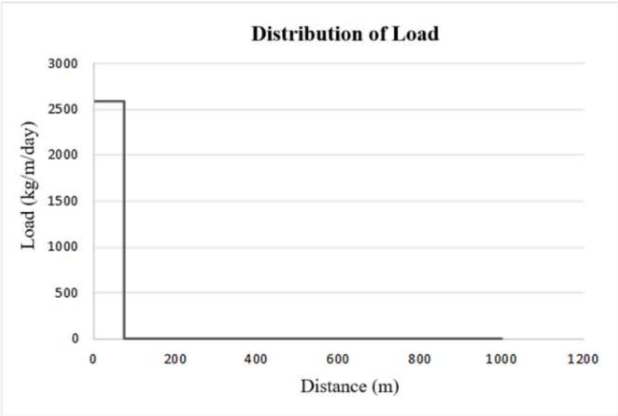

Figure 3 The distribution of load along the river

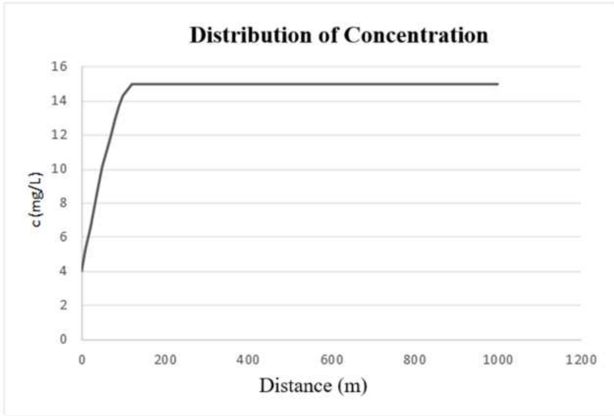

Figure 4 The distribution of concentration along the river

In case of dispersion coefficient (molecular and turbulent diffusion): α= 40 (m^2/s)

Calculation results of load capacity and distance x_0 according to the formulas 26, 27, 25 are presented below (Table 3):

Table 3 The calculation results of load capacity and distance x0

Total Load Capacity (kg/day)	Load Capacity along river (kg/day)	Upstream (kg/day)	x_0 (m)
388078	318958	69120	126

The distribution of concentration c along the river and the load along the river is presented in Table 4, and Figures 4, 5 below:

Distribution of concentration c along river and load along river with = 40.

Table 4 The distribution of concentration c along the river and the load along the river with α= 40 (m^2/s)

x (m)	c(x) (mg/l)	ρ(x)	
		kg/m/day/m^2	kg/m/day
0	4	8.64	2592
10.182	5.32	8.64	2592
20.365	6.61	8.64	2592
30.547	7.85	8.64	2592
40.730	9.04	8.64	2592
50.912	10.16	8.64	2592
61.095	11.21	8.64	2592
70.004	12.06	8.64	2592
80.187	12.93	8.64	2592
90.369	13.69	8.64	2592
100.552	14.29	8.64	2592
110.734	14.73	8.64	2592
120.916	14.97	8.64	2592
126.008	15	8.64	2592
127.000	15	0.003	0.9
600	15	0.003	0.9
700	15	0.003	0.9
800	15	0.003	0.9
900	15	0.003	0.9
1000	15	0.003	0.9

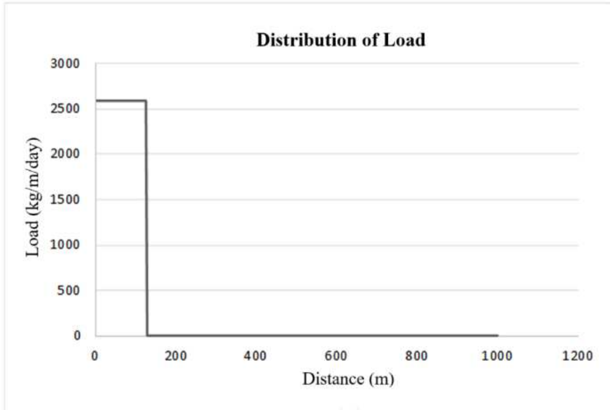

Figure 5 The distribution of load along the river

It can be seen that in the field = 40 (m^2/s) the load carrying capacity of the river section increases to about 128002 kg/day (about 49%) compared to the case of α=0, and the distance x_0 increases to about 50 m. Thus, the influence of dispersion coefficient is very large on the LC of the river section and should be considered in the calculation.

5 Conclusion

This study successfully developed an analytical solution for optimizing the pollution load capacity of a river segment, addressing both theoretical and practical aspects of water quality management. The derived solutions for cases with and without dispersion effects provide a clear methodology for determining the maximum allowable pollutant discharge while adhering to environmental standards.

The application to a specific river segment highlighted the significant impact of dispersion coefficients on the river's load capacity, with a 49% increase observed when dispersion was considered. These findings underscore the importance of incorporating dispersion processes in pollution load calculations to achieve accurate and sustainable results.

Future research could extend this model to more complex river systems, including multi-dimensional flows and dynamic boundary conditions. Additionally, integrating real-time monitoring data could enhance the model's predictive capabilities. This work serves as a valuable tool for policymakers and environmental engineers in designing effective pollution control strategies, ultimately contributing to the preservation of water resources for future generations.

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Review process
Single-blind peer review process.

Acta Tecnología - International Scientific Journal about Technologies
Volume: 11 2025 Issue: 3 Pages: 127-136 ISSN 2453-675X

https://doi.org/10.22306/atec.v11i3.290 *Received: 16 May 2025; Revised: 14 July 2025; Accepted: 12 Sep. 2025*

Impact of weather conditions on forecasting the number of road accidents in Poland

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Keywords: traffic accident, pandemic, weather conditions, forecasting, exponential smoothing.
Abstract: The incidence of road traffic accidents in Poland remains significantly high. When compared to the average levels recorded across European Union (EU) member states, Poland's rate is approximately 1.3 times greater. The COVID-19 pandemic contributed to a temporary reduction in road accidents. The primary objective of this study is to forecast the number of road accidents in Poland under varying weather conditions. The analysis is based on monthly accident data for the years 2007-2021, obtained from national police records. Using this historical data, projections for the years 2022-2024 were developed. The findings suggest that, despite minor downward trends, the level of road traffic incidents is likely to remain comparable to pre-pandemic patterns. It is important to note, however, that the pandemic has introduced distortions that may affect the accuracy of the forecast. The predictive analysis was conducted in Statistica using selected time series models. Forecasts for 2022-2024 reveal that the majority of accidents are expected to occur under favorable weather conditions, with an average of 24,342 incidents. This is likely associated with increased traffic volume during such conditions. Nevertheless, extreme weather events pose heightened risks: heavy rainfall can lead to as many as 4,347 accidents, while strong winds may contribute to up to 12,880 incidents. Additionally, intense sunlight—through reduced visibility—accounts for an average of 4,150 accidents annually. Although fog and snowfall are less frequent (averaging 109 and 352 incidents respectively), they represent particularly hazardous conditions due to compromised road traction.

1 Introduction

Road accidents are incidents that result not only in injuries or fatalities among road users but also in significant property damage. According to the World Health Organization (WHO), approximately 1.3 million people lose their lives each year due to road traffic crashes. In many countries, road accidents account for nearly 3% of their gross domestic product (GDP). Furthermore, they remain the leading cause of death among children and young adults aged 5 to 29 [1]. In response to this global challenge, the United Nations General Assembly has adopted an ambitious goal: to reduce road traffic deaths and injuries by half by the year 2030.

The severity of a traffic accident is a key factor in assessing its consequences. Accurate prediction of accident severity is crucial for authorities aiming to develop effective traffic safety policies designed to prevent crashes, minimize fatalities and injuries, and reduce material losses [2,3]. Identifying critical determinants of accident severity is a fundamental step in formulating countermeasures that can mitigate or eliminate severe outcomes [4]. In this context, Yang et al. proposed a multi-node deep neural network (DNN) framework to predict varying levels of injury severity, fatalities, and property damage. This approach facilitates a comprehensive and precise assessment of accident severity [5].

Accident data are typically obtained from various sources, most commonly collected by governmental agencies. These data are gathered from police accident reports, insurance company records, and hospital databases. Once collected, the information is often compiled and analyzed at a broader scale within the transport sector [6].

Today, intelligent transportation systems (ITS) play a vital role in the collection and analysis of road accident data. Modern vehicles equipped with GPS devices generate continuous data streams [7]. Additionally, microwave vehicle detection systems installed on roadways capture information such as speed, traffic flow, and vehicle types [8]. License plate recognition technologies further expand the capacity to gather traffic data over time [9]. Social media can also serve as an unconventional data source, though the accuracy of this information is often limited due to the inexperience or unreliability of individuals posting such content [10].

In order to ensure the accuracy and reliability of traffic accident analyses, it is essential to integrate and reconcile data from multiple sources. The combination of heterogeneous datasets significantly enhances the quality of the resulting insights [11].

Vilaca et al. [12] conducted a statistical analysis aimed at evaluating accident severity and establishing relationships between crash types and the characteristics of those involved. Their study offered recommendations for improving traffic safety standards and related public policies. Similarly, Bak et al. [13] analyzed traffic safety in a selected region of Poland by examining accident counts and underlying causes. The research employed multivariate statistical methods to assess the safety behaviors of those responsible for accidents.

The selection of accident data sources for analysis largely depends on the specific traffic safety problem under consideration. Incorporating statistical models along with real-world driving data or intelligent traffic system outputs helps improve the accuracy of forecasts and supports effective accident prevention strategies [14].

A variety of forecasting methods are found in the literature. Among them, time series models are the most widely used for predicting accident counts [15,16]. However, such methods have limitations, including the inability to evaluate the quality of prior forecasts and the presence of autocorrelated residuals [17]. Procházka et al. [18] applied a multi-seasonality model for forecasting, while Sunny et al. [19] utilized the Holt-Winters exponential smoothing technique. Nevertheless, these models often lack the capacity to incorporate exogenous variables [20,21].

Vector autoregressive (VAR) models, though effective, require a large number of observations to estimate parameters reliably [22]. Other autoregressive techniques have also been used, such as the models by Monedero et al. [23] and Al-Madani [24], which were applied to fatality prediction. Regression curve-fitting models are also employed, though they typically assume simple linear relationships [25] and require that the series be stationary with an appropriate autoregressive order [26].

