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Preface

Scientific research is a cornerstone of progress and innovation, driving the continuous evolution of knowledge across multiple disciplines. The studies presented in this volume represent a rich diversity of academic inquiry, each contributing unique insights to their respective fields. From groundbreaking work in sustainability and renewable energy systems to advancements in materials science and bioengineering, this compilation underscores the critical role of science and technology in addressing global challenges.

This book explores a wide range of topics, from theoretical and applied mathematics to the latest developments in engineering and biological sciences. It includes research on the enhancement of mechanical properties in materials, innovative approaches in agricultural resilience, and the intersection of public policy and citizen needs. These studies not only push the boundaries of what is possible but also provide practical solutions to real-world problems.

The breadth of subjects covered in this volume reflects the interdisciplinary nature of modern scientific exploration. Whether through the study of complex systems, the application of advanced computational models, or the investigation of biological mechanisms, each chapter contributes to a deeper understanding of the world around us. The insights gleaned from this research hold the potential to influence a wide array of industries, from energy and agriculture to healthcare and urban development.

This collection stands as a testament to the collaborative efforts of researchers dedicated to advancing their fields. Their work enriches the academic community and offers pathways toward a more sustainable, innovative, and scientifically informed future. It is my hope that this book will serve as both a resource and an inspiration for researchers, practitioners, and policymakers alike.

Prof. Dr. Mehmet Çevik
Editor

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Advancing Sustainable Development Goals through the Use of Biocomposites for a Greener Future

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Abstract

The pursuit of sustainable development has intensified the need for eco-friendly alternatives in various industries. Biocomposites, which combine natural fibers with renewable, biodegradable matrices, are emerging as a viable solution to replace traditional composites. These materials offer comparable, if not superior, mechanical properties while significantly reducing environmental impact. Biocomposites integrate natural fibers such as hemp, flax, jute, and bamboo with biopolymers like polylactic acid (PLA), contributing to sustainability by lowering carbon footprints and offering end-of-life options like biodegradability. Unlike synthetic composites that rely heavily on petroleum-based resins, biocomposites are designed for easier degradation, thereby minimizing long-term environmental harm. The use of biocomposites supports several Sustainable Development Goals (SDGs). They support SDG 9 by promoting innovation in industry through sustainable material solutions. SDG 12 is advanced by encouraging responsible consumption and production practices, while SDG 13 benefits from reduced greenhouse gas emissions. Biocomposites also support SDG 15 by utilizing agricultural by-products, which enhances land management and reduces waste. Despite their potential, biocomposites face several challenges. Their production may compete with food resources, impact water availability, and require significant energy, which could undermine their sustainability. Scalability issues, along with the need for improved performance and cost-effectiveness, remain significant obstacles. Furthermore, biocomposites must compete with well-established, cost-effective synthetic materials that dominate the market. Case studies demonstrate the application of biocomposites across various sectors, including automotive, construction, consumer goods, aerospace, sports equipment, and biomedical fields. The future of biocomposites depends on advancing research and development to enhance material properties, scalability, and economic viability. Policy recommendations include offering incentives for biocomposite production, providing research funding, and establishing standards to facilitate broader adoption.

Keywords: Biocomposites, sustainable development goals, sustainable materials, environmental impact, renewable resources, life cycle assessment

1. Introduction

Due to their excellent mechanical properties and light weight, composite materials are substantial across various industries, including automotive, aerospace, aeronautics, naval, and sports. On the other hand,

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growing environmental concerns are leading to a decline in the use of materials derived from fossil fuels. Additionally, the push to reduce greenhouse gas emissions and adhere to stricter fuel efficiency regulations necessitates the use of lighter materials with a smaller carbon footprint (Mahmud et al., 2021). As a result, traditional composite materials are gradually being replaced by more sustainable and lightweight alternatives, such as biocomposites.

A biocomposite is a material that integrates natural fibers, which may originate from plant or animal sources, with a matrix derived from renewable resources, typically biodegradable polymers or resins. This combination aims to offer comparable or enhanced mechanical properties to those of traditional composites while emphasizing environmental sustainability. Biocomposites utilize natural fibers such as hemp, flax, jute, and bamboo, paired with biopolymers like polylactic acid (PLA), to promote more sustainable material choices. Unlike traditional composites, which often depend on synthetic resins, biocomposites are designed with the potential for easier degradation at the end of their lifecycle, thus reducing long-term environmental impacts and shifting towards a more eco-friendly alternative (John & Thomas, 2008).

Biocomposites differ from traditional composites primarily in their use of natural fibers and renewable materials, which can reduce reliance on petroleum-based resources and lower environmental impact. While traditional composites often feature synthetic fibers and matrices known for their high strength and durability, biocomposites offer comparable performance in some applications but may face challenges in terms of consistency and long-term durability. Overall, biocomposites present a more sustainable alternative, though their performance and cost-effectiveness need to be evaluated relative to conventional materials.

Biocomposites are increasingly popular due to rising oil prices, supportive legislation on synthetic composite recycling, and their strong mechanical properties. Research aims to improve their performance for demanding applications, with key factors including the matrix choice, reinforcement concentration and orientation, shaping processes, and component interactions. A significant challenge remains the limited understanding of their mechanical behaviour in structural uses (Hassani et al., 2023).

Biocomposites can be classified based on their biodegradability. Biodegradable biocomposites, which use matrix materials such as PLA, PHA, or TPS combined with natural fibers like hemp or flax, are designed to decompose over time, making them suitable for compostable packaging and agricultural films. In contrast, non-biodegradable biocomposites incorporate synthetic or semi-synthetic resins with natural fibers, providing durability and strength but lacking decomposition. Similarly, biodegradable bioplastics, including PLA and PHA, break down under composting conditions. Non-biodegradable bioplastics, made from bio-based materials such as bio-based PET, do not decompose easily and are employed in applications requiring higher durability, such as textiles and durable goods. Therefore, it is important to recognize that not all biocomposites are biodegradable (Ryan et al., 2018).

The use of biopolymers and biocomposites began in 1844 with Goodyear's patent of vulcanized rubber, which improved the performance of natural rubber composites used for products like balloon cloths and raincoats. This was followed by the development of materials such as nitrocellulose, rayon, and Galaith, the first mass-produced bioplastic. During World War II, hemp composites were explored as an alternative to steel, with Ford creating a car prototype using hemp-reinforced soy resin, but production was halted due to regulatory issues. The rise of petrochemical-based polymers in the post-war era led to a focus on synthetic materials, although natural fibers were used in some automotive products. The oil crises of the 1970s spurred interest in non-petrochemical materials, leading to the development of biocomposites, though many were only partially made from natural sources. Despite progress in green biocomposites, commercialization remains limited, with notable materials including PLA, PHAs, and TPS, and natural fibers like hemp and cotton being used, though standardization challenges persist (Manu et al., 2022).

In 2022, global plastic production reached 400.3 million tonnes (European Bioplastics, 2023). Of this total, 1.813 million tonnes were bio-based plastics, with only 48% being biodegradable. This means that biodegradable plastics make up just 0.2% of the overall production volume. According to *Bioplastics—Facts and Figures* (European Bioplastics, 2023), the production volume of biodegradable plastics is projected to increase gradually (see Figure 1).

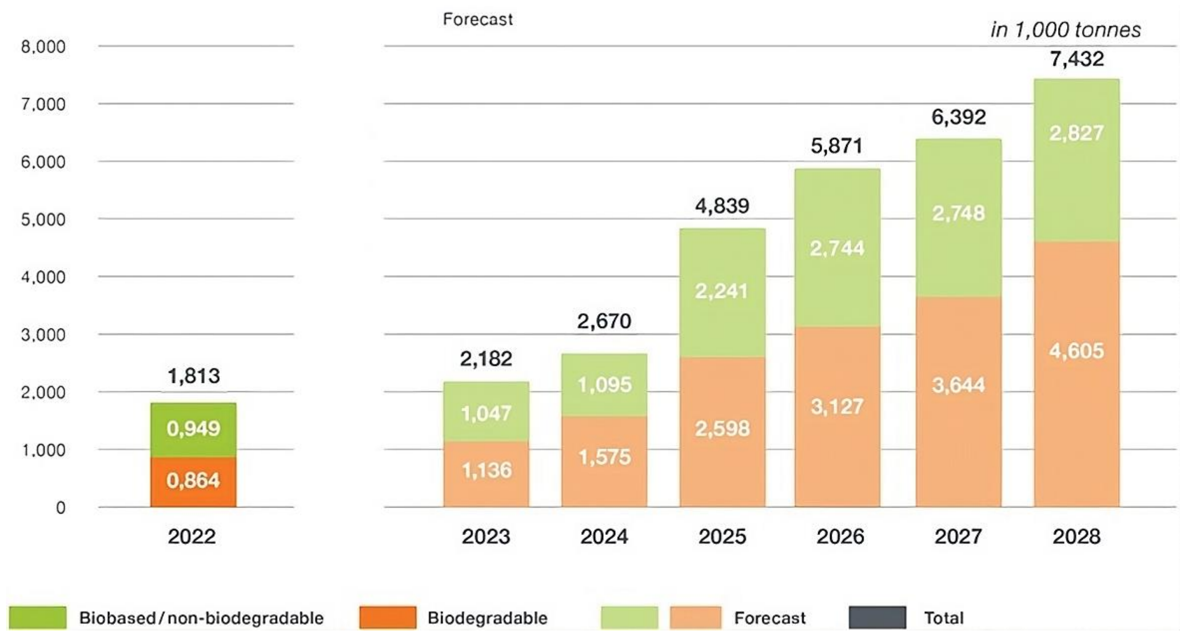

Figure 1. Global bioplastics production and forecast. Source: European Bioplastics, 2023

Bioplastics are increasingly utilized across a range of applications, including packaging, consumer products, electronics, automotive, and textiles. In 2023, packaging continues to dominate as the largest market segment for bioplastics, accounting for 43 percent (934,000 tonnes) of the total market (Nova Institute, 2024). Figure 2 illustrates the global production capacities of bioplastics by market segment.

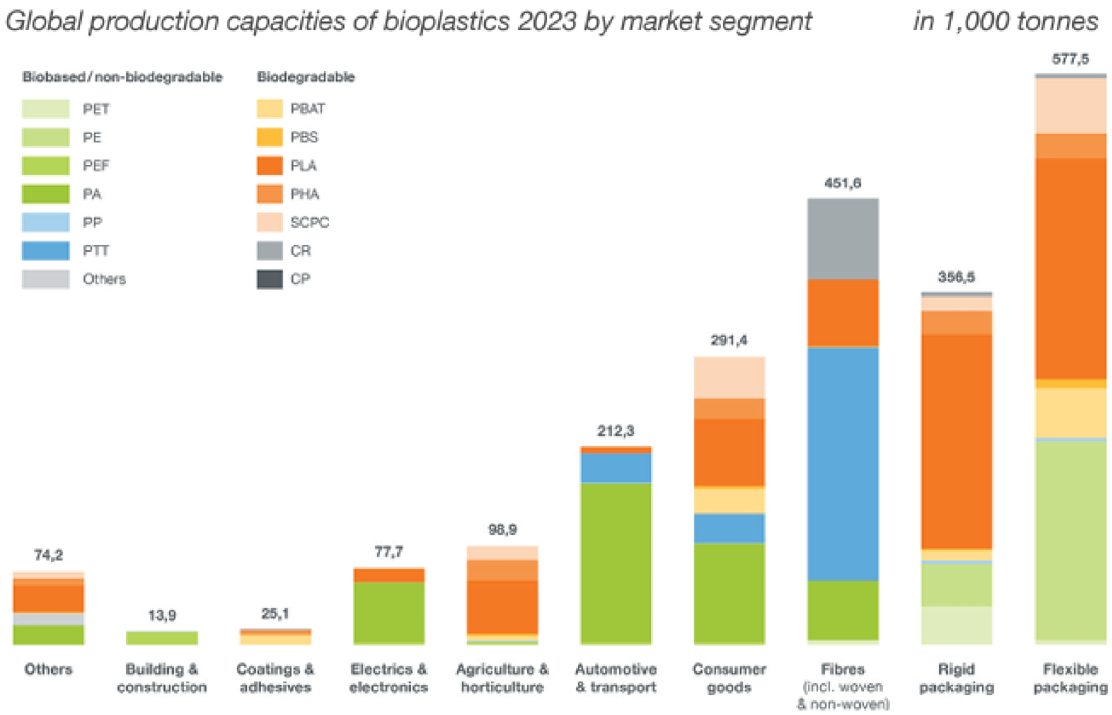

Figure 2. Global production capacities of bioplastics 2023 by market segment. Source: European Bioplastics, 2023

Bioplastic alternatives are available for nearly every conventional plastic material and its respective application. With significant advancements in polymers like polylactic acid (PLA), polyhydroxyalkanoates (PHA), and polyamides (PAs), along with consistent growth in polypropylene (PP), production capacities are expected to rise substantially over the next five years. Figure 3 illustrates the global production capacities of bioplastics by material type.