Biswas et al. [27] employed a Random Forest regression model for traffic accident prediction. This method, while capable of handling groups of correlated features, often favors smaller feature subsets and is sensitive to variations in input, which may result in instability and overfitting in peak predictions [28,29]. Chudy-Laskowska and Pisula [30] tested an autoregressive quadratic trend model, a univariate periodic trend model, and an exponential smoothing model. Moving average models, though simple, suffer from limitations such as low accuracy, data loss within sequences, and poor handling of trends and seasonality [31].

Procházka and Camej [32] implemented the GARMA method, which imposes constraints on parameter space to ensure stationarity. ARMA models are commonly used for stationary series, while ARIMA and SARIMA are suited for non-stationary data [19,32-34]. These models are highly flexible but can be challenging to identify and interpret without extensive expertise [35]. Furthermore, ARIMA models are inherently linear, which limits their applicability to nonlinear phenomena [20].

Chudy-Laskowska and Pisula [36] also used ANOVA for forecasting accident counts. While informative, this method requires additional assumptions, such as sphericity, the violation of which may lead to misleading conclusions [37]. Artificial neural networks (ANNs) are increasingly utilized for forecasting in this domain. However, they demand specialized knowledge, are sensitive to initial conditions, and are often criticized as "black-box" models due to their lack of interpretability [36,38,39].

A novel approach involves using the Hadoop framework, as demonstrated by Kumar et al. [40], although this method is not well suited for small datasets [41]. Karlaftis and Vlahogianni [34] applied the GARCH model, which, while powerful, is computationally complex and difficult to calibrate [42,43]. McIlroy and colleagues used the Augmented Dickey-Fuller (ADF) test [44], although its effectiveness can be limited by low statistical power when detecting autocorrelation in the error terms [45].

Data mining techniques have also been used to forecast accident frequency [46,47], though they may produce overly general or ambiguous outputs due to the volume of unstructured data [48,49]. Some researchers, including Sebe et al. [50], propose combining multiple models to enhance predictive performance. Parametric models are another alternative, as outlined by Bloomfield [51].

Research on the impact of weather on forecasting the number of traffic accidents in Poland is important because weather significantly affects driving safety. Downpours, snow or fog increase the risk of collisions, so better forecasts will help alert drivers and services. This will reduce the cost of accidents - rescues, traffic jams and road repairs.

Today, the climate is changing - violent storms and glaze are more common in Poland, so up-to-date data is needed. Police and road managers could use such forecasts to better manage traffic, such as sending more patrols to dangerous areas.

In addition, Poland can learn from Western countries, where weather warning systems are more developed. New technologies, such as artificial intelligence, will help predict dangers more accurately. As a result, safety and traffic flow will improve.

Therefore, the purpose of this article is to develop an adaptive model for forecasting the number of traffic accidents in Poland, taking into account meteorological variables such as precipitation, temperature and visibility, in order to improve the accuracy of predictions.

2 Methodology

A substantial number of fatalities continue to occur on Polish roads. Although a gradual year-over-year decline has been observed, the overall figure remains alarmingly high. While the COVID-19 pandemic temporarily reduced the number of road accidents, the incidence remains significantly elevated. A monthly analysis of the data reveals distinct fluctuations, though the overall trend indicates a continued decrease in accident frequency. Despite this, Poland still reports a considerably higher number of accidents compared to the European Union average.

The data also show that the lowest number of accidents tends to occur during foggy conditions, likely due to more cautious driver behavior and reduced speeds. In contrast, the highest accident rates are observed during clear weather conditions, possibly due to increased traffic volume and riskier driving behavior. These findings highlight the importance of implementing targeted measures to further reduce accident rates and to identify the specific conditions under which accidents are most likely to occur (Figure 1).

The literature review and methodology for this study proceeded as follows: Based on statistical data provided by the Polish Police concerning road accident frequency under varying weather conditions, a set of forecasts was generated using 15 exponential smoothing models within the Statistica software environment. Subsequently, forecast errors were calculated for each model. The model yielding the lowest forecast error was selected as the most accurate predictor of future accident trends.

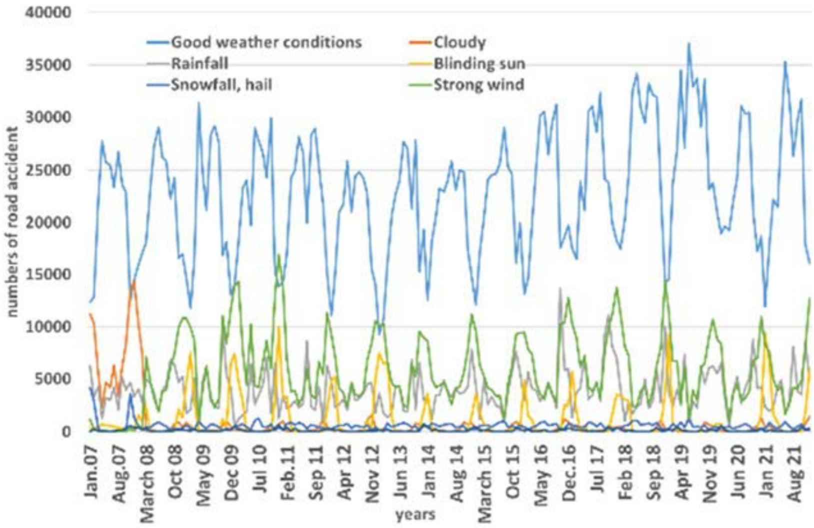

Figure 1 Number of accidents in Poland from 2007 to 2021

The variability in the number of road accidents under different weather conditions was assessed using the Kruskal-Wallis test. In this analysis, the test statistic was 133.8816 with a significance level of p = 0.000. These results provide strong evidence to reject the null hypothesis of equal mean accident levels across weather conditions. Thus, it can be concluded that the average number of road accidents significantly differs depending on the prevailing weather.

Furthermore, the analysis confirms a consistent decline in the average number of road accidents over the studied period. There is also a distinct variation in accident frequency relative to weather conditions: the highest number of accidents occurs during favorable weather, while the lowest number is observed in adverse weather conditions. This trend is likely attributable to more cautious driving behavior during poor weather, such as reduced speed and heightened attention (Figure 2).

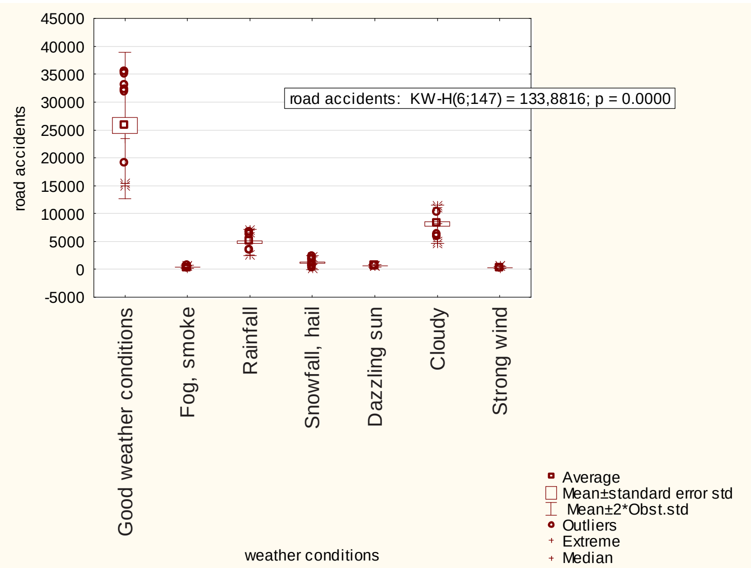

Figure 2 Comparison of the average number of road accidents in Poland by weather conditions

Based on the analysis of the number of road accidents in Poland, it can be concluded that they are seasonal in nature with a downward trend. Therefore, for further analysis, selected time series models were used to determine the projected number of road accidents in the analyzed period depending on the prevailing weather conditions. Weather conditions were divided into the following categories:

- good weather conditions,
- fog, smoke,
- precipitation,
- snowfall, hail,
- blinding sun,
- cloudy,
- strong wind.

3 Forecasting the number of road accidents

To forecast the number of traffic accidents, selected exponential smoothing models were employed. This method involves representing the time series of the forecasted variable using a weighted moving average, where the weights decline exponentially for past observations. These weights were optimally determined by the Statistica software, in which the analysis was conducted. The forecast is thus based on a weighted average of both current and historical data points. The accuracy of the forecast produced using this method is highly dependent on the selection of the specific model and its parameter settings.

The following errors of expired forecasts determined from equations (1-5) were used to calculate measures of analytical forecasting perfection:

- ME – mean error
  $$ME = \frac{1}{n}\sum_{i=1}^{n}(Y_i - Y_p) \qquad (1)$$
- MAE –mean everage error
  $$MAE = \frac{1}{n}\sum_{i=1}^{n}|Y_i - Y_p| \qquad (2)$$
- MPE –mean percentage error
  $$MPE = \frac{1}{n}\sum_{i=1}^{n}\frac{Y_i - Y_p}{Y_i} \qquad (3)$$
- MAPE - mean absolute percentage error
  $$MAPE = \frac{1}{n}\sum_{i=1}^{n}\frac{|Y_i - Y_p|}{Y_i} \qquad (4)$$
- MSE – mean square error
  $$MSE = \frac{1}{n}\sum_{i=1}^{n}(Y_i - Y_p)^2 \qquad (5)$$

where:
n – the length of the forecast horizon,
Y – observed value of road accidents,
Y_p – forecasted value of road accidents.

In order to compare the number of accidents during a pandemic and if it did not exist, the mean absolute percentage error was minimized. To forecast the number of accidents depending on the prevailing weather conditions, data from the Polish Police from 2007-2021 was used. The forecast results for the prevailing weather conditions are shown in Figures 3-9. The different forecasting methods used in the study are coded M1, M2,......, Mn. The forecasting techniques used in the study are as follows:

M1 - moving average method 2-points,
M2 - moving average method 3-points,
M3 - moving average method 4-points,
M4 - exponential smoothing no trend seasonal component: none,
M5 - exponential smoothing no trend seasonal component: additive,
M6 - exponential smoothing no trend seasonal component: multiplicative,
M7 - exponential smoothing linear trend seasonal component: none HOLTA,
M8 - exponential smoothing linear trend seasonal component: additive,
M9 - exponential smoothing linear trend seasonal component: multiplicative WINTERSA,
M10 - exponential smoothing exponential seasonal component: none,
M11 - exponential smoothing exponential seasonal component: additive,
M12 - exponential smoothing exponential seasonal component: multiplicative,
M13 - exponential smoothing fading trend seasonal component: none,
M14 - exponential smoothing fading trend seasonal component: additive,
M15 - exponential smoothing fading trend seasonal component: multiplicative).

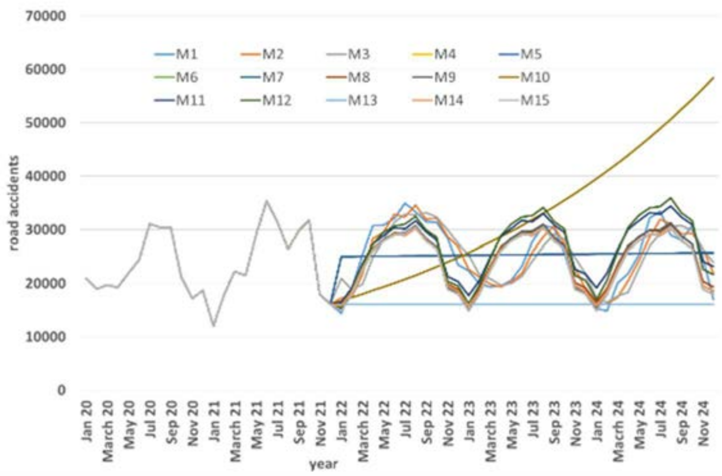

Figure 3 Forecasting the number of traffic accidents during good weather conditions from 2022 to 2024

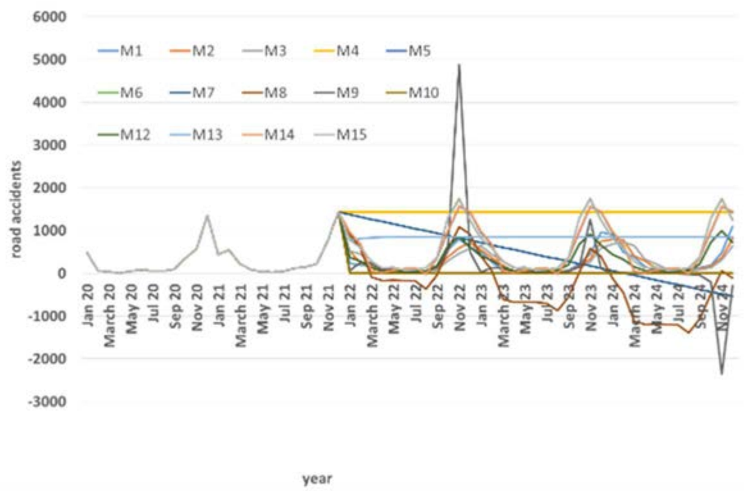

Figure 4 Forecasting the number of traffic accidents during cloud cover from 2022 to 2024

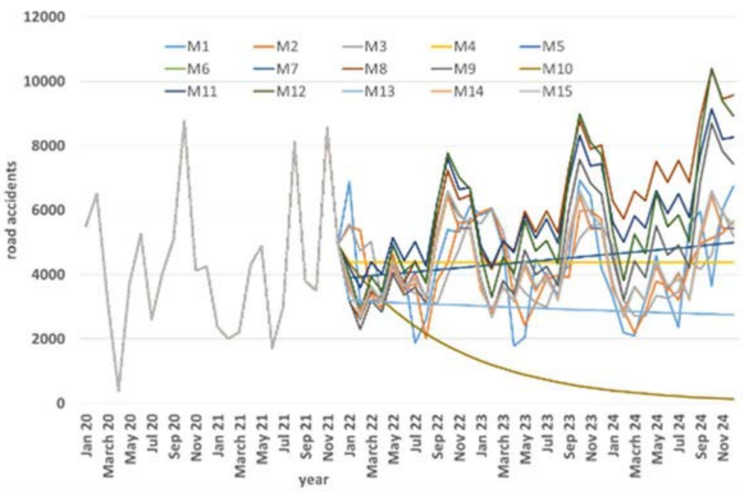

Figure 5 Forecasting the number of accidents during rainfall from 2022 to 2024

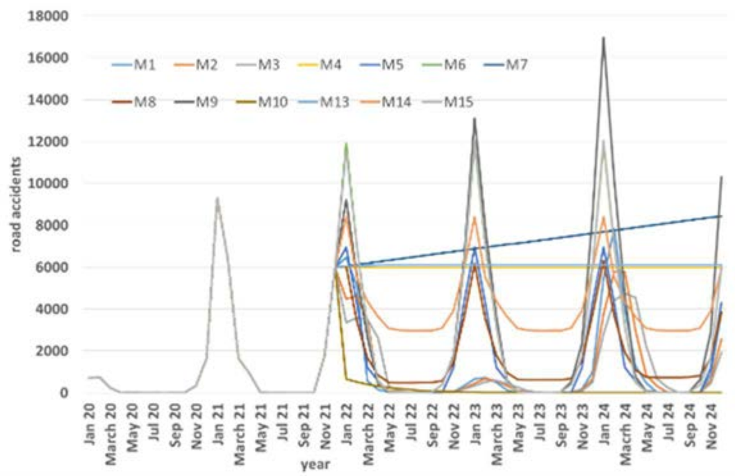

Figure 6 Forecasting the number of traffic accidents during solar glare from 2022 to 2024

Volume: 11 2025 Issue: 3 Pages: 127-136 ISSN 2453-675X

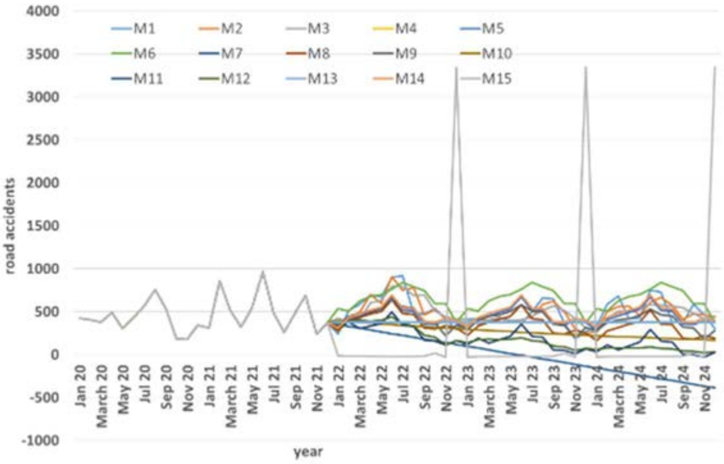

Figure 7 Forecasting the number of road accidents during snow and hailstorms from 2022 to 2024

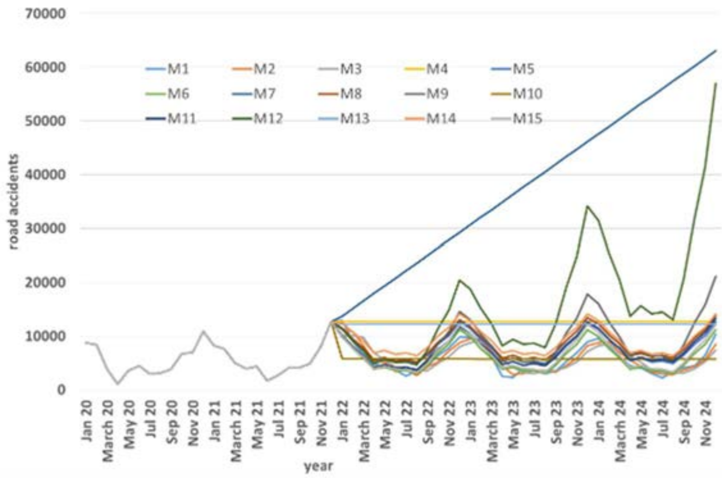

Figure 8 Forecasting the number of road accidents during high winds from 2022 to 2024

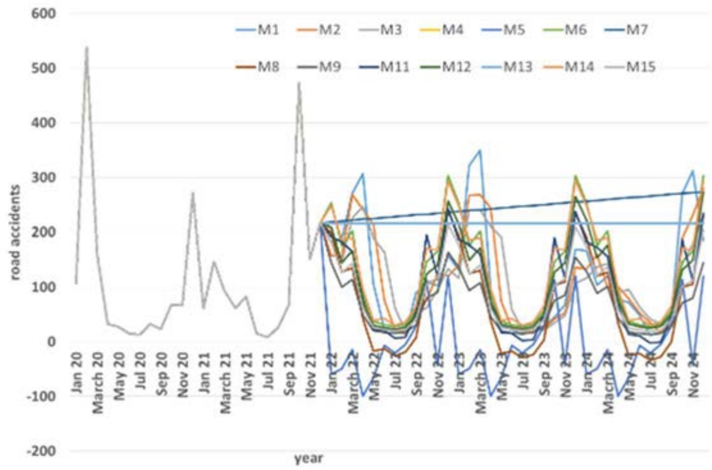

Figure 9 Forecasting the number of traffic accidents during fog, smoke in 2022-2024

Based on the results obtained, it can be concluded that not all of the applied forecasting methods proved effective for the case under study. In the subsequent step, the forecasting model with the lowest Mean Absolute Percentage Error (MAPE) was identified and presented as the most accurate method. The following methods were selected as the best forecasting methods for each day of the week:

- Good weather conditions - M5
- Overcast - M12
- Rainfall - M10
- Dazzling sunshine - M14

- Snowfall, hail - M8
- Strong wind - M1
- Fog, smoke - M12

The analysis of the obtained data suggests that the effectiveness of the forecasting method depends on the prevailing weather conditions. In most cases, the lowest MAPE values were achieved using exponential smoothing techniques. Based on these results, a forecast of the number of traffic accidents under varying weather conditions was generated and is presented in Figure 10 and Table 1. The corresponding forecast errors are summarized in Table 2.

The results indicate that traffic accident levels are expected to remain similar to those observed prior to the COVID-19 pandemic, with only a slight decline. However, it is important to acknowledge that the pandemic has introduced anomalies that may have affected the accuracy of the forecasting models. A MAPE value of 10% or lower is considered indicative of an effective forecasting method. An exception was observed in the case of sun glare, for which all methods produced relatively high error values, likely due to greater variability and unpredictability in such conditions.