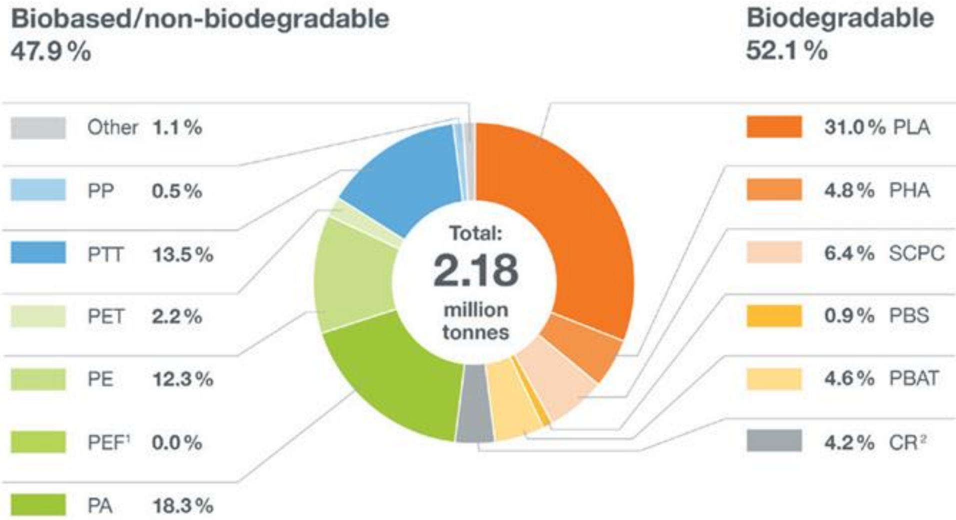

Figure 3. Global production capacities of bioplastics 2023 by material type. Source: European Bioplastics, 2023

2. Relation with Sustainable Development Goals (SDGs)

The SDGs were determined to address urgent global issues such as poverty, inequality, and climate change in a coordinated and effective manner. They provide a unified framework that fosters international collaboration and resource sharing to tackle these challenges (Fonseca et al., 2020; Raman et al., 2023; Alsayegh et al. 2023). By setting clear and measurable targets, the SDGs guide policy decisions and actions at various levels to promote sustainable development. They aim to balance economic growth, social inclusion, and environmental protection to ensure a more equitable and resilient future. Ultimately, the SDGs help track progress and hold stakeholders accountable, ensuring that efforts lead to meaningful and lasting impacts.

Biocomposites can be related to several SDGs, including:

1. **SDG 9: Industry, Innovation, and Infrastructure** - Biocomposites play a crucial role in advancing sustainable industrial practices by offering innovative material solutions that reduce dependence on conventional, resource-intensive composites. Their integration into manufacturing processes promotes eco-friendly production methods and contributes to the development of greener infrastructure. By incorporating biocomposites, industries can enhance their overall sustainability, fostering advancements in technology and infrastructure that align with eco-friendly principles.
2. **SDG 12: Responsible Consumption and Production** - By offering a more sustainable alternative to conventional materials, biocomposites support the goal of reducing waste and promoting the use of renewable resources. They provide a viable alternative to traditional materials, which are often derived from non-renewable resources and contribute to environmental degradation. By using renewable resources and offering better end-of-life options, such as compostability or reduced toxicity, biocomposites help minimize waste and promote more sustainable consumption patterns. Their adoption supports the goal of more responsible production practices and the efficient use of resources, contributing to reduced environmental impact across various sectors.

3. **SDG 13: Climate Action -** The shift to biocomposites helps address climate change by reducing reliance on fossil fuels and decreasing greenhouse gas emissions associated with traditional plastic and composite materials. Biocomposites, made from renewable resources, typically have a lower carbon footprint and can help mitigate climate change by sequestering carbon during the growth of their raw materials. Their use contributes to a broader strategy for climate action, aligning with efforts to cut emissions and reduce overall environmental impact.
4. **SDG 15: Life on Land -** Biocomposites can support sustainable land management practices by utilizing natural fibers from agricultural by-products or waste, thereby promoting more efficient and environmentally friendly resource use. By utilizing natural fibers sourced from agricultural by-products or waste, biocomposites support sustainable land management and promote efficient resource use. This practice reduces the need for additional land resources for raw material extraction, thus mitigating the environmental impacts associated with traditional material production. Biocomposites help enhance soil health and support biodiversity by recycling agricultural waste, contributing to more sustainable land management practices and the conservation of terrestrial ecosystems.
5. **SDG 11: Sustainable Cities and Communities -** In urban development and construction, biocomposites offer sustainable alternatives to conventional building materials, which can reduce the carbon footprint of infrastructure projects. Their use in construction not only promotes the development of greener buildings but also helps improve the environmental performance of urban areas by lowering energy consumption and reducing greenhouse gas emissions. By integrating biocomposites into city planning and development, communities can advance towards more sustainable and resilient urban environments.

These connections highlight the role of biocomposites in advancing sustainability across various sectors.

3. Challenges in Relation to the SDGs

Biocomposites, while supporting the implementation of SDGs, present several challenges in relation to the SDGs. The following overview categorizes these challenges according to the relevant SDGs:

1. **SDG 2: Zero Hunger -** Using agricultural resources for biocomposites may compete with food production, which could endanger food security. This competition also affects the availability of resources needed for agriculture.
2. **SDG 6: Clean Water and Sanitation -** Cultivating plants for biocomposites may require significant water resources, potentially impacting water availability in regions where water is already scarce. The use of chemical treatments in processing natural fibers can lead to water pollution if not managed properly.
3. **SDG 7: Affordable and Clean Energy -** The production of biocomposites can be energy-intensive, which may compromise their overall sustainability if the energy used is derived from non-renewable sources. To enhance their environmental benefits, it is essential to improve the energy efficiency of biocomposite production processes. Achieving better energy efficiency aligns with clean energy goals and helps minimize the carbon footprint associated with biocomposite manufacturing.
4. **SDG 8: Decent Work and Economic Growth -** While biocomposites can create new job opportunities, the sector's growth needs to be managed to ensure decent working conditions and fair wages. Biocomposites often have higher production costs compared to conventional materials, which can impact their market competitiveness and economic growth.
5. **SDG 9: Industry, Innovation, and Infrastructure -** Developing cost-effective and efficient biocomposite production technologies remains a challenge. Innovation is needed to improve their performance and reduce costs. Establishing infrastructure for biocomposite production and recycling can be challenging, particularly in regions with limited industrial facilities.

6. **SDG 12: Responsible Consumption and Production -** Comprehensive lifecycle assessments are needed to evaluate the environmental impact of biocomposites from production to disposal. This includes assessing their biodegradability and overall environmental footprint. Effective waste management systems must be in place to handle biocomposite materials at the end of their life cycle, ensuring they do not contribute to environmental pollution.
7. **SDG 13: Climate Action -** While biocomposites can reduce reliance on fossil fuels, their production processes can still contribute to greenhouse gas emissions. Efforts to minimize the carbon footprint are essential. The impact of climate change on the availability of raw materials for biocomposites must be considered, as extreme weather events can affect supply chains.
8. **SDG 15: Life on Land -** The cultivation of plants for biocomposites requires land, which can impact ecosystems and biodiversity if not managed sustainably. By promoting sustainable land management practices, it is essential to ensure that biocomposite production does not contribute to deforestation or habitat loss.

Addressing these challenges involves a multi-faceted approach, including improved technology, sustainable practices, and comprehensive policies to align biocomposite development with the SDGs.

4. Environmental Benefits

Engineers, designers, manufacturers, and researchers are increasingly adopting Life Cycle Assessment as a comprehensive environmental impact analysis tool to effectively demonstrate the advantages of biocomposites over traditional fiber-reinforced polymers (FRPs). Life Cycle Assessment provides a thorough evaluation by assessing each phase of a product's life cycle, from raw material extraction and production to usage and disposal. This method gathers and analyzes data on material inputs, energy consumption, waste outputs, and emissions through various scientific techniques, allowing for a detailed understanding of the environmental and health impacts associated with the product system (Fitzgerald et al., 2021).

In the context of sustainable recovery, Life Cycle Assessment highlights several key benefits of biocomposites:

Reduced Resource Depletion: Biocomposites utilize renewable resources, such as natural fibers and bio-based resins, which lessens the dependency on finite materials and supports the conservation of non-renewable resources (Mohanty et al., 2002; Shanmugam et al., 2021).

Decreased Pollution: The production processes for biocomposites generally result in lower emissions and a reduced reliance on harmful chemicals compared to traditional FRPs, leading to decreased environmental pollution and fewer health risks (Al-Oqla and Omari, 2017; Shanmugam et al., 2021).

Waste Management: Biocomposites offer better end-of-life options, such as recyclability and biodegradability, which contribute to more effective waste management and minimize the environmental impact of disposal (Das et al., 2016; Beigbeder et al., 2019).

The primary advantage of biocomposites lies in their dual benefits: they utilize renewable resources and are designed to have a lower environmental impact throughout their lifecycle. The natural fibers used in biocomposites are typically by-products of other industries or agricultural waste, which helps in reducing resource consumption and waste generation (Ahmad et al., 2022; Biswal et al., 2019). Moreover, the biodegradability of the matrices means that, when disposed of properly, biocomposites can break down into harmless substances, thus alleviating the burden on waste management systems (Mohanty, et al., 2000).

5. Economic Impacts

The economic impacts of using biocomposites are multifaceted, influencing both the production industry and broader economic contexts. One major advantage is the potential for cost savings through the use of renewable and locally sourced materials. Biocomposites often rely on natural fibers and bio-based resins, which can be less expensive than traditional petroleum-based materials, especially in regions where these resources are abundant. Additionally, the use of biocomposites can reduce dependency on volatile fossil fuel markets, offering more stable raw material costs and potentially lowering overall production expenses (Akram et al., 2023). Innovations in biocomposite technology include the incorporation of advanced processing techniques and the development of new types of natural fibers and biopolymers. These advancements aim to improve the mechanical properties, durability, and aesthetic qualities of biocomposites, making them suitable for a wider range of applications.

Recent studies (Vinod et al., 2020; Karimah et al., 2021; Mahmud et al., 2021; Andrew and Dhakal, 2022; Elfaleh et al., 2023; Chichane et al., 2023) have shown that biocomposites can achieve performance characteristics comparable to, or even exceeding, those of traditional materials. For instance, improvements in fiber-matrix bonding, optimization of fiber content, and the use of hybrid composites (which combine different types of natural fibers) have led to enhanced strength and durability. These advancements not only broaden the potential applications of biocomposites but also make them a viable alternative in demanding scenarios.

The rise of biocomposites opens significant job creation opportunities in green technology and sustainable industries, as new roles emerge in the cultivation, processing, and innovation. This growth fosters employment in sectors such as agriculture, manufacturing, and research, driving economic development and supporting a transition to a more sustainable economy (Mohanty et al., 2005).

On the consumer side, biocomposites can lead to economic benefits through increased market demand and the creation of new business opportunities. As sustainability becomes a higher priority for consumers and businesses alike, products made from biocomposites are likely to see greater market acceptance and growth (Shaikh & Kumar, 2023). Companies that invest in biocomposites can differentiate themselves in the marketplace by appealing to environmentally conscious consumers and adhering to increasingly stringent regulations on sustainability. This market shift not only boosts sales for companies that adopt biocomposites but also drives innovation and competition within the industry.