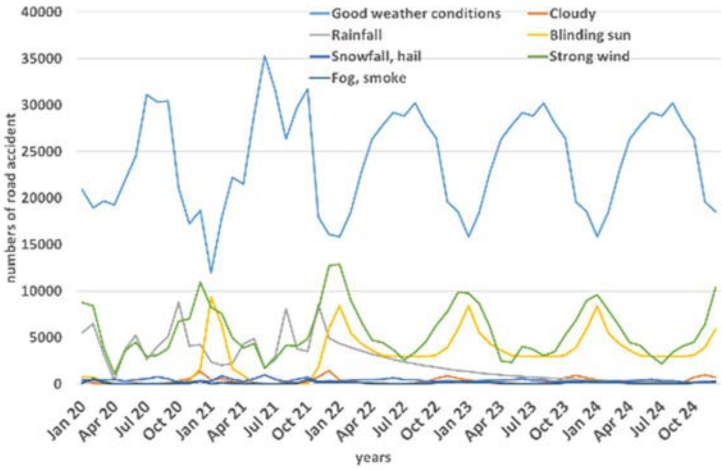

Figure 10 Optimal forecast number of road accidents depending on weather conditions in 2022-2024

Table 1 Forecast values

Road accidents	Good weather conditions	Cloudy	Rainfall	Blinding sun	Snowfall. hail	Strong wind	Fog. smoke
max	30224.98	990.85	4346.5	8417.73	639.59	12879.5	272.68
min	15830.15	36.28	134.9	2960.12	164.23	2176.5	23.6
Average	24342.424	300.5264	1242.331	4150.047	351.6436	5746.472	108.9183

Table 2 Forecast errors

forecast error/ weather conditions	Good weather conditions	Cloudy	Rainfall	Blinding sun	Snowfall. hail	Strong wind	Fog. smoke
ME	291.44	311.48	1727.71	24.32	1.11	258.47	51.01
MPE	2461.46	434.77	2113.51	935.34	290.30	2271.72	71.61
MSE	10166119.83	1217794.35	7987983.38	2554231.66	243922.08	11503810.33	15540.12
MAPE [%]	0.37	3.36	20.40	155.35	6.60	10.24	0.02
MAE [%]	11.58	78.16	57.05	952.11	110.42	42.42	60.37

The road accident forecast for 2022-2024 shows that most incidents occur in good weather conditions (24,342 on average), due to higher traffic volumes. However, extremes are dangerous: during a downpour (max. 4,347 accidents) and strong winds (max. 12,880), the risk rises sharply. The blinding sun causes an average of 4,150 accidents, mainly through reduced visibility. Fog and snow, although less frequent (109 and 352 accidents on average), are particularly dangerous due to low grip.

Based on the study, it can be concluded that the largest errors are observed in rainfall and strong winds, indicating that the model has difficulty predicting accidents in extreme conditions. The smallest errors are observed in good weather conditions and fog/smoke, suggesting that the model is reasonably accurate under stable conditions.

Detailed analysis by weather conditions:

a) Good weather conditions

Low MAPE (0.37%) and MAE (11.58%) - the model performs very well.

High MPE (2461.46) - may indicate systematic underestimation of accidents.

b) Overcast

Moderate MAPE (3.36%), but high MAE (78.16%) - model performs well under overcast, but absolute errors are significant.

c) Rainfall

Very high MSE (7987983.38) and MAPE (20.40%) - model has great difficulty predicting accidents during rain.

High ME (1,727.71) - strong overestimation of the number of accidents.

(d) Blinding sun

Extremely high MAPE (155.35%) and MAE (952.11%) - the model completely fails under such conditions.

Low ME (24.32) - errors may be tolerable, but the spread is huge (high MSE).

(e) Snow and hail

Relatively low MSE (243922.08) and MAPE (6.60%), but high MAE (110.42%) - the model partially copes, but absolute errors are large.

(f) Strong winds

High MSE (11503810.33) and MAPE (10.24%) - as with rain, the model has trouble forecasting.

High MPE (2271.72) - strong overestimation.

g) Fog and smoke

Lowest MAPE (0.02%)

Taking into account the problems that occur during forecasting, the following conclusions can be drawn: Extreme conditions (blinding sun, rainfall, strong wind) lead to large forecast error and High MPE and MSE indicate the need for model calibration, especially for precipitation. Analyzed the model worked well during good weather, fog.

The model performs best under stable weather conditions, while the largest errors occur under precipitation, strong winds and blinding sun. It is necessary to optimize the algorithms for these phenomena to improve forecast accuracy.

4 Conclusion

The forecast of the number of road accidents in Poland was developed using exponential smoothing methods implemented in the Statistica software. The weighting parameters were optimized by the program to minimize both the Mean Absolute Error (MAE) and the Mean Absolute Percentage Error (MAPE).

The findings indicate that the number of traffic accidents is likely to remain at a level similar to that observed before the COVID-19 pandemic, with a slight downward trend. However, it should be emphasized that the pandemic introduced irregularities that may have affected the reliability of the results. In most cases, a forecast error of no more than 10% confirms the effectiveness of the selected forecasting methods—except for one outlier.

The traffic accident forecast presented in this study can serve as a foundation for future policy development aimed at reducing accident rates in the analyzed regions. An example of such a measure is the introduction of stricter penalties for traffic violations in Poland, which came into effect on January 1, 2022.

In their future research, the authors plan to incorporate additional variables that influence accident frequency in Poland. These factors may include traffic volume, day of the week, and the age of the accident perpetrator, among others.

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Review process
Single-blind peer review process.

Acta Tecnología - International Scientific Journal about Technologies
Volume: 11 2025 Issue: 3 Pages: 137-140 ISSN 2453-675X

https://doi.org/10.22306/atec.v11i3.292 *Received: 20 May 2025; Revised: 03 July 2025; Accepted: 03 Sep. 2025*

Logistical aspects of mining rescue in Slovakia – status, challenges and perspectives

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Keywords: mining rescue, logistics, occupational safety, emergency service, Slovakia.

Abstract: Mining rescue in Slovakia represents a specific component of the rescue system with a long tradition and a significant position in the field of occupational health and safety. Its main task is to resolve underground emergencies, including accidents, collapses, fires or gas leaks, while the activities of mining rescue workers require high professional preparedness and logistical coordination. The article focuses on the analysis of the strengths and weaknesses of the mining rescue system in Slovakia with regard to organizational, technical, logistical and social aspects. The paper presents findings from literature, legislation and practical experience, supplemented by the international context and recommendations for further development.

1 Introduction

Mining is a risky activity. Underground accidents often require immediate intervention by specialized units that have expert knowledge, physical preparedness and specific technical means. Mining rescue in Slovakia has a tradition of more than a century and is one of the professions that require a high level of solidarity, dedication and logistics of interventions.

Figure 1 Mine rescuers inspecting parts of the mine

Mining is one of the traditional sectors of the Slovak economy, and its historical importance is linked to mining towns, metallurgy and industrial development. Despite the decline of coal and ore mining, mining rescue remains an important part of the country's security system. Its importance goes beyond the mining operations themselves, as the know-how and capacities of the Main Mining Rescue Station (HBZS) are also used in interventions in the chemical industry, in construction or in solving accidents in underground structures (tunnels, collectors) (Figure 1).

The purpose of this article is to analyze the current state of mining rescue in Slovakia, identify its strengths and weaknesses, and emphasize its social and moral significance [1]. At the same time, attention is also paid to aspects of logistics and the organization of interventions, which are key to effective management of crisis situations. It clarifies why it is necessary to examine this area also from the perspective of logistics. Logistics is a key element in the management of human resources, technology, materials, and time factors in crisis situations. Effective logistics can decide the speed and success of the intervention, and thus the saving of human lives.

2 Literature review and legislative framework

The issue of mining rescue is enshrined in the legislation of the Slovak Republic, in particular in Act No. 51/1988 Coll. on mining activities, explosives and state mining administration and in related decrees. The role of coordination and methodological management is fulfilled by the Main Mining Rescue Station (HBZS) in Prievidza and the Main Mining Office (HBÚ) [1]. Mining rescue is presented rather marginally in the professional literature. In Slovakia, the basic source of methodological and technical knowledge is the Main Mining Rescue Station in Prievidza (HBZS), which regularly publishes activity reports, intervention statistics and professional methodologies.

According to available sources [1,2], Slovakia is one of the few European countries where mining rescue is still systematically developed and maintained as an independent organizational unit. The European Agency for Safety and Health at Work [3] emphasizes the importance of specialized rescue services in preventing and resolving crises, with logistical preparation and the availability of equipment being among the decisive factors for the success of the intervention. An international perspective is provided by EU-OSHA, which analyzes occupational risks in mining and related industries. Studies by the Technical University of Košice (TUKE), especially in the area of process safety and reliability, contribute to the issue of crisis management logistics. On the academic campus, the Department of Mining and Geotechnics regularly publishes studies on safety and rescue [4-6]. Czech literature is also worth mentioning (Mining Rescue Corps, HBU), which presents experiences from acute interventions in the Ostrava-Karvinský district. This knowledge is transferable to Slovak conditions due to the similarity of the legislative environment and the nature of mining operations [7].

3 Organization of mining rescue services in Slovakia

Mining rescue services in Slovakia are centrally organized through the HBZS in Prievidza. The HBZS provides [1,4,7]:

- emergency units for mining operations,
- professional training and education of rescuers,
- special equipment (breathing equipment, detection devices, measuring equipment),
- research and development of technical means,
- coordination of interventions throughout the territory of the Slovak Republic.

The legislative framework is determined by the Mining Act No. 44/1988 Coll. and implementing regulations, which stipulate the obligation of employers to provide mining rescue services.

4 Logistic processes in mining rescue

The intervention of mine rescuers is a complex logistical operation. Logistics plays a key role in three basic levels [8]:

Personnel logistics – selection, training and emergency provision of teams, mobilization of the team at short notice.

Material logistics – management and maintenance of special equipment (breathing apparatus, vehicles, measuring equipment), preparation of equipment and transport to the intervention site, supply of oxygen equipment and energy.

Information logistics – flow of information between the intervention team, HBZS, operations and state administration bodies, cooperation with other components (firefighters, paramedics, police).

According to HBZS, logistics represents up to 40% of the overall success of the intervention, since even a top-trained team without the necessary resources and coordination is unable to intervene effectively.