However, the transition to biocomposites also presents economic challenges. Initial investments in research and development, as well as in new manufacturing processes, can be high. The scalability of biocomposites and their integration into existing production lines may require significant capital and technological adjustments (Shanmugam et al., 2021; Manu et al., 2022). Furthermore, the performance of biocomposites in comparison to traditional materials can influence their adoption rates, with potential implications for long-term economic viability. Balancing these costs with the environmental benefits will be crucial in determining the overall economic impact of biocomposites as they become more widely used.

6. Case Studies and Applications

6.1. Automotive Industry

Ford has integrated biocomposites into its vehicles, notably using hemp-reinforced materials in interior panels of the Model T and more recently in door panels and dashboards (Yadav et al., 2024). Similarly, BMW has utilized natural fiber composites in their i-series vehicles, incorporating flax and kenaf fibers to reduce weight and enhance sustainability (Mohammed et al., 2021). This use of hemp-reinforced biocomposites supports SDG 9 by driving innovation in sustainable automotive manufacturing and advancing greener industrial practices. It also aligns with SDG 12 by reducing reliance on petroleum-based plastics and integrating renewable resources, which contributes to responsible production and improved resource efficiency. Ford’s and BMW’s initiatives not only reduce the carbon footprint associated with traditional materials but also promote broader industry adoption of biocomposites, advancing sustainable practices across various sectors.

6.2. Construction Industry

In construction, biocomposites are making notable contributions to sustainability through materials like bamboo-based composites and hempcrete. Bamboo, jute, hempcrete, camelina, flax, kenaf, sisal, coir, abaca, bagasse, and many other composites, used in flooring, wall panels, and furniture, offer a renewable and eco-friendly alternative to traditional wood products (Binici et al., 2016; Yıldızhan et al., 2018; Kolak and Oltulu, 2023; Bhuiyan et al., 2023; Rbihi et al., 2024). Hempcrete, which combines hemp fibers with lime, serves as an effective insulation material and contributes to wall construction with impressive durability and thermal performance. This aligns with SDG 11 by promoting sustainable urban development through eco-friendly building materials that enhance energy efficiency in buildings. Additionally, hempcrete supports SDG 13 by sequestering carbon dioxide during hemp growth and reducing the reliance on carbon-intensive materials like conventional concrete, thus contributing to climate change mitigation. Hempcrete's advantages in insulation and its low carbon footprint underscore its role in advancing sustainable construction practices and addressing environmental challenges associated with building materials.

6.3. Consumer Goods

Biocomposites are significantly impacting the consumer goods sector. IKEA, for example, incorporates natural fiber composites into its furniture, utilizing materials such as bamboo and recycled wood fibers (Cosmo & Yang, 2017; Partanen & Carus, 2019). This approach not only supports SDG 11 by promoting sustainable urban development through environmentally friendly products but also aligns with SDG 15 by encouraging better land management practices. By using renewable materials, IKEA reduces the environmental impact on forests and supports sustainable land use. Their commitment to biocomposites highlights a dedication to environmental sustainability, reducing reliance on non-renewable resources, and advancing circular economy principles. This initiative demonstrates how widespread adoption of biocomposites can enhance the sustainability of consumer goods and contribute to more eco-friendly urban environments.

6.4. Aerospace Industry

The aerospace industry has seen notable advancements with the use of biocomposites in aircraft components. Boeing, for instance, has implemented natural fiber-reinforced composites in interior cabin parts to reduce the aircraft's overall weight and enhance fuel efficiency (Mansor et al., 2019; Norkhairunnisa et al., 2022). Similarly, Airbus has developed biocomposite panels that combine natural fibers and bio-based resins to improve the environmental performance of aircraft interiors (Norkhairunnisa et al., 2022). These initiatives align with SDG 13 by reducing the carbon footprint of aviation and supporting climate change mitigation efforts. They also contribute to SDG 9 by advancing innovation in aerospace materials and promoting sustainable technology in the industry. Boeing's approach highlights the potential of biocomposites to lower greenhouse gas emissions and integrate sustainable materials into high-performance applications, potentially inspiring further innovations in the aerospace sector.

6.5. Sports Equipment

In the sports equipment sector, biocomposites are making significant strides towards sustainability. For example, Wilson has developed bio-based tennis rackets utilizing natural fiber composites like flax and hemp, which offer a combination of strength and flexibility while reducing dependence on synthetic materials (Truong, 2020; Malkar et al., 2023). Similarly, the use of biocomposite materials in surfboards, incorporating bio-resins and natural fibers, illustrates the broader application of these materials in minimizing the environmental impact of recreational equipment. These innovations support SDG 12 by providing sustainable alternatives to traditional synthetic materials, promoting responsible production practices. They also align with SDG 9 by showcasing industry innovation in sports equipment and enhancing product performance with eco-friendly materials. Wilson’s bio-based tennis rackets demonstrate how integrating renewable resources into consumer products can achieve sustainability goals and inspire more eco-conscious choices, reflecting a growing trend towards applying biocomposite technology in everyday items.

6.6. Biomedical Applications

Biocomposites, which leverage various types of cellulose, are increasingly utilized across a range of biomedical applications. These applications include tissue engineering, wound dressings, skin replacements, drug delivery systems, and dental treatments (Ahmed et al., 2018; Aisyah et al., 2020; Karimah et al., 2021; Nejatian et al., 2017). Additionally, cellulose-based biocomposites hold significant promise in specialized areas such as cardiac applications, orthopaedics, and ophthalmology. To enhance their utility, especially within the biomedical field, researchers have developed numerous chemical derivatives and modifications of cellulose. These alterations aim to optimize the properties of cellulose-based biocomposites, thereby expanding their potential uses and effectiveness in medical contexts.

7. Challenges and Limitations

Although there are numerous advantages to using biocomposites, industry statistics reveal that their market penetration remains limited compared to traditional materials. Most current bioplastics and biocomposites are designed to replace existing materials without altering product design or manufacturing processes (Dicker et al., 2014) This slow adoption can be attributed to a combination of technical and perceptual challenges (Manu et al., 2022).

Being bio-based does not necessarily guarantee biodegradability, as evidenced by materials like natural rubber. Similarly, materials such as Bio-PP/PET and Bio-Resins, while derived from natural sources, are not biodegradable; they are processed into plastics that still behave like conventional polymers at the end of their lifecycle. Although these materials reduce reliance on fossil fuels, their end-of-life processes mirror those of traditional plastics. Therefore, it's crucial to accurately define what constitutes a 'bio' or 'green' material, as consumer perception often associates these terms with biodegradability. Studies, such as those by Durif et al. (2010) and Güven et al. (2024), indicate that consumers equate green products with those that are renewable, bio-based, and biodegradable.

7.1. Scalability

Scaling up the production of biocomposites presents significant challenges that need to be addressed to meet growing market demands. One major issue is the consistency and reliability of sourcing raw materials, as the availability of natural fibers and biopolymers can fluctuate based on agricultural conditions and supply chain disruptions. Additionally, existing manufacturing processes may require significant modifications to handle biocomposite materials, which can involve substantial investment in new equipment and technology. The transition from small-scale research and development to large-scale production involves overcoming hurdles related to cost efficiency, production speed, and quality control. Establishing a robust supply chain and scaling up production processes while maintaining cost-effectiveness and product consistency are critical to achieving commercial viability. Addressing these scalability issues is essential for making biocomposites a competitive alternative to traditional materials in various industries.

7.2. Performance

The performance of biocomposites compared to traditional materials is a key area of concern. While biocomposites offer several environmental benefits, such as reduced reliance on fossil fuels and enhanced sustainability, their performance characteristics may not always match those of conventional materials. For instance, biocomposites may have lower mechanical strength, reduced durability, or limited resistance to environmental factors compared to synthetic composites. Issues such as moisture absorption, biodegradation rates, and the overall lifespan of biocomposites need to be thoroughly evaluated to ensure they meet the performance standards required for specific applications. Furthermore, the integration of biocomposites into existing product designs and manufacturing processes may require careful consideration to ensure they do not compromise functionality or safety. Comparing the performance of biocomposites with traditional materials, identifying potential limitations, and addressing these challenges through further research and development are crucial steps in advancing biocomposite technology and expanding its applications.

8. Future Directions

8.1. Research and Development

The field of biocomposites offers substantial potential for innovation and enhancement. Future research should focus on several key areas to improve the properties and applications of biocomposites. This includes developing advanced materials with enhanced mechanical and thermal properties, increasing the durability and lifespan of biocomposites, and exploring new natural fibers and biopolymers that can be utilized. Additionally, research into improving the compatibility and bonding between natural fibers and matrix materials can lead to more effective and versatile biocomposites. There is also a need for the development of scalable and cost-effective production methods that can make biocomposites more commercially viable. Investigating the environmental impact and life cycle analysis of new biocomposite formulations will ensure that they meet sustainability goals and contribute positively to reducing overall environmental footprints.

8.2. Policy Recommendations

To promote the adoption and integration of biocomposites into mainstream use, several policy recommendations should be considered. Governments and regulatory bodies could implement incentives such as tax credits or subsidies for companies that produce or use biocomposites, thereby lowering costs and encouraging wider adoption. Policies should also be developed to support research and innovation in biocomposite technologies, including funding for research projects and grants for start-ups working in this field. Additionally, creating standards and certifications for biocomposites can help ensure quality and reliability, facilitating their acceptance in various industries. Integrating biocomposites into national and international sustainability strategies and green procurement policies can further drive their use and encourage industries to prioritize sustainable materials in their supply chains. Finally, fostering partnerships between academia, industry, and government can help align research efforts with market needs and accelerate the development and deployment of biocomposite technologies.

9. Conclusion

Biocomposites present a promising pathway toward a greener future, aligning with global sustainability goals by offering viable alternatives to conventional materials. Their integration into various industries, from automotive to aerospace, underscores their potential to advance Sustainable Development Goals (SDGs), particularly in areas such as responsible consumption, climate action, and sustainable cities.

The environmental benefits of biocomposites are substantial. By leveraging renewable resources and offering improved waste management options, they reduce dependency on non-renewable materials and lower pollution levels. Life Cycle Assessment has demonstrated that biocomposites can significantly mitigate resource depletion and pollution compared to traditional fiber-reinforced polymers. Their inherent biodegradability and reduced environmental footprint further bolster their role in supporting sustainable development.

Economically, biocomposites open up new avenues for cost savings and job creation. The utilization of locally sourced, renewable materials can stabilize raw material costs and stimulate economic growth in green technology sectors. Innovations in biocomposite technology also enhance performance characteristics, making them increasingly competitive with traditional materials. However, the transition to widespread biocomposite use involves overcoming challenges such as high initial costs, scalability issues, and performance concerns. Addressing these challenges requires concerted efforts in research and development, along with supportive policies and infrastructure development.

Despite the progress made, the limited market penetration of biocomposites highlights the need for continued advancement and adoption. The development of more efficient production processes, improved material properties, and comprehensive lifecycle assessments are critical for enhancing the viability and attractiveness of biocomposites. Policy measures, including incentives for biocomposite production and usage, can further accelerate their integration into mainstream applications.

In conclusion, biocomposites hold significant potential to contribute to a more sustainable and eco-friendly future. Their application across diverse sectors demonstrates their ability to support multiple SDGs while providing a practical alternative to conventional materials. By addressing current limitations and fostering innovation, biocomposites can play a key role in advancing global sustainability efforts and shaping a greener future.

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2

Finite Element Analysis of Adhesive Debonding-Induced Delamination in Wind Turbine Blade Spar Caps: Comparative Failure Analysis and Simulation Insights

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Abstract

In wind turbine blades, employing the Finite Element Method (FEM) to detect potential failure modes before manufacturing offers significant value and cost savings compared to traditional structural tests. This paper investigates the conditions that cause delamination in spar caps and how this delamination is initiated, using the FEM. The study investigates the onset and progression of delamination in wind turbine blade spar caps due to adhesive separation using FEM. A comparative failure analysis is conducted using the Puck criterion, Cohesive Zone Method (CZM), crack initiation, and Virtual Crack Closure Technique (VCCT) method. The study yields significant insights into the effects of cracks on delamination and structural collapse. The adhesive debonding feature (Glue Breaking) is found to have a positive influence on simulation results. The advantages of the VCCT compared to the CZM are also discussed.