4.1 Strengths of mining rescue services in Slovakia

Strengths include:

- Long tradition and experience: Centralized structure and high expertise of HBZS, Slovakia has a built system of mine rescue stations, which have a number of successful interventions.
- Expertise and preparedness: Mine rescuers undergo specialized training, regular exercises and psychological preparation. Experience from interventions outside mining (tunnels, chemical operations).
- Technical equipment: Modernized breathing apparatus, monitoring equipment and special transport vehicles increase the effectiveness of interventions.
- Logistical coordination: A clearly set command and communication system enables rapid mobilization of forces and resources.
- Social credit: The profession of a mine rescuer is associated with a high degree of respect and trust of the public. Connections with international rescue organizations.

4.2 Weaknesses and challenges

Weaknesses and challenges include:

- Decline in mining activity: Insufficient funding due to the decline in mining in Slovakia leads to a reduction in the number of active rescuers and threatens the continuity of the system.
- Financial constraints: Outdated technology and the need for its modernization, insufficient resources for modernization of technology and infrastructure limit the development of services.
- Personnel capacities: Personnel weakening due to the departure of experienced experts, recruiting new rescuers is difficult due to specific requirements and risks.
- International isolation: The Slovak system is less connected to foreign initiatives compared to other EU countries.
- Administrative burden: A high level of bureaucracy slows down the process of innovation and flexibility of the system.

4.3 Social and moral significance

Mining rescue is not just a profession, but also a mission. Rescuers protect human lives, property and the environment through their work (Figure 2). In the eyes of the public, they are a symbol of solidarity and courage. Their work goes beyond mining itself - their experience is also applied in emergency situations outside mining, such as floods or technological accidents (Figure 3).

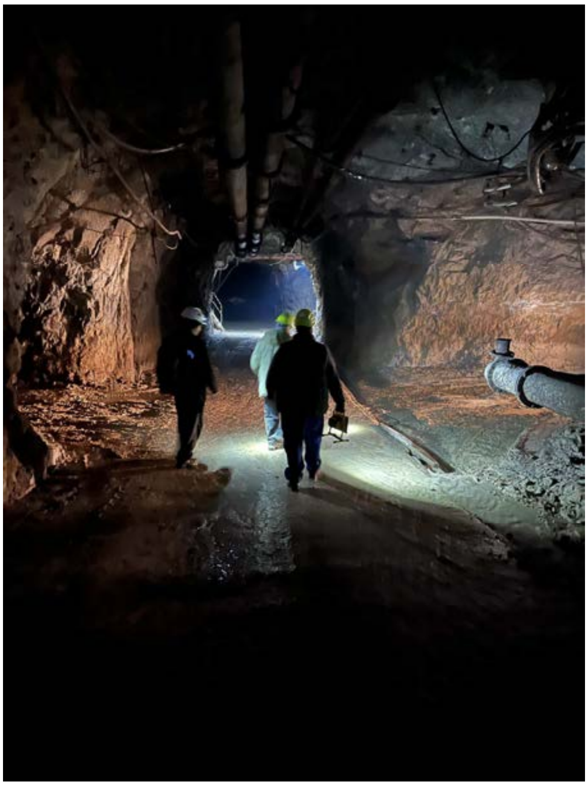

Figure 2 Mine rescuers in the mining area

Figure 3 Technology in the mining area

5 Comparison of mining rescue services

Mining rescue in Slovakia is based on strong traditions and many years of experience, but for an objective assessment of its current level, it is necessary to compare it with foreign models that offer inspiring solutions in the field of organization, technical support and financing. Countries with the most significant standards in the field of mining safety include Germany, the Czech Republic, Poland and Australia, each of which represents a different approach to the systemic provision of rescue services [8].

Germany is characterized by a high degree of centralization and state funding, which ensures the stability and continuity of rescue services. Preventive measures, mandatory training and strict legislation are at the forefront, which significantly reduces the risk of serious incidents. An important element is the use of advanced monitoring technologies - for example, systems for continuous monitoring of gas concentrations, movement of people or stability of mining areas. Logistical readiness is supported by a network of centralized rescue stations, which enable rapid mobilization of units and equipment.

Poland represents a different model, in which there is a noticeable greater involvement of private entities in the organization of the mine rescue service. Although the state retains a regulatory and supervisory role, a significant part of the responsibility lies directly with the mine operators. This model brings advantages in the form of higher technological variability and more flexible financing, but at the same time creates challenges in the area of coordination and a unified approach to large-scale interventions. Poland is an example of a country where modern technologies (e.g. robotic devices or thermal imaging systems) significantly improve intervention readiness, but the problem remains the lack of qualified personnel and the need for their systematic replenishment.

Australia is an example of a comprehensive approach to industrial safety, in which mining rescue is fully integrated. Rescue units operate within a broad framework of industrial protection, which combines legislation, trade unions, inspectorates and employers themselves. There is a significant emphasis on transparency - all incidents are systematically recorded and publicly analyzed. The Australian model is among the most technologically advanced: it uses drones, remotely controlled robots, automated monitoring systems and sophisticated simulation technologies that allow for the prediction of risks and the optimization of interventions.

Slovakia can boast a long tradition and high level of expertise of rescue workers, who are also respected in the international environment. A strong point is also a strong connection to state authorities and security forces. However, a weak point is the lack of technological modernization and financial sustainability of the system, which is associated with the gradual decline of mining. Compared to countries such as Germany or Australia, Slovakia has not yet reached the level of automation and use of modern technologies, which represents room for future development.

The future of mining rescue is inextricably linked to the challenges of energy transformation, the decline of traditional mining and the changing risk environment. Inspiration from the experiences of developed countries is therefore a key prerequisite for the Slovak system to remain functional, effective and socially recognized.

6 Discussion

A comparison with foreign countries shows that the Slovak system has a high professional quality but lags behind in the financial and technical areas. In the Czech Republic and Poland, the financing of rescue services is tied to state resources to a greater extent than in Slovakia. In addition, modern digital technologies are used in Germany and Austria to monitor interventions in real time. Logistics is therefore an area where the Slovak mining rescue service has significant room for improvement - especially in the areas of digitalization, predictive maintenance of equipment and modern human resource management [9,10].

7 Conclusions

Mining rescue in Slovakia is a unique system that, despite the decline in mining activities, plays an important role in the country's safety infrastructure. The analysis showed that the strengths are expertise and centralized structure, and the weaknesses are financing and technical support.

The aim of the article was to point out the importance of mining rescue not only from the point of view of logistics, but also from the point of view of the social and moral dimension. In the future, it is necessary to look for solutions that will ensure its sustainability and adaptation to new challenges. Logistics is a determining tool for increasing the efficiency of rescue interventions. The result is a recommendation to focus in the future on:

- ensuring a stable and sustainable financing model,
- a higher level of technological modernization (modernization of equipment, digitalization of information flows)
- more intensive international cooperation in training, exchange of experience and transfer of know-how.

Only in this way will it be possible to maintain a high level of safety and preparedness of mining rescue workers in the 21st century.

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Review process
Single-blind peer review process.

Acta Tecnología - International Scientific Journal about Technologies
Volume: 11 2025 Issue: 3 Pages: 141-146 ISSN 2453-675X

https://doi.org/10.22306/atec.v11i3.293 *Received: 21 May 2025; Revised: 11 Aug. 2025; Accepted: 14 Sep. 2025*

Glance on maze wanderer robot

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Keywords: robotic maze wanderer, design, deployment.
Abstract: Intelligent machines that can perform tasks that they have been programmed to perform are called robots. They have demonstrated importance in reducing the amount of human labour, particularly in industries. Robots are the technological advancement that would undoubtedly make life easier and more convenient. The design, programming, and implementation of a maze-wanderer robot that uses obstacle avoidance to determine its motion direction are the main topics of this paper. The robot's intelligence will be provided by a program. Additionally, the paper will be limited to a motorized vehicle that has been endowed with the intelligence to successfully navigate a specific maze.

1 Introduction

Robots are intelligent machines that can carry out preprogrammed tasks. They have proven important in reducing the amount of work that humans do, particularly in industries. Robots would be the solution if there was one technological development that would undoubtedly make life simpler and more convenient [1].

The manufacturing sector is where robots are most commonly used. Long-term repetitive tasks can cause people to grow bored and weary of their work, which may lead them to start performing their duties against their will. At this point, the individual will not be as productive and efficient as they were at the beginning of their career. Additionally, because humans are naturally tired, there is a limit to how long we can work. The significance of robots becomes apparent at this point. They can be programmed to operate continuously throughout the production process, delivering the same high-quality output. As a consequence, there are more manufactured goods of consistently high quality and fewer products with flaws [2,3].

There are numerous advantages for industries using robotics. As a result of increased productivity, businesses will generate higher profits. Also, because defective products are reduced to nearly zero, the company will lose less money. In all manufacturing sectors, automation and robotics are becoming more and more significant. In many industries, humans can be replaced by robots. When it comes to jobs requiring accuracy, speed, endurance, and dependability, robots perform better than humans. Dangerous and filthy tasks can be safely completed by robots. Robots can process multiple tasks at once and don't require the same environmental comforts as humans [4-6].

Robot lawnmows can be guided by a path in factories that use the same path for repetitive tasks, eliminating the need for a human operator. More advanced path followers can be used to deliver drugs in a hospital and mail inside an office building. Autonomous vehicles that drive on freeways may eventually use the technology, which has been proposed for operating mass transit systems in factories and other industries [7,8].

The capabilities of rescue robots under development include searching, mapping, and reconnaissance; removing debris; delivering supplies, including medical supplies; and even evacuating victims [9,10].

It is clear from the aforementioned applications that robots are a crucial tool for our daily tasks. In order to satisfy the device's constantly increasing demand, engineers have endeavoured to ensure that this instrument is properly designed and implemented, taking into account safety, accuracy and precision, cost, and efficiency.

2 Implementation methodology

2.1 Hardware development

The hardware component needs to be properly designed to guarantee that the operation will function as intended. Determining how to use the H-bridge and sensor to control the DC motors and how to link this circuit to the micro-controller circuit is the primary task. The program code for the microcontroller controls both the microcontroller and the H-bridge. The power supply unit, sensory array module, central processing unit (controller), and drive system, also known as the motor control unit, are the three circuits that make up the main circuit. These circuits are covered in the following sections.

2.1.1 Central processing unit (controller)

An electronic system known as a control unit receives inputs from a variety of sensors that gather environmental data and can operate the output devices in accordance with the conditions imposed by different limitations. A programmable logic device known as a microcontroller makes up the control unit. The microcontroller is a kind of electronic device that can be pre-configured to meet our needs. Various input and output pins on each microcontroller allow for the connection of various I/O devices. Other peripherals of the microcontroller are also integrated into the same chip. Thus, all other peripherals are integrated into a single microprocessor, which is what a microcontroller is. We use a microcontroller as the control unit whenever we need to manage the systems dynamically based on the environment.