Keywords: Spar cap, finite element method, structural collapse, delamination, crack, buckling, puck criterion, Virtual Crack Closure Technique (VCCT), Cohesive Zone Model (CZM)

1. Introduction

In wind turbine construction, the blades are a crucial and durable component. High wind speeds may lead to strength issues for the turbine tower and blades, resulting in the deformation or breakage of the turbine components. Spar caps, which are beam structures spanning the blades, play a vital role in carrying loads and enhancing the stiffness of the blades. These caps are typically constructed from multiple layers of composite materials with fibers oriented in various directions to provide strength and stiffness in all orientations. Spar caps are critical for ensuring the aerodynamic performance and structural integrity of the blades, serving as the primary load-bearing element that resists wind-induced bending forces. This component directly absorbs the force exerted on the blades by the wind and governs the deflection and vibration of the blades.

Delamination, the separation of layers in composite materials, presents a significant challenge in wind turbine blade engineering. This issue typically originates in the spar cap section, as it is subject to the highest stress levels. The force exerted by the wind can lead to the separation of layers within the spar cap. Delamination between plies is a prevalent failure mode in composite structures. In the context of

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modeling failure growth after crack initiation, this paper will compare the VCCT and CZM methods, which are commonly employed in FEM programs (Brøndsted et al., 2023).

In FEM, the structure or material is discretized into a mesh of elements, and the governing equations are solved at each node of the mesh. CZM elements are used to model the cohesive zone, and they are usually placed in the FEM mesh along the expected crack path. CZM has several advantages over other fracture modeling techniques, such as Linear Elastic Fracture Mechanics (LEFM):

• CZM can describe the nonlinear behavior of materials near the crack tip.

• CZM can also be used to simulate crack initiation and propagation.

• CZM can model interface fracture, such as delamination, in adhesively bonded structures.

When cohesive elements are used to model delamination initiation and growth in composite materials, no assumptions need to be made about the initial defect, separation, or crack location and the direction of delamination propagation. Due to the incompatibility in the properties of the individual layers, delamination occurs at stress-free edges, ply drops (both internal and external) where thicknesses must be reduced, and in areas subject to out-of-plane bending, such as the bending of curved beams. For compatibility with the cohesive zone model in studying failure growth using the sticky zone model, it has been suggested that the initial stiffness must be infinitely high to model a perfect bonding across the interface. However, the finite element formulation must introduce a finite stiffness to the interface element.

As an initial criterion, the element is assumed to be elastic (in this case, linear) until the maximum stress is reached. After exceeding this, the element enters the diffusion regime with further loading. The cohesive zone is represented by a tension-separation law, which describes the relationship between the tractions acting on the crack surfaces and the separation of these surfaces. However, the mesh size is limited due to the need to protect various elements in the cohesive zone, posing a significant computational challenge. The computer's power is increasing exponentially, and it may not be long before full-scale structures grasp this powerful and effective technique.

Crack propagation via the virtual crack closure technique (VCCT) has been directly applied to the FEM. This method allows crack propagation when the local crack tip strain energy release rate calculated from node displacements and forces exceeds a critical value. A limitation of this approach is that it requires a defect to be introduced initially. Therefore, an initial crack is initiated using the Crack Initiator feature. A set of element faces is used to define the location of the crack. The failure growth of the crack created will also grow using VCCT-based crack propagation.

In this study, a crack is initiated at the material interface, and the failure zone is created to expand at the interface. Crack initiation is commenced using the Delamination feature, where a stress criterion determines when and where a failure will occur. Adhesive separation failure and failure modes that may cause delamination in the spar caps of the RÜZGEM 5-m wind turbine blade were studied (Muyan and Çöker, 2019). The blade type was analyzed on MSC Apex/Nastran and MSC Marc/Mentat to verify the data obtained from article studies previously created with different programs and experimental tests.

2. Finite Element Analysis Details

2.1. Boundary Conditions of RUZGEM 5-m Wind Turbine Blade Model

In the RUZGEM 5-m wind turbine blade and its spar cap, the adhesive region with 3D solid elements was created to connect the pressure side and two shell structures, such as a spar cap. The RUZGEM 5-m wind turbine blade is fixed at the blade root, and the spar cap supports the blade with adhesive bonding. The wind load on the blade exposed to 10 m/s wind speed was simulated and the blade root section is fixed as the boundary condition. The pressure distribution on the blade was first calculated using the MSC Cradle due to the wind flow. The material safety coefficient is accepted as 2.5. The number of shell elements and nodes is approximately 60 thousand, and the element sizes are generally around 15 mm. The material model in the finite element model created using the blade was verified through modal analysis in MSC Apex finite element software (see Figures 1 and 2). Nonlinear static and buckling analyses were performed in MSC Marc/Mentat (Batmaz et al., 2021).

This static analysis study investigated the failure using the Puck criterion, crack formation, and delamination analysis methods (VCCT or CZM). The accuracy of the stress states was examined on the structure by comparing them with the reference values, based on the presence of contact state (contact status changes or the use of 3D interface solid elements as adhesive surfaces, etc.) and the effects of whether or not there is an adhesive breaking feature (Glue Breaking). The Delamination tool is specific to MSC Marc and suitable for VCCT and CZM. The Crack Iniator tool was used. The adhesive region with 3D solid elements was created to connect the pressure side and two shell structures, such as a spar cap (Mankins, 1995).

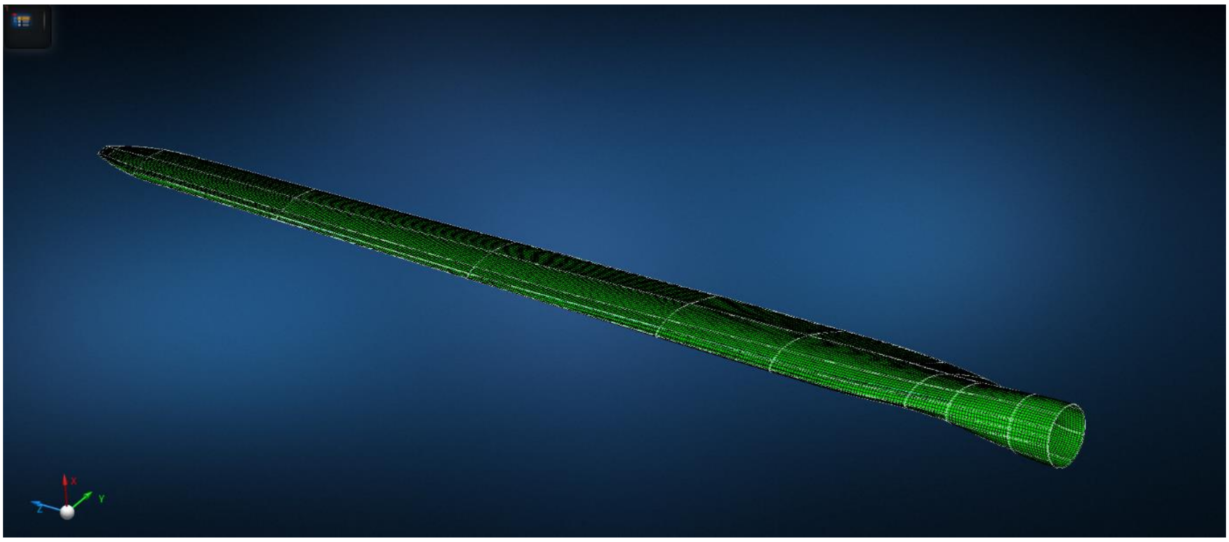

Figure 1. RUZGEM 5-m wind turbine blade

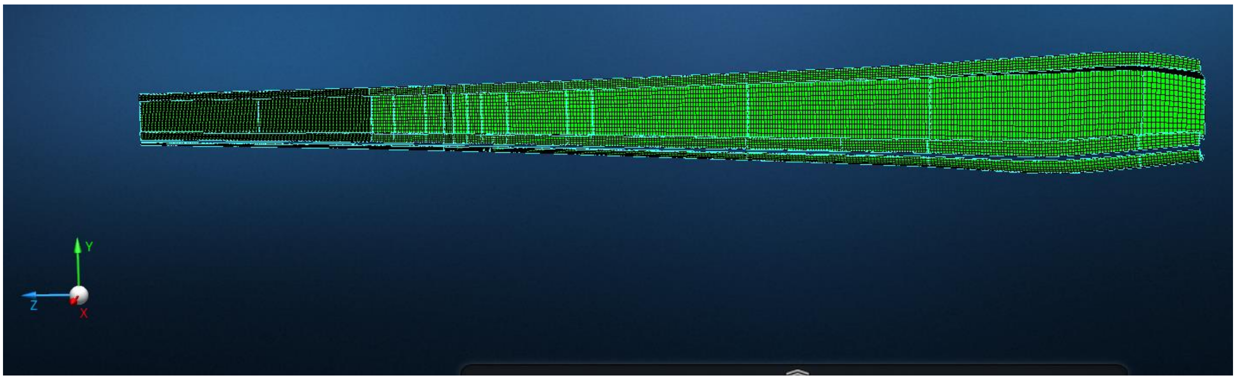

Figure 2. Spar caps of RUZGEM 5-m wind turbine blade

2.2. Materials of RUZGEM 5-m Wind Turbine Blade Model

In assembling the finite element model of the RÜZGEM 5-meter blade, the design of the composite laminates and the blade structure for the root and trailing edge/spar web panels considered four different materials. Specifically, two types of glass fabric (Triax and UD), steel, and polymeric foam (Divinycell H45) were used as core materials for the sandwich structures (Table 1). The blade is entirely made of glass reinforcements. The outer surface of the blade is covered with a transparent Gel Coat and a layer of 300 g/m² CSM 300 fiberglass. The Divinycell H45 foam used at the trailing edge has a thickness of 10mm in the area from 0.7m to 2m, and 5mm in the area from 2m to 3m. The Triax fabrics on the suction and pressure sides are laid in such a way that the ±45 layers are in contact with the molds. Similarly, the Triax layers of the inner blade structure have a ±45 layer in contact with the mold The structural analysis of the blade was carried out layer by layer using the relevant stress analysis tools. This means the triaxial layer was modeled as three different layers at +45, -45, and 0 degrees in both the FE and cross-sectional models. These layers have the same properties as the measured UD material but have different thicknesses; h_{0UD} = 0.716 mm, h_{0TRI} = 0.483 mm, h_{+45TRI} = 0.238 mm, h_{-45TRI} = 0.238 mm (Philippidis and Roukis, 2013).

Table 1. Material properties of RUZGEM 5-m Wind Turbine Blade Model (Batmaz et al., 2021)

Materials/Engineering Constants	Density (kg/m^3)	Modulus (GPa)	Strength (MPa)	Poisson Ratio
Lamina (Triax)	1896	E_1= 24.84 E_2= 9.14 G_{12}=2.83	S_{XT} = 191.73 S_{XC} = 101.16 S_{YT} = 16.86 S_{YC} = 50.41 S_{SH} = 11.29	0.29
Steel	7850	E= 210	S=581.80	0.30
Gelcoat	1200	E= 3.98	S=35.29	0.34
CSM 300 (UD)	1896	E= 9.14	S=16.86	0.29
Divinycell H45 (Foam)	48	E_1= 55E-03 E_2= 55E-03 G_{12}= 15E-03	S_T =1.40 S_C =0.60 S_{SH} =0.56	0.40
Adhesive	1400	E= 3.00 G_{12}= 1.59	S= 7.8	0.30

2.3. Contact Status of RUZGEM 5-m Wind Turbine Blade Model

In the predicted adhesive separation failure area, the cohesive zone was defined with adhesive models (see Figure 3). Glue contact was preferred so that the connection between the adhesive and composite parts is suitable for the multi-point constraint method (Batmaz et al., 2021). In this study, a new investigation was conducted using the Glue Breaking effect instead of the MPC algorithm in MSC Marc/Mentat.

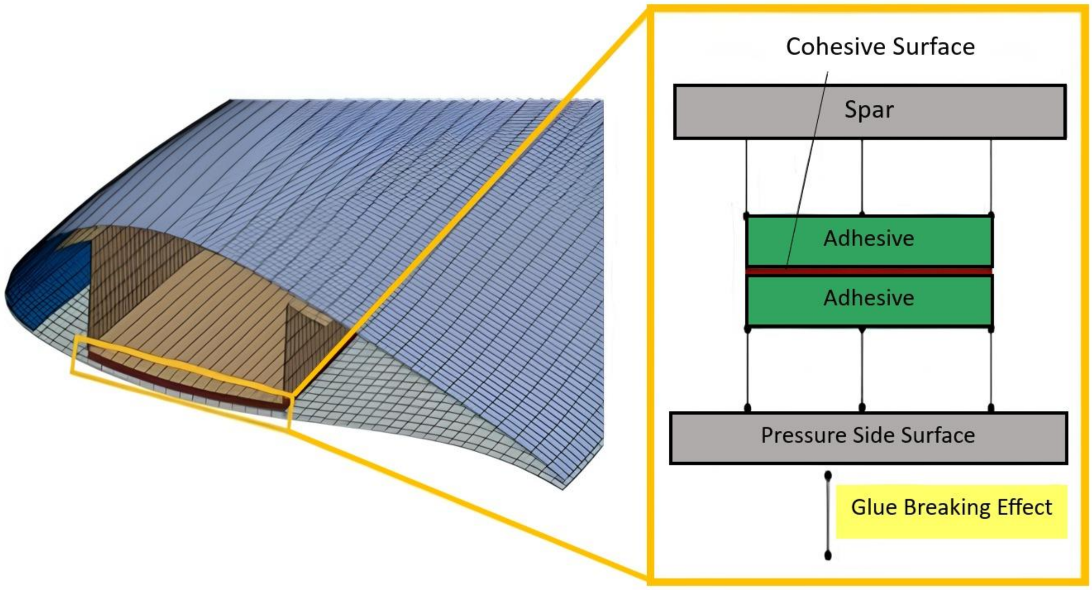

Figure 3. Schematic of the adhesive model (Batmaz et al., 2021)

The spar cap acts like a supported beam, absorbing the main lateral bending loads. The spar caps keep the suction and pressure side surfaces separate during deflection. The shell is needed to create the actual aerodynamic shape, and the upper and lower blade sections must be glued together to have numerous bonding points. The structure is connected to the support elements with adhesive contacts (see Figure 4); by choosing the Puck failure criterion, fiber and matrix failure are considered separately. By selecting the Gradual Selective method, it is assumed that the toughness gradually decreases as failure occurs, and this selection indicates that the failure progresses slowly (Figure 5).

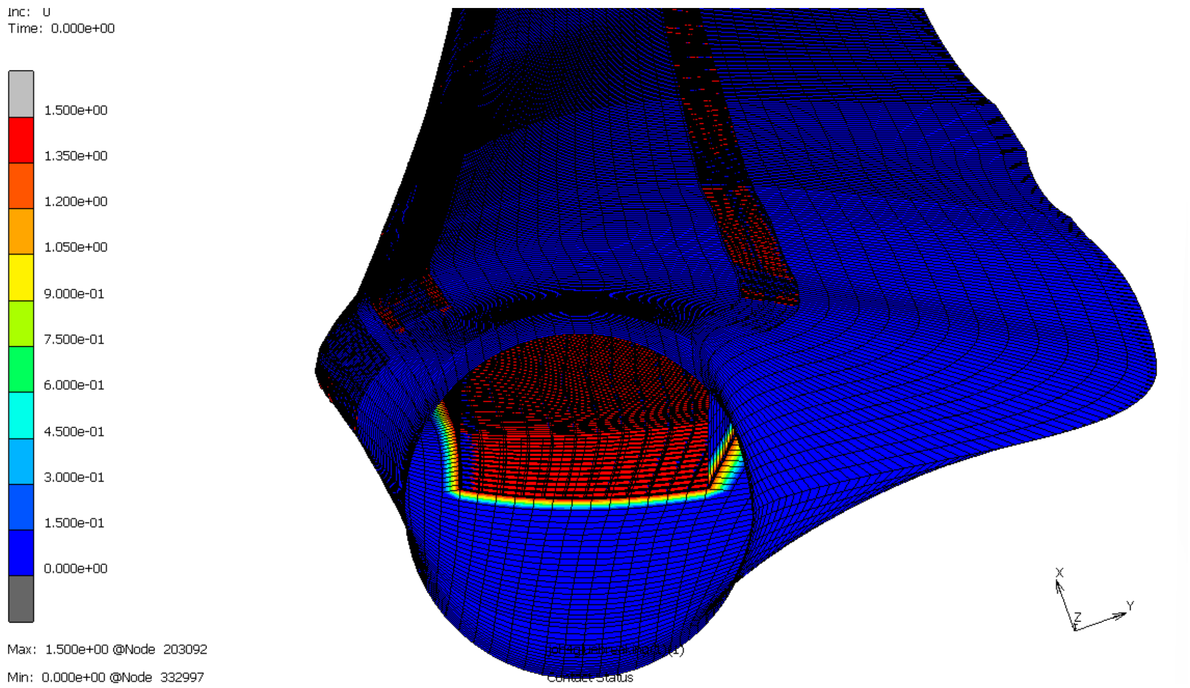

Figure 4. Adhesive contact situation in the blade structure

In this method, it is assumed that the material continues to be loaded after the failure occurs. The stiffness is reduced to such an extent that the maximum failure index remains below 1.0. Thus, this situation shows that the material is not completely damaged, but its carrying capacity has decreased. Delamination will begin when the interlayer strain energy release due to shear and tensile stress gradients occurring in discontinuities exceeds the critical threshold called fracture toughness (Boyano et al., 2017). In the Delamination command of MSC Marc, the mesh can be degraded at the interface between two materials or within a material. Normal and tangential stresses control fragmentation at the material interface, and these stresses are transformed to align with it. This effect is achieved by selecting "Material Interface" in the Delamination tool, which plays a crucial role in the delamination process. The Upon Delamination command then determines the subsequent actions after the failure. Simulation tools that involve any separation (delamination, Glue Breaking, breaking index, etc.) work together according to the formula of Eq. 1: If it is greater than 1, the sticky connection becomes passive.

$$\left(\frac{\sigma_n}{S_n}\right)^m + \left(\frac{\sigma_t}{S_t}\right)^n > 1 \qquad (1)$$

The stress-based criterion uses the following strength law formulation: Delamination Index Normal and Delamination Index Tangent.

- σ_n is the calculated normal contact stress: 0.6 MPa
- σ_t is the calculated contact tangential stress: 2.1 MPa
- S_n Normal Stress Threshold: 1.2 MPa
- m Normal Stress Exponent: 2

• S_t Tangential Stress Threshold: 2.4 MPa

• n Tangential Stress Exponent: 2

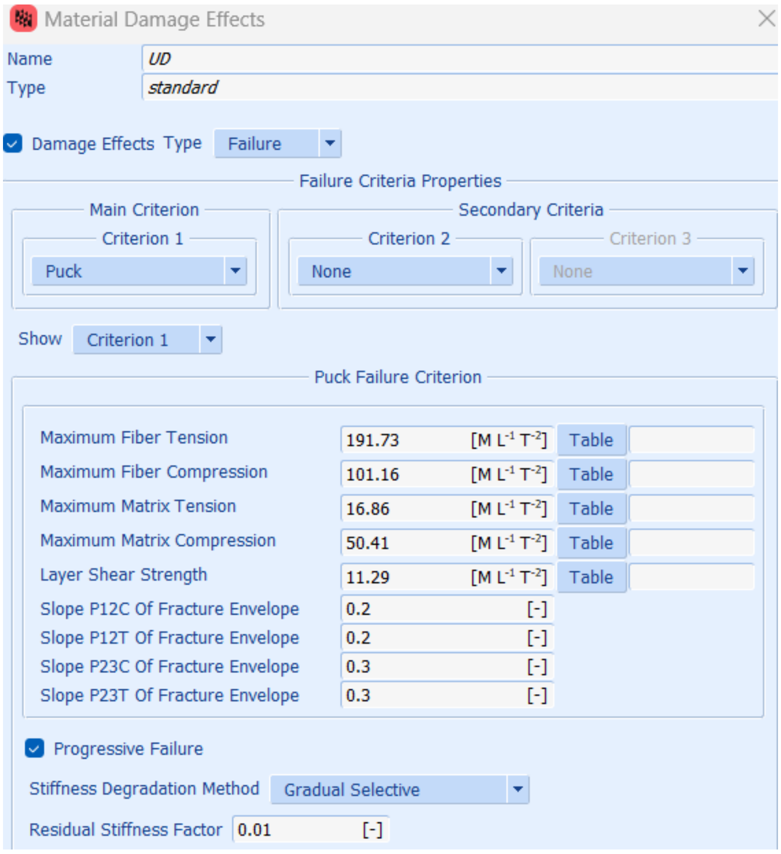

Figure 5. Puck failure criterion features

Glue Breaking in MSC Marc introduces a unique approach to modeling the failure of adhesive bonds. This method converts adhesive contact to normal contact and offers a fresh perspective on adhesive bond behavior modeling. It provides essential information about the performance and failure of assembled structures and significantly improves the modeling process. The structure does not stick again, but it continues to make regular "Touch Contact" (see Figures 6 and 7) (Mankins, 1995).

MSC Marc is finite element software used to model crack growth, and interface elements can only be used as 3D elements. For this reason, the adhesive area was created as a 3D solid instead of a shell structure. Element 75 (Thick Shell), 149 (3D Solid Composite Structural Element), and 188 (3D Interface Structural Element) were used as element types (see Figures 8 and 9).

- Element 75 is a very efficient and straightforward four-node element that exhibits correct behavior in shell structures. Due to its simple formulation, it is less tiring for the solver than standard higher-order shell elements and is, therefore, preferred in nonlinear analysis.

- Different material properties can be used for other layers within Element 149 (8 nodes). The thickness (or percentage of thickness) and material set ID can be entered for each layer via the COMPOSITE option.

- Element 188 is an eight-node interface element that can simulate the onset and progression of delamination. The behavior of the element is defined via the cohesive model definition option. Since the volume of the element is zero, there is no mass associated with the element (MSC Manual, 2003).