Acta Tecnología - International Scientific Journal about Technologies
Volume: 11 2025 Issue: 3 Pages: 141-146 ISSN 2453-675X

2.1.2 Design of the obstacle sensing unit

Using reflected infrared light from its light source, each infrared range sensor calculates the distance to an object. This can be seen in Figure 1. The sensor can measure the angle at which reflected light enters the detector thanks to its electronics. The detector receives light at a sharp angle when the sensor is near an object. The detector receives light at a slight angle when it is far from an object. A variable analogue voltage is produced by the sensor based on the angle at which the reflected light enters the detector. By using this method, the sensor becomes insensitive to both the reflectivity of the object being detected and ambient light, guaranteeing that the output voltage depends only on the distance to the object being detected.

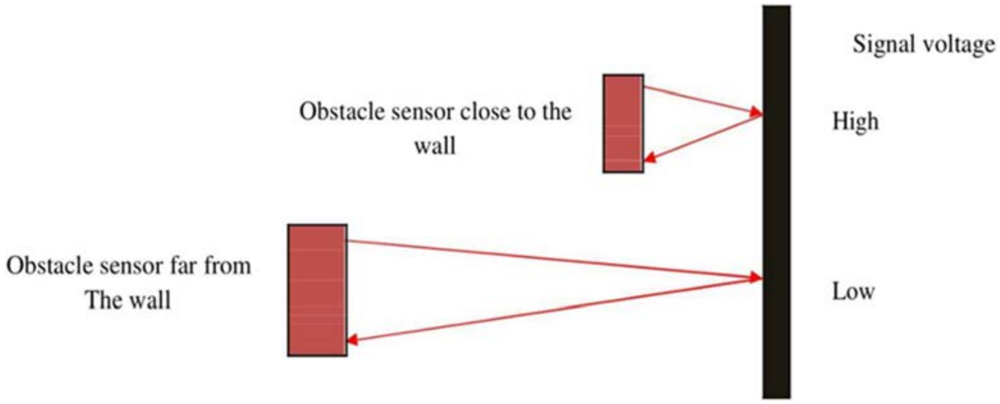

Figure 1 Sensing distance to the obstacle

Two configurations of break beam sensors and reflectance sensors can be used to implement the infrared-based object detector. The second setup will be incorporated into the robot's control system since it is highly appropriate for the robot's portability, which requires both the infrared fradiation (IR) source and the IR detector to be on the robot. The fundamental infrared emitter-detector circuit is depicted in Figure 2.

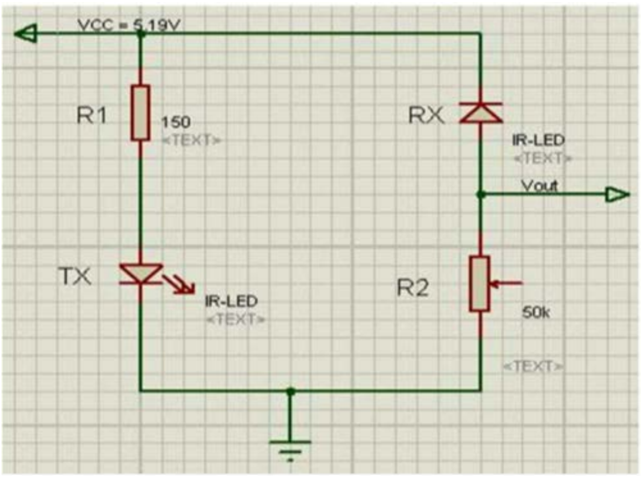

Figure 2 Infrared emitter-detector basic circuit

To stop the light-emitting diode (LED) from melting itself, R1 is set to 220Ω. The robot's sensitivity to the distance between it and the obstacle is determined by the resistance value of R2. For R1 = 220Ω, R2 = 22KΩ, and Vcc = 5.19V, the value of Vout is approximately 2.05V when there is no obstruction in front of the sensor. When an obstruction approaches within 15 cm, the value increases to 3.78V, and when the obstruction approaches within 5 cm, the value saturates to 5.06V.

In a similar manner, six units of the above-designed obstacle detector circuits will be used: two for detecting obstacles on the left wall while moving forward, and two for detecting obstacles in front and turning right if it encounters one. One on the right to tell you when to go forward when you're in reverse, and one on the back to help you turn when you're reversing. The microcontroller to be used only has six pins that can convert analog to digital, so all of the sensor outputs are analogue. Together with the microcontroller that will convert analog to digital, it also handles signal processing.

2.1.3 Design of the control signals processing unit

The control signals processing unit receives input signals from the obstacle detection unit's output signals.

Acta Tecnología - International Scientific Journal about Technologies
Volume: 11 2025 Issue: 3 Pages: 141-146 ISSN 2453-675X

These comprise the remaining six inputs from the circuits used for obstacle detection. As a result, the obstacle detection unit will provide six digital inputs to the control signals processing unit. The first step is to use the microcontroller's analogue to digital conversion feature to transform the analogue input signals into digital signals. The digital signals are then subjected to logical operations; for the obstacle detection circuits, the circuit with the highest value that is, the circuit that receives the highest value because of complete stability is chosen to indicate the robot's direction of motion, and for the obstacle sensors, the values are used to determine whether motion in a particular direction is allowed. Six infrared sensors will be installed on the robot, all of which will be positioned carefully to detect its motion. The sensors are oriented as depicted in Figure 3.

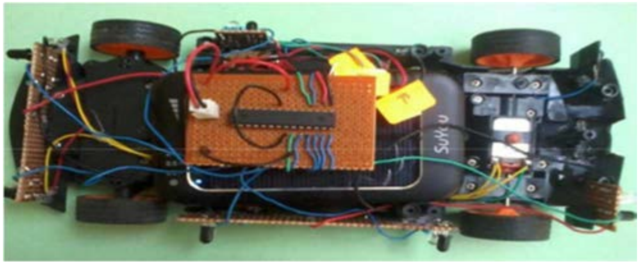

Figure 3 Orientation of the IR infrared sensors

It is anticipated that the robot will use six sensors in total. Given that the different sensors will be providing varying readings at any given moment, this suggests that there will be a variety of combinations.

2.2 Software development

The software's main goal is to always keep control of the hardware and solve the maze to figure out where to go. Reading the sensors, adjusting the motor speed, and interacting with any external peripherals are all part of controlling the hardware.

2.2.1 Algorithm

Finding its way out of the maze is the main objective of a robot. To do this, the robot employs a specific maze-searching algorithm. A great deal of research has already been done and is being done on searching strategies. Because of this, robots typically employ one or more of the three searching algorithms listed below: wall follower, depth first search, and flood fill. This only takes into account the wall follower algorithm.

2.2.2 Wall follower algorithm

Other names for the wall follower, the most well-known maze-navigating rule, are the left-hand rule and the right-hand rule. Keeping one hand in contact with one of the maze's walls will ensure that the robot doesn't get lost and will reach a different exit if the maze is simply connected, meaning that all of its walls are connected to either the outer boundary or each other. If not, the robot will return to the entrance. Another explanation for the effectiveness of wall following is topological. Should the walls be joined, they could be distorted into a circle or loop. Then, wall following becomes nothing more than a full circle walk. The boundaries between the connected parts of the maze walls are exactly the solutions, even if there are multiple solutions, to support this theory.

It is not guaranteed that this method will help achieve the goal if the maze is not simply connected (for example, if the start or endpoints are in the center of the structure or if the pathways cross over and under each other). It is possible to perform wall-following in 3D or higher-dimensional mazes if the higher-dimensional passages can be deterministically projected onto the 2D plane. The current orientation must be known, though, in order to identify which direction is the first on the left or right, unlike in 2D. Figure 4 below depicts a basic maze that was used as the foundation for an example of how the robot would move through it until it reached the exit.

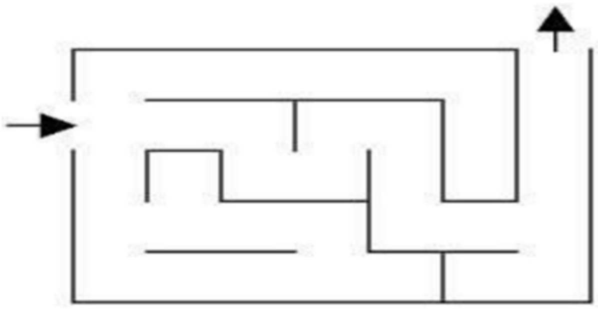

Figure 4 Simple maze for wall follower algorithm

As seen in Figure 5, the final implementation was completed with the entire system, including sensors, the CPU, and the power supply, and then coupled with the radio-controlled toy car below.

Figure 5 Final implementation

2.2.3 Programming environment

Arduino is a single-board microcontroller, intended to make the application of interactive objects or environments more accessible. The hardware consists of an open-source hardware board designed around an 8-bit Atmel AVR microcontroller, or a 32-bit Atmel ARM. Current models feature a USB interface, 6 analogue input pins, as well as 14 digital I/O pins which allow the user to attach various extension boards.

It comes with a simple integrated development environment (IDE) that runs on regular personal computers and allows writing programs for Arduino using C or C++ to the atmega 328 then the chip was transferred to the robot´s board. The Figure 6 and Figure 7 show the Arduino Uno board and the pin mapping for the chip.

Figure 6 Arduino Uno board

Figure 7 Atmega pin mapping

3 Simulation results

3.1 Simulation of the obstacle sensors

To determine whether there was an obstruction in the robot's path, six obstacle sensors were employed. Since each sensor was similar (having roughly the same output voltage for a specific distance from the obstacle), they all responded similarly. The circuit diagram for the robot's obstacle detector is shown in Figure 8.

In the study of the obstacle sensor, given a voltage value (Vcc) of 4.86 volts, a resistance value (R1) of 220 ohms, and another resistance value (R2) of 22 kilo-ohms, the obstacle was displaced linearly along the direction of the sensor. As a result, the distance of the obstacle from the sensor (d) and the sensor's output voltage (Vout) were calculated and tabulated in Table 1.

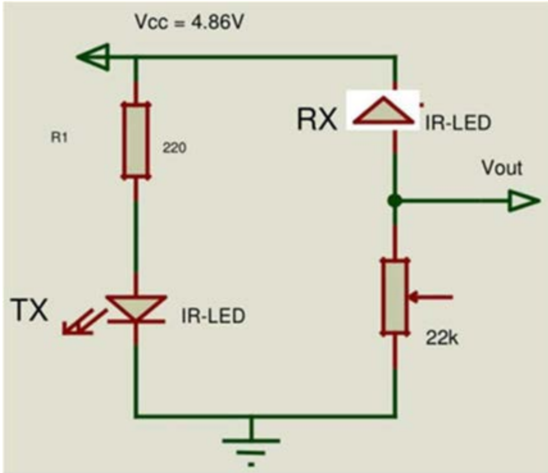

Figure 8 Obstacle detector circuit diagram

Table 1 Results of the obstacle sensors

Number	Distance, d (cm)	Output voltage (volts)
0	No obstacle	1.73
1	35	2.30
2	30	2.41
3	25	2.57
4	20	2.77
5	15	3.03
6	10	3.44
7	5	4.12
8	4	4.35
9	3	4.53
10	2	4.69
11	1	4.70

Figure 9 displays a plot of the obstacle sensor's output voltage in volts against the light source's distance from the sensor in centimetres.

A 1/d^2 variation in both distance and output voltage can be observed from the plot of the obstacle sensor's output voltage in volts against the light source's distance from the sensor in centimeters, where d (cm) is the source's distance from the sensor. Consequently, the output voltage rises as the obstacle's (the robot's path) distance from the sensor decreases.

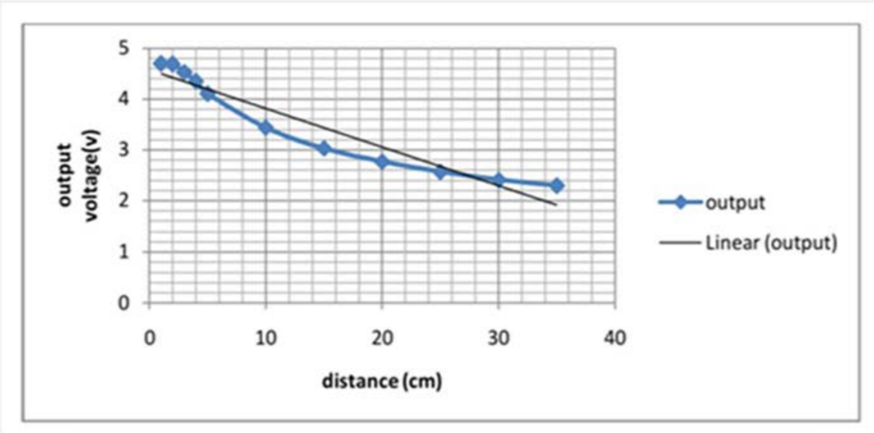

Figure 9 Variation of voltage with distance for obstacle sensors

3.2 *Simulation of the signal processing unit*

The control signals processing unit receives its inputs from the obstacle detection unit's output signals. These comprise the six digitally-based inputs from the obstacle detectors. This suggests that there are six digital inputs on the control signals processing unit. In the signal processing unit test, every single input signal from every sensor provided specific instructions for the signal processing unit's output. The different possible states of the robot are shown in Table 2 below, along with a suggested control action for each.

Table 2 States of the robot and the corresponding instructions

Number	Sensor	Instruction
1	Left _forward sensor	Move forward
2	Left _reverse sensor	Move forward with a left turn if left _forward sensor is clear.
3	Forward _left sensor	Move forward with a right turn if the left _forward is blocked
4	Forward _right sensor	Move forward with a right turn if it's not clear, else reverse with left turn until it's clear if all other options are not clear
5	Reverse sensor	Move reverse with left turn until forward right is clear.
6	Right _forward sensor	Move forward with right turn if it's clear and front and left not clear.

4 Conclusions

The wall follower algorithm technique was used in this paper to design and implement a maze wanderer robot. The device fulfills a fundamental requirement when designing any high-level robot since controlling a robot's movement is essential for practically all types of robots. Additionally, the wall follower algorithm was found to have accurate control, quick processing, a lower error rate, and above all cost effectiveness when compared to depth first and flood-fill algorithms.

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Review process
Single-blind peer review process.

https://doi.org/10.22306/atec.v11i3.296 *Received: 15 June 2025; Revised: 29 July 2025; Accepted: 15 Sep. 2025*

Impact of green logistics and its significant importance in SCM operations-overall glance

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Keywords: green logistics, enhancing efficiency, carbon emissions, sustainable logistics.
Abstract: Green logistics is a term that is important in the context of logistics management operations that have an influence on the environment. Green logistics focusses on systematically measuring, analyzing, and reducing the environmental effect of logistics. This covers every action related to the forward and backward flow of information, products, and services from the point of origin to the point of consumption. Green inventory management, green facility placement, the operational effects of environmental restrictions, ethical purchasing, green technology selection, and eco-design principles are all related to it. It seeks to use a balance between environmental and economic efficiency to build a sustainable firm value. For a sustainable global future, green logistics must be implemented. An attempt has been made in this article to survey the significance of green logistics in the current technological landscape. In order to gather data regarding the application of green logistics in organizations, the survey form has been created to include respondents of all ages.

1 Introduction

A key component of supply chain management in 2025 is "green logistics," which seeks to lessen the adverse environmental effects of logistics activities. It is important because it lowers carbon emissions, enhances brand image, and complies with regulations. Along with cost savings, companies can increase operational efficiency by implementing green practices.

1.1 Important green logistics aspects

Diminished Carbon Footprint: Green logistics aims to cut greenhouse gas emissions from storage, goods and other logistics-related activities. Numerous tactics, such as utilizing electric cars, planning routes more efficiently, and implementing renewable energy sources, can help achieve this.

Increased Operational Efficiency: Green logistics encourages the use of technology that can simplify processes, cut down on inefficiencies, and boost overall productivity, such as data analytics and route planning software.

Possible Cost Savings: Green logistics can result in real cost savings by maximizing fuel consumption, cutting waste, and enhancing operational effectiveness, in addition to benefits for the environment and branding.

Better Image of the Brand: Companies that put sustainability and green logistics first draw in eco-aware clients and investors, which boosts the reputation of their brands.

Regulatory Compliance: Green logistics techniques assist companies in remaining in compliance and avoiding fines as a result of numerous governments enforcing more stringent environmental laws.

1.2 Instances of green logistics at work

Vehicles that run on hydrogen and other alternative fuels: Converting to these vehicles greatly lowers air pollution and carbon emissions.

Route optimization: Delivery routes can be made more efficient by using technology to cut down on trip time and fuel usage.

Eco-friendly packaging: Reusable or biodegradable packaging materials minimize waste as well as their detrimental impacts on the environment. Green logistics is not only a trend but also essential for companies looking to prosper in 2025 due to rising consumer demand for sustainable goods and services and increased environmental consciousness. Businesses may boost their financial line, improve their brand image, and help create a more sustainable future by adopting green practices.

1.3 What is the term "green logistics" and what does it include?

The Association of Supply Chain Management (ASCM) Dictionary defines green logistics as a supply chain that takes into account how its operations affect the environment, takes steps to comply with environmental safety regulations, and informs partners and customers of these actions. This includes green reverse logistics, where the provider is in charge of getting rid of packing materials and materials that are harmful to the environment, like heavy metals.

1.4 What makes green logistics critical?

While putting green logistics into practice benefits our environment greatly, it also helps businesses save more money and boost production efficiency. Additionally, consider the perspective of the consumer: if you had the option, wouldn't you feel more comfortable selecting a business that was contributing to environmental awareness? Based on their own assessment of which brands are dedicated to sustainability, 68% of consumers want to base their future purchases, according to Forbes.

Thus, green logistics has become a crucial component of supply chain management because it will not only save your business time and money, but it will also improve the perception of your brand.

1.5 Green logistics started when?

In the 1970s, as people's awareness of the mounting problems posed by climate change increased, the idea of, or demand for, green logistics first emerged. Growing regulatory demands and technology developments brought about by this awareness aided in the development and diffusion of green logistics in the business sector. Companies started to evaluate the environmental impact of their operations and implement changes to include eco-friendly logistics systems and more sustainable supply chain administration in order to mitigate the environmental harm caused by consumer demand for more environmentally friendly brands and products.

1.6 The development of environmentally friendly transportation

1970s: Concerns about the oil crisis and environmental consciousness lead to the first Earth Day.

Environmental restrictions began to take shape in the 1980s, notably the Brundtland Report and the modifications to the Clean Air Act.

In the 2000s, supply chain management as a whole began to incorporate green logistics and corporate social responsibility (CSR) more heavily.

2010: To increase productivity and cut emissions, businesses start implementing cutting-edge technologies like telematics, GPS tracking, and route optimization software on a large scale.

2012: The Paris Agreement places more emphasis on the necessity of reducing carbon emissions in all areas, including logistics, the construction of green warehouses and distribution centres, and the use of energy-efficient architecture and renewable energy sources.

2020s: Businesses pledge to lower greenhouse gas emissions while expanding the use of hybrid and electric vehicles in logistics fleets. The circular economy, which emphasizes recycling and reuse in supply chains to reduce waste, gains popularity.

As new technologies and environmental concerns increase, green logistics keeps changing. The next stage of green logistics development is probably going to be driven by additional advancements in automation, circular economy principles, and sustainable materials in the future.

2 Literature review

2.1 Review on green logistics

Mary Catherine Osman et al. [2023], in order to comply with emerging market trends and public demands for environmentally friendly freight transportation, logistics networks must implement a number of Green Logistics Practices (GLPs). Investigating the potential effects of using fossil fuels as a GLP on system design and corporate strategy is the aim of this study. A review of the literature indicates that there is a dearth of research on the utilisation of fossil fuels [1]. The findings of a literature review indicate that there is a dearth of knowledge about the use of fossil fuels.

Dharmendra Hariyani et al. [2024], green supply chain management (GSCM) must be used by organizations because of restrictions and increased environmental consciousness. Despite extensive research on the topic, little is known about how exactly GSCM concepts relate to sustainable sourcing and distribution. The study intends to elucidate the fundamental ideas of GSCM, distinguish between sustainable sourcing and distribution concepts, assess theoretical frameworks that direct GSCM practices, look into new developments, and pinpoint obstacles and difficulties in GSCM. This review uses the Scopus database to examine GSCM with an emphasis on sustainable sourcing and distribution [2].