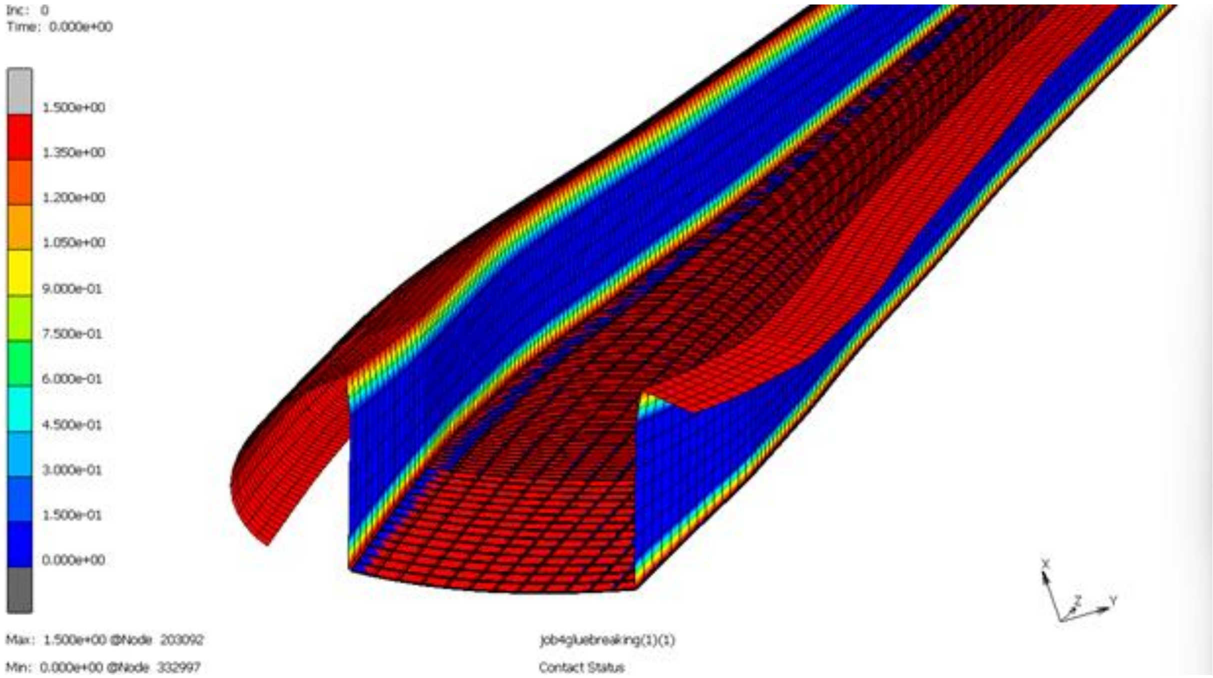

Figure 6. Glue contact situation in the spar cap

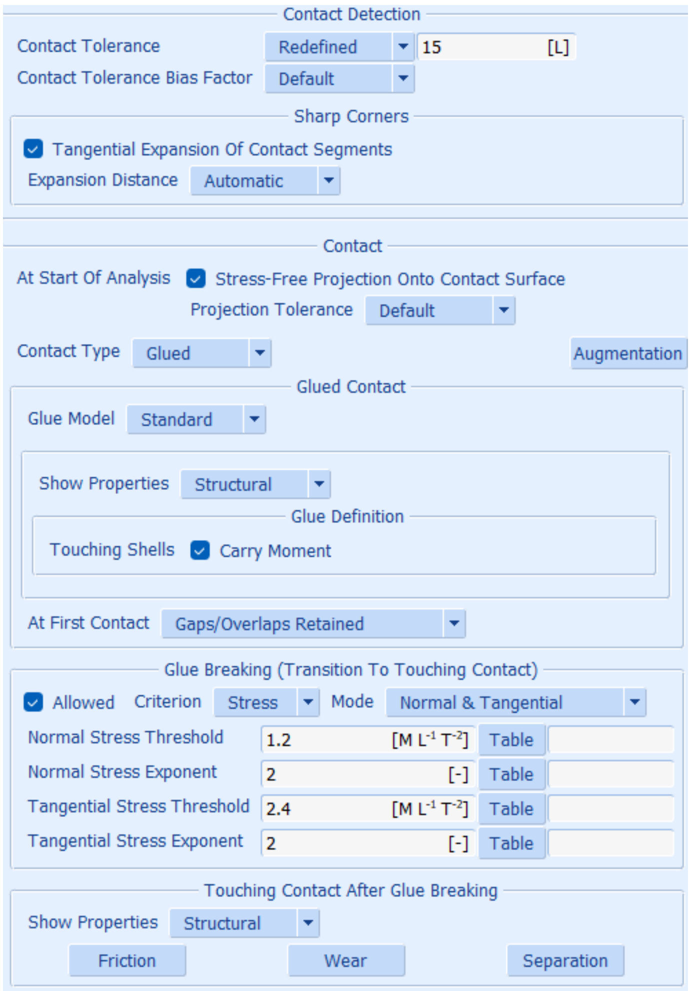

Figure 7. Glue Breaking according to adhesive bonding and interface material properties

CZM is a numerical technique for simulating fracture and delamination in materials and structures (see Table 2). In other words, it is a method for modeling the behavior that occurs when two composite layers separate. This method is valuable in analyzing structures subjected to loading conditions that may trigger crack propagation.

The Mode-I critical opening displacement v_{nc} can be calculated assuming the mode-I penalty hardness $K = 10^6$ N/mm^3 for the model: $v_{nc} = \tau_{nc}/K = 4 \times 10^{-6}$ mm.

- The Mode-I maximum opening displacement v_{nm} can be calculated assuming a bilinear relationship for tensile and opening displacement: $v_{nm} = (2G_{Ic})/(\tau_{nc}) = 0.067$mm.
- The maximum stress ratio β_1 (Shear/Normal) and cohesive energy ratio β_2 (Shear/Normal) are calculated as follows: $\beta_1 = \tau_{tc}/\tau_{nc} = 2$ ve $\beta_2 = G_{IIc}/G_{Ic} = 5$

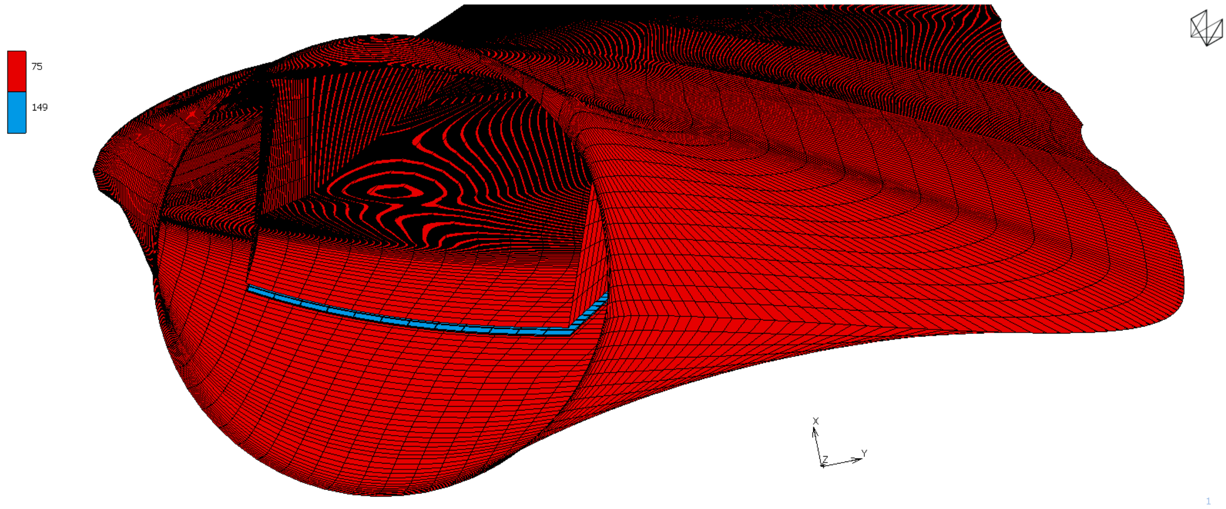

Figure 8. The local coordinate system with elements 75 and 149

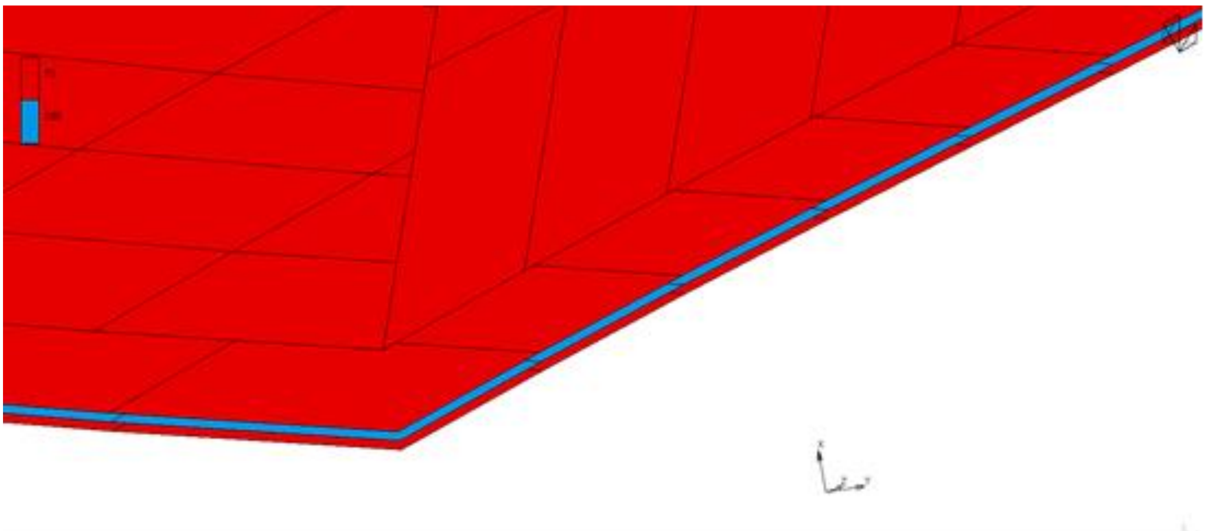

Figure 9. Element 188 as an interface element

Table 2. Cohesive zone interface properties

	Interface Strength (MPa)	Fracture Toughness (N/m)	Cohesive Stiffness (N/m^3)	B-K Criterion
Batmaz et al., 2021	$t_n = 1.2$ $t_{sh} = 2.4$	$G_{IC}= 40$ $G_{IIC}= 200$ $G_{IIIC}= 200$	$K_{nn} = 3E14$ $K_{ss} = 1.15E14$ $K_{tt} = 1.15E14$	$\eta= 3.8$

Values calculated for the Turon Model in the interface are: (see Figure 10)

- $G_c= 0.04\ kJ/m^2$
- $v_{nm} = 0.067$ mm
- $v_{nc} = 4 \times 10^{-6}$ mm
- Parameter Eta (η) = 3.8

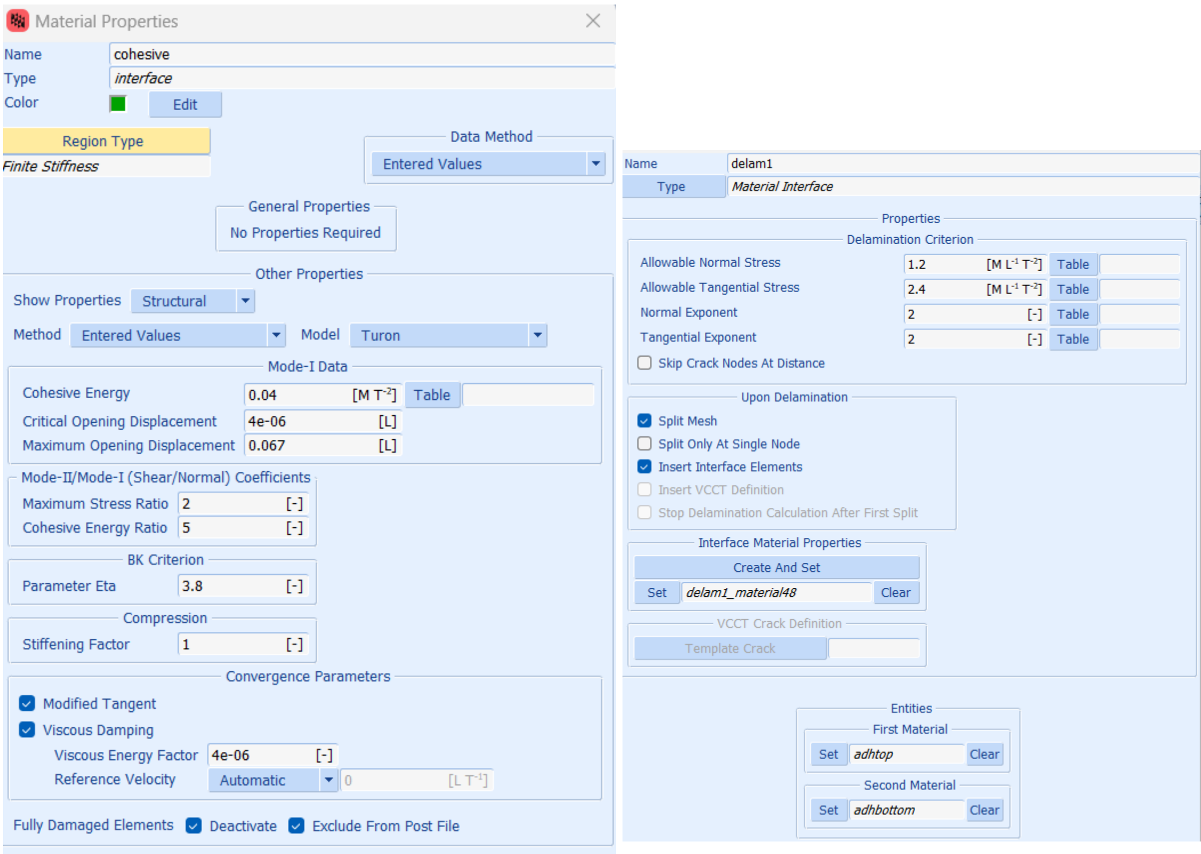

Figure 10. RUZGEM Turon Model and delamination type and features

The VCCT method is a powerful fracture mechanics tool to predict the crack tip's strain energy release rate (SERR). It can be used with various material models, including linear elastic, elastic-plastic, and cohesive zone models. It is used for crack growth prediction, fracture toughness evaluation, or design optimization of cracked structures.