Jamal Fortes [2009], providing a concise summary of the literature on green supply chain management (GrSCM) during the last two decades is the aim of this paper. Waste management, green manufacturing, green operations, green design, and reverse logistics are the primary themes that arose from the literature. The establishment of social and environmental sustainability in operations management and the supply chain has advanced significantly thanks to sustainable development. In the late 1980s, manufacturers implemented a greener approach in their operations systems, going beyond what was mandated by the law [3].

Zhuoyan Qin [2019], the public suggested that enterprises be held to higher standards for green management and environmental preservation. The introduction of green supply chain management has given businesses additional possibilities. This page compiles the relevant research on green supply chain management, the relationship between green supply chain management and business performance, and possible future research trends and problems [4].

Yi wang et al. [2023], nowadays, social and economic progress is characterized by greening and digitization. Digital technology is widely recognized by the business and academic communities as a key enabler of green supply chain management. The new field of technology is constantly changing due to the quick development of digital technology and the start of the Industry 4.0 era. As a result, academic research in this area is expanding but has not yet reached saturation. In addition, the study explores how these technologies might lower energy and resource inputs as well as pollution emissions, thus increasing the green supply chain's operational efficiency and yielding social, economic, and environmental advantages [5].

Abhijna Neramballi et al. [2017], in a market with intense competition, businesses extend their supply chain globally. Laws, environmental groups, stakeholders, and consumers are all putting pressure on businesses to focus more on the environmental impacts of their supply chains. Due to this development, supply networks are increasingly more concerned with sustainability, which has caused Green Supply Chain Management (GSCM) to flourish. This project intends to create a conceptual model that will arrange the vast amount of literature in the field of GSCM in order to enhance supply chain performance generally and the environment in particular [6].

Roya Anvari et al. [2023], reviewing and categorizing the literature in three different but somewhat related supply chain domains—Reverse Supply Chain (RSC), Closed Loop Supply Chain (CLSC), and Green Supply Chain (GSC)—is the first attempt at this task. Therefore, each of these three topics has been divided into several criteria, each of which is an assessment of several connected conditions. Through a review of previous research and a summary of the key findings, this study attempts to achieve the stated goals. The first section will go over what has been done, and the second half will go over what has been discovered [7].

Mutua Mutie Daniel et al. [2022], activities related to distribution and transportation play a significant role in an organization's resource usage and environmental damage. Air emissions from automobiles and associated organizational activities can have an adverse effect on the environment, leading to localized smoke, acid rain in the area, and climate change [8].

Jasneet Kaur et al. [2018], in order to gain a competitive edge, boost customer satisfaction, improve brand image, and, of course, have fewer negative environmental effects, companies are increasingly talking about green supply chain management. Performing a literature review on the obstacles to the green supply chain and suggesting a categorization system to rank the most significant ones is the main goal of this study [9].

Nekmahmud Md et al. [2020], using Green Supply Chain Management (GSCM), industry in developed countries is creating answers to the global sustainability challenge. Similarly, the companies of poor countries are trying to apply GSCM for sustainable development. This study aims to conduct a thorough evaluation of the literature on GSCM practices and investigates the present status of the practice in Bangladesh [10].

Christian Ayemoma Apolaagoa et al. [2023], the concept of Green Supply Chain Management (GSCM) and its impacts are examined in this research using bibliometric analysis and a relational approach to the corpus of recent literature. Its primary source of data is the Scopus database. Refined search parameters were used to retrieve 652 documents by 1959 writers in order to discover relevant papers in the topic of study. The publications studied were those released from 2017 to 2022 [11].

M.K.Dhillon et al. [2023], in order to inform future research, this study aims to synthesize the diverse body of existing knowledge on flexible and green supply chain management (FGSCM) in emerging economies and identify research gaps . Through the triangulation of network analysis, text mining, and systematic literature review, we built a novel structured systematic literature review. The outcomes of the review were analysed using institutional theory and contingency theory [12].

Sudhanshu Gupta [2017], in the area of sustainable development, significant strides have been made in enhancing the ecological and social sustainability of operations management and the inventory network. In the late 1980s, several producers and manufacturers went above and beyond the call of duty to establish more environmentally friendly and sustainable business structures. This study aims to give a concise summary of the many studies and publications that have been written over the past 25 years regarding green supply chain management (GrSCM) [13].

Dasanayake et al. [2022], environmental contamination is one of the main issues of the decade that continues to worsen due to the careless actions of corporations worldwide. Most industries are concentrating on implementing green supply chain techniques in order to achieve sustainability in the Triple Bottom Line (TBL) and overcome the challenges posed by pollution. The study's objectives are to determine how multinational firms are using Green Supply Chain Practices (GSCP) to improve their organizational contribution to environmental sustainability and to conduct a comprehensive analysis of green practices and how the logistics and supply chain sector can use the "sustainability" concept to reduce adverse environmental effects [14].

Jeya Rani et al. [2025], the only emphasis of the current research study is how it helps Sabaari Logistics Pvt. Ltd., a developing Indian logistics company, improve its logistics performance. As green sustainability gains more attention globally, logistics companies have been reorienting from conventional approaches to more sustainable and environmentally friendly methods. Transportation, warehousing, packaging, and waste treatment are just a few of the supply chain operations that are subject to green supply chain management, or GSCM. Energy-efficient warehouse systems, ecologically acceptable packing materials, optimized routes, and the use of fuel-efficient vehicles are all examples of these at Sabaari Logistics [15].

Fuyume Sai [2019], recently, the logistics service industry has been increasingly concerned about environmental sustainability. Although there are an increasing number of studies on sustainable initiatives among logistics service providers (LSPs) in the body of current literature, limited study has been done between LSPs and shippers. Japan (2006–2017). Unlike the questionnaire- and interview-based studies found in the literature, we use a text mining technique to analyse the co-occurring links of data, i.e., connections of the practices, and present the collaborative sustainability actions carried out through the provision and demand for logistics services [16].

G L F Benachio et al. [2019], the construction industry is one of the largest producers of waste worldwide. To address this issue, the idea of environmental sustainability in the industry can be applied in a number of ways, such as waste reduction, carbon emission reduction, improved material selection, and more. Building sustainability can be improved by implementing Green Supply Chain Management (GSCM), as these areas include multiple stakeholders throughout the project life cycle [17].

Zhenjing Gu et al. [2022], logistics are essential to the economic development of any country or region. Urbanization and international trade affect logistical performance. The efficiency of logistics is significantly impacted by urbanization. However, logistics has disadvantages as a significant energy user. As logistics performance increases, urbanization and greater mobility result in higher carbon emissions. The efficiency of logistics has a favorable impact on trade openness, which lowers carbon emissions. Consequently, it is essential to comprehend the role of logistics from an economic and environmental perspective [18].

3 Case study of green logistics

In this section attempt has been made to collect survey information from respondents working in various organization like Industries, College etc. In this case study number of responses obtained were 2 both were from technical educational institutions in India.

The following survey questionnaire framed while collecting data from the respondents

Q1. "To what extent are you aware of the concept of green logistics?"
Q2. "Have you implemented any green logistics practices in your organization?"
Q3. "How important is green logistics in your organization's strategic goals?"
Q4. "What are your long-term goals for green logistics?"
Q5."What are the main areas of focus for research and development in green logistics?"

These are the above metrics set in the questions as mentioned here.

3.1 Results and discussion

The Figure 1, it is illustrated that 100 % of the respondents have given their preferences to use of electric vehicles by reducing carbon emissions. Thus, it controls the environment pollution by increasing the efficiency of logistics. Overall, it improves the sustainability of operations by safely transferrin the items as well planned by organization.

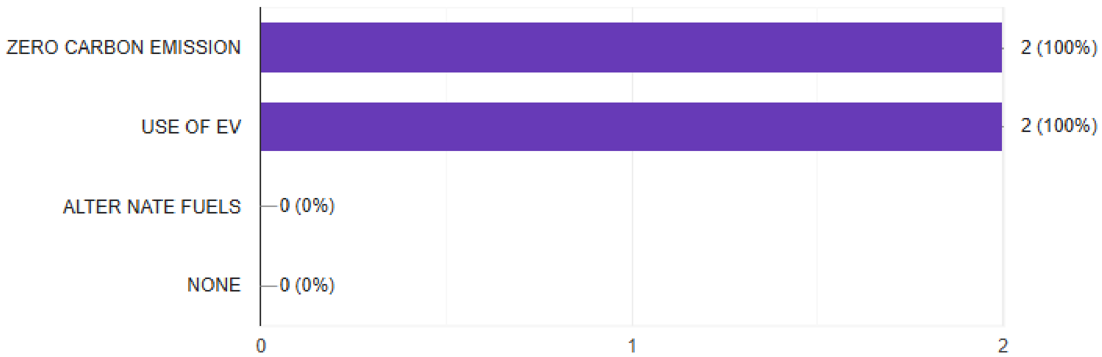

Figure 1 Green logistics metrics

4 Conclusion

Green logistics, which has both financial and environmental advantages, is an essential component of sustainable business practices. Employing eco-friendly supply chain practices can help companies lower their carbon footprint, increase productivity, and improve the perception of their brands. A smart step that sets companies up for long-term success in a market that is changing quickly is the adoption of green logistics.

A closer look at green logistics' conclusion is provided here:

Advantages of Green Logistics.

Effects on the Environment:

Decreased Carbon Footprint: Green logistics reduces greenhouse gas emissions, which makes the environment cleaner.

Conservation of Resources: Ecological methods such as recycling and waste minimization aid in the preservation of natural resources.

Decreased Pollution: Businesses can lessen air and noise pollution by employing eco-friendly transportation and route optimization.

Problems and Things to Think About:

Costs associated with implementation: Although the long-term advantages of green logistics exceed the initial outlay, companies may still need to cover the upfront expenses of new procedures and technologies.

The limitations of the infrastructure.

Some places might not have the infrastructure required to facilitate green logistics, such electric vehicle charging stations.

Supply Chain Intricacy:

Green supply chain integration can be difficult and necessitates cooperation and communication

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Review process

Single-blind peer review process.

JOURNAL STATEMENT

Journal name:	**Acta Tecnología**
Abbreviated key title:	Acta Tecnol
Journal title initials:	AT
Journal doi:	10.22306/atec
ISSN:	2453-675X
Start year:	2015
The first publishing:	October 2015
Issue publishing:	Quarterly
Publishing form:	On-line electronic publishing
Availability of articles:	Open Access Journal
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Publication ethics:	COPE, ELSEVIER Publishing Ethics
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