A new 3D VCCT is created from the Cracks tab under the Fracture Mechanics command in the Toolbox. Two criteria are used to control crack growth: the delamination criterion and the crack growth criterion. The delamination criterion decides whether the crack will separate from the material interface. Once cleavage occurs, the delamination criterion is disabled. The crack growth criterion determines when and how much the crack will grow. This criterion also has two main parameters: G_C and Crack Growth Increase. To summarize, G_C is the crack growth resistance. Crack growth occurs when $G > G_C$. Crack Growth Increment determines how much the crack must grow once growth is detected (Figure 11).

Crack Initiator, another failure model method, is used to identify the beginning of a crack within a structure. This tool can be applied without using the Delamination option. To use the Crack Initiator, the faces of elements that represent the location of the crack initiation are selected. The selected area should be more significant than necessary (Figures 12 and 13).

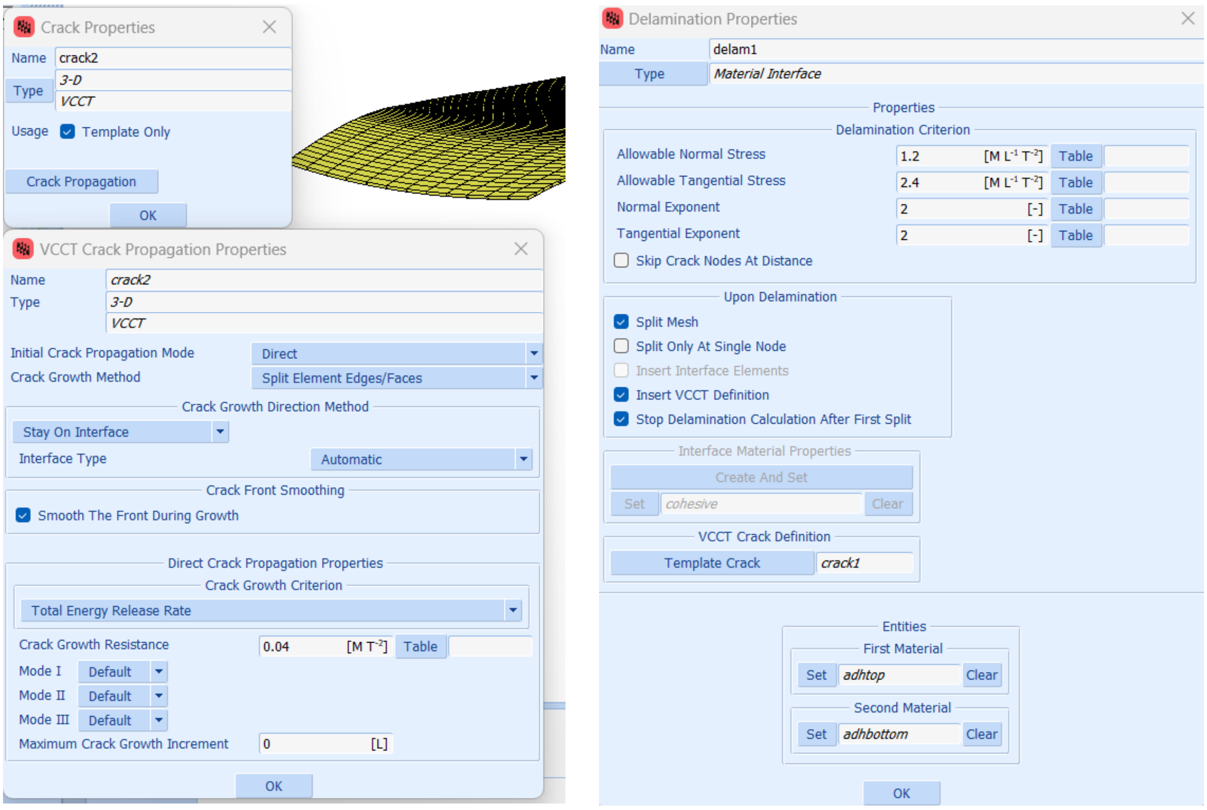

Figure 11. Crack formation and propagation characteristics and VCCT method

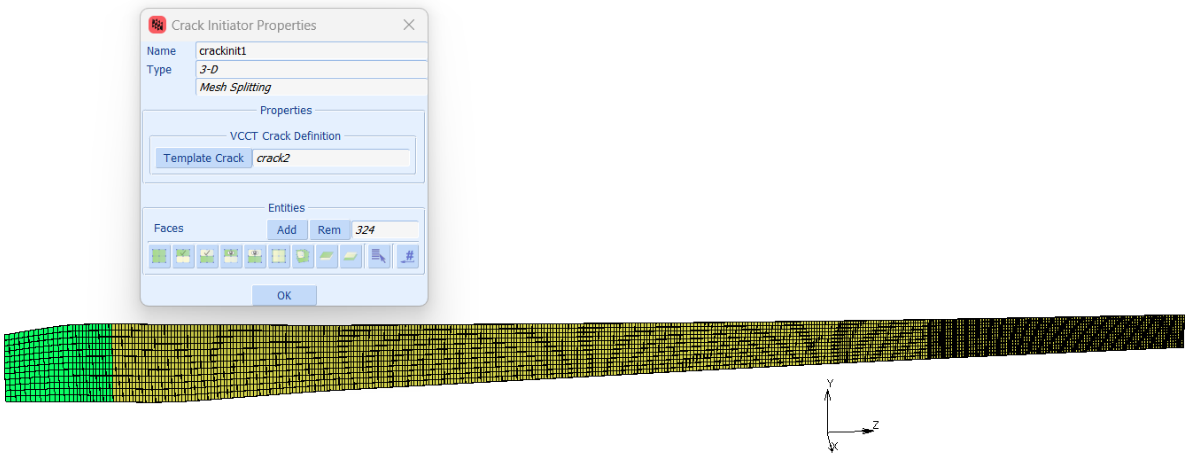

Figure 12. Crack region selection and Template Crack creation

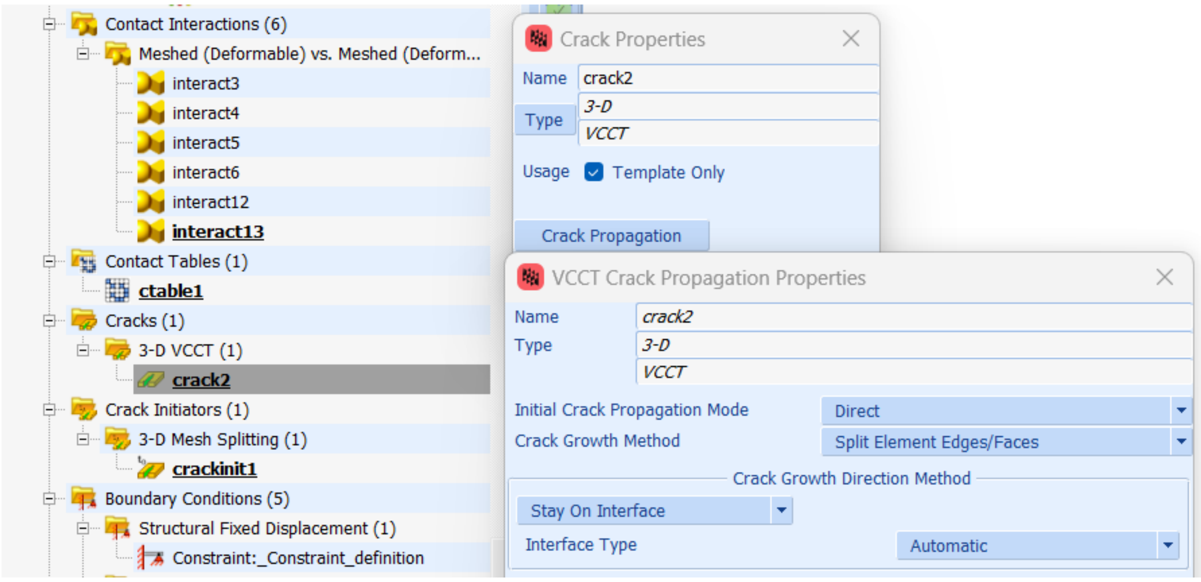

Figure 13. Crack propagation characteristics of RUZGEM 5-m wind turbine blade

3. Result and Discussion

The failure of spar caps and spar webs in the root transition area is a critical factor in blade failure. Local buckling also contributed to the primary failure mechanism by facilitating deformation perpendicular to the plane. In large blades, the stresses in the thickness of the blade that cause adhesive separation and delamination failure in the blade root transition area must be considered in the FEM. These stresses can weaken the bonds between spar caps and webs and lead to delamination (Figure 14).

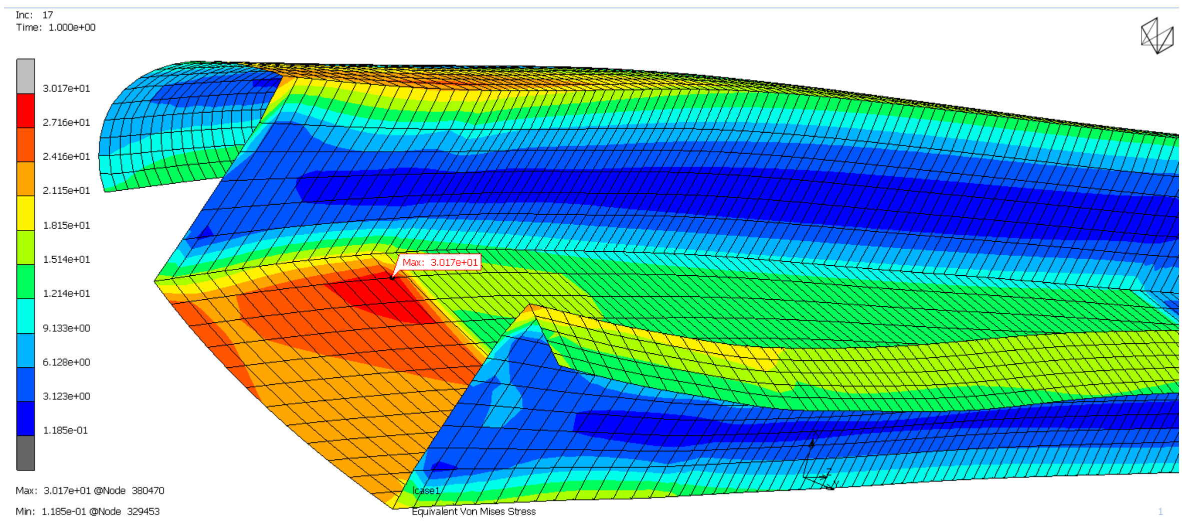

Figure 14. Spar cap stress distribution

The Puck progressive failure criteria model shows that laminate failure begins in the root transition region of the blade, where the spar meets the aerodynamic shell surface. Failure proceeds predominantly in the aerodynamic shell. The sudden thickness/stiffness change in this region and the tapering and ply differences resulting from the laminate thickness change cause a sudden increase in the stress values and, therefore, the failure indices resulting from the bending moment (see Figures 15, 16, and 17).

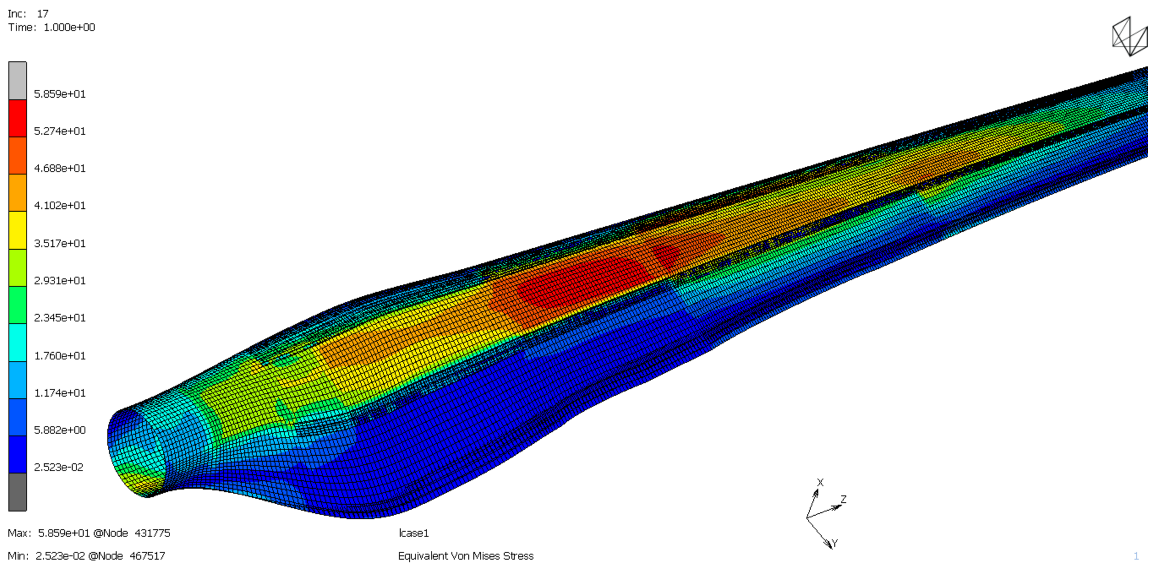

Figure 15. Equivalent von Misses stress for pressure side

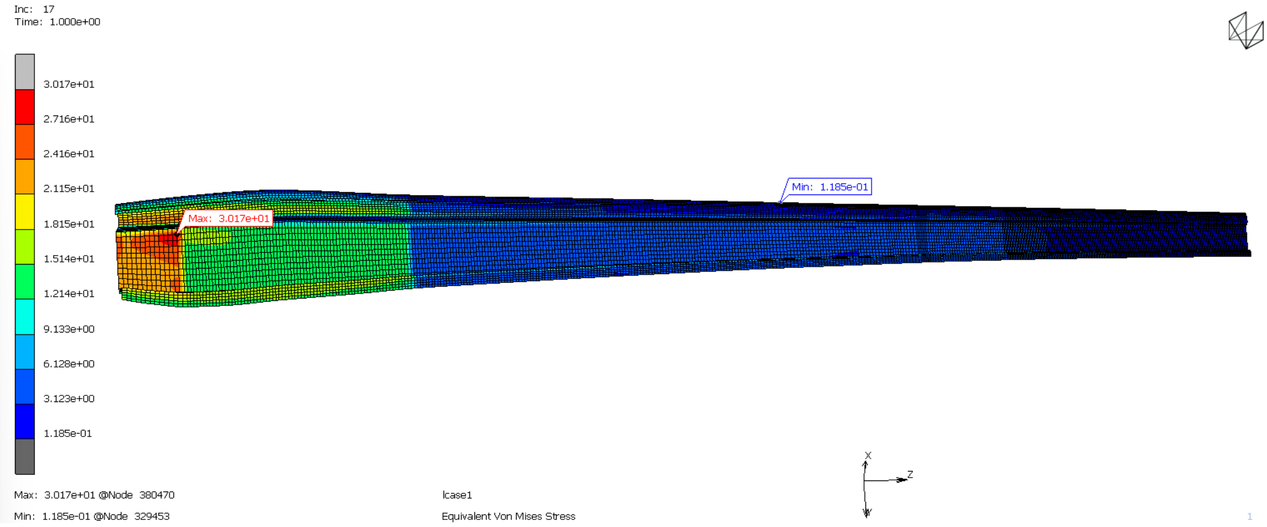

Figure 16. Equivalent stress distribution for spar surfaces

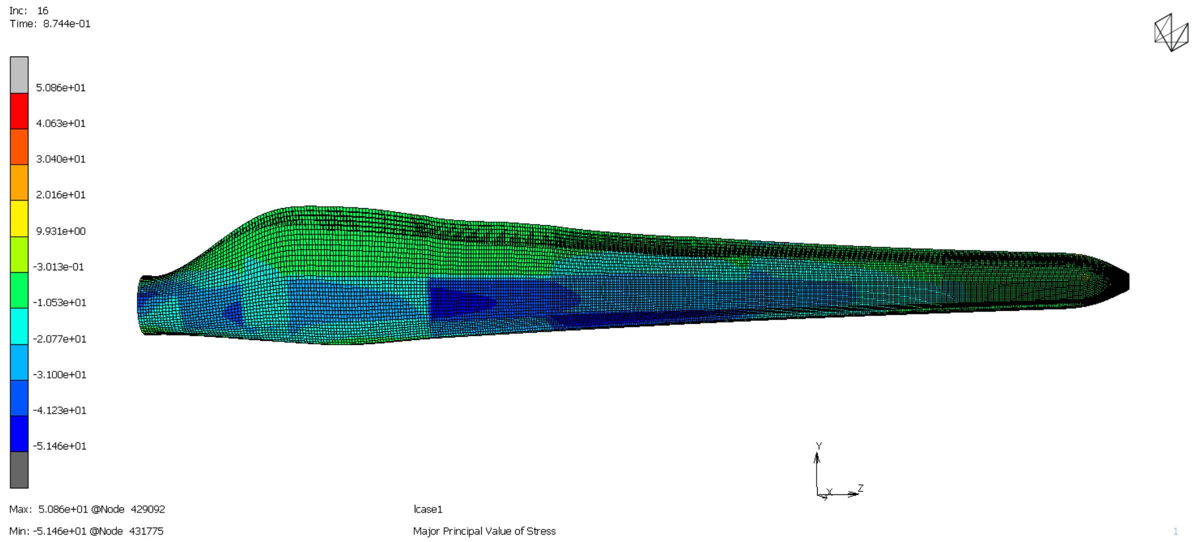

Figure 17. Equivalent stress distribution for the suction side

When the Selective Gradual Degradation command is applied to the RUZGEM 5-meter model, the damage and stress increase mainly occur in the aerodynamic shell and the spar cap region opposite this shell.

- r_1 depends on fiber breakage: first and second failure index: 1- fiber stress or 3- matrix stress (see Figures 18 and 19)

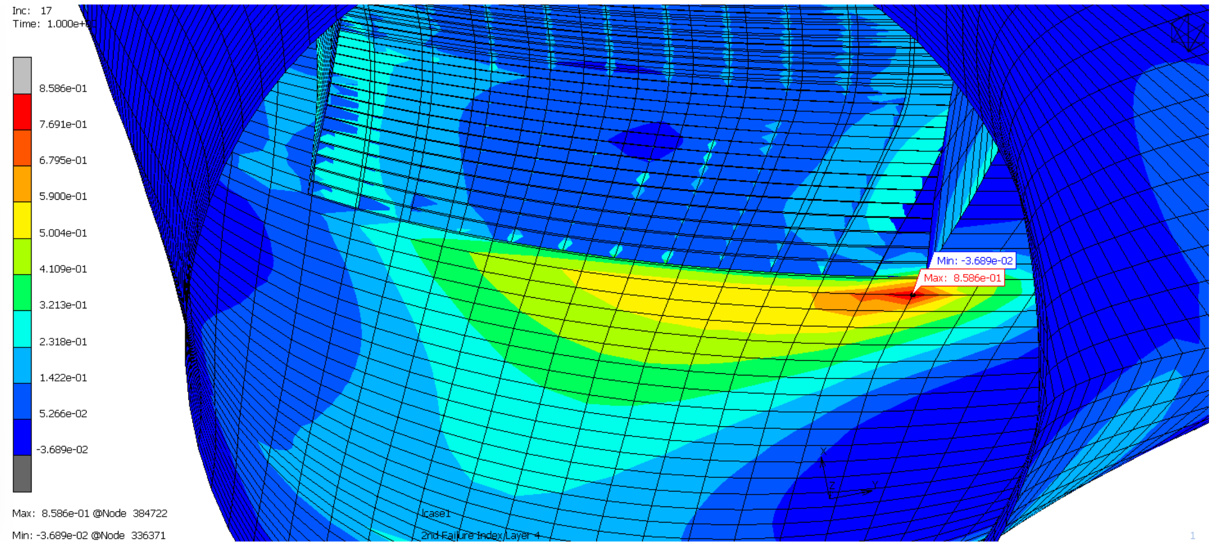

Figure 18. Increase around spar cap- 2nd Failure index in 4th Layer

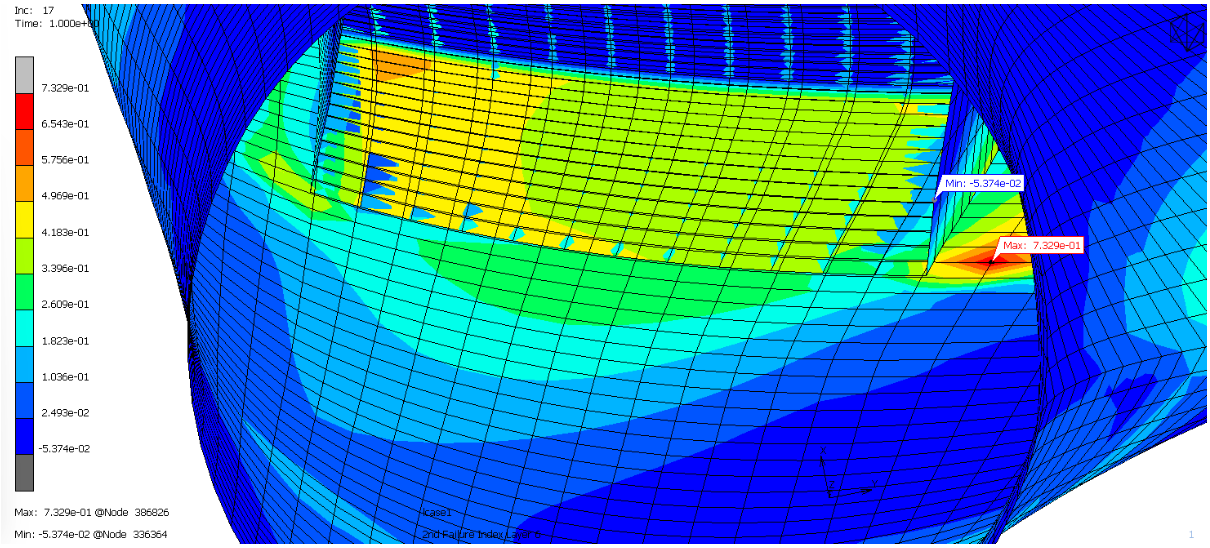

Figure 19. Increase around spar cap - 2nd Failure index in 6th Layer

- r_2 depends on the matrix failure (third, fourth, and fifth failure index): 2- fiber compression or 4 - matrix compression mode B (for solid elements using this material, only the fourth failure index is used for matrix compression) or 5- matrix compression mode C (see Figures 20 and 21).

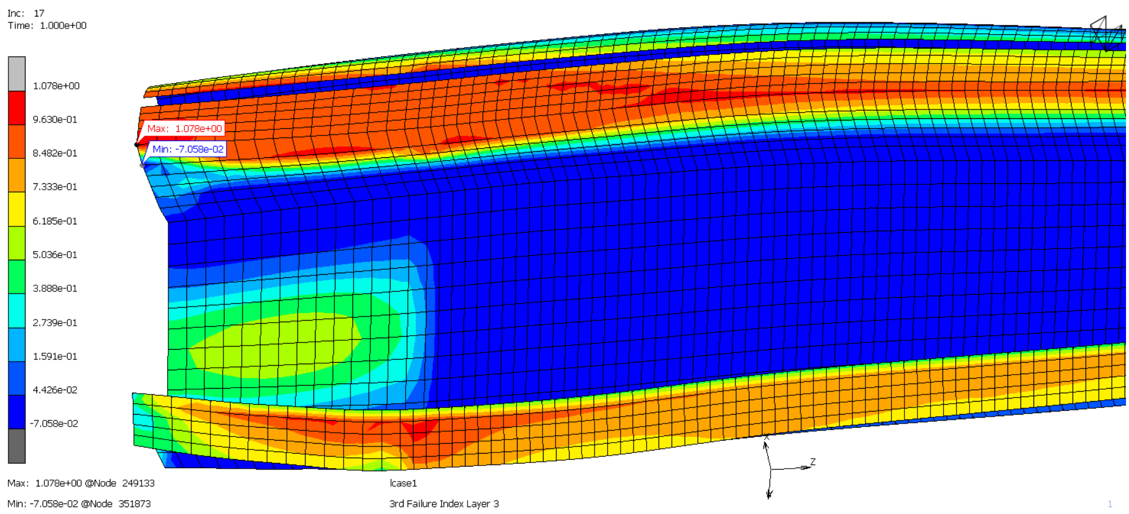

Figure 20. Increase around spar cap-3. Failure index layer 3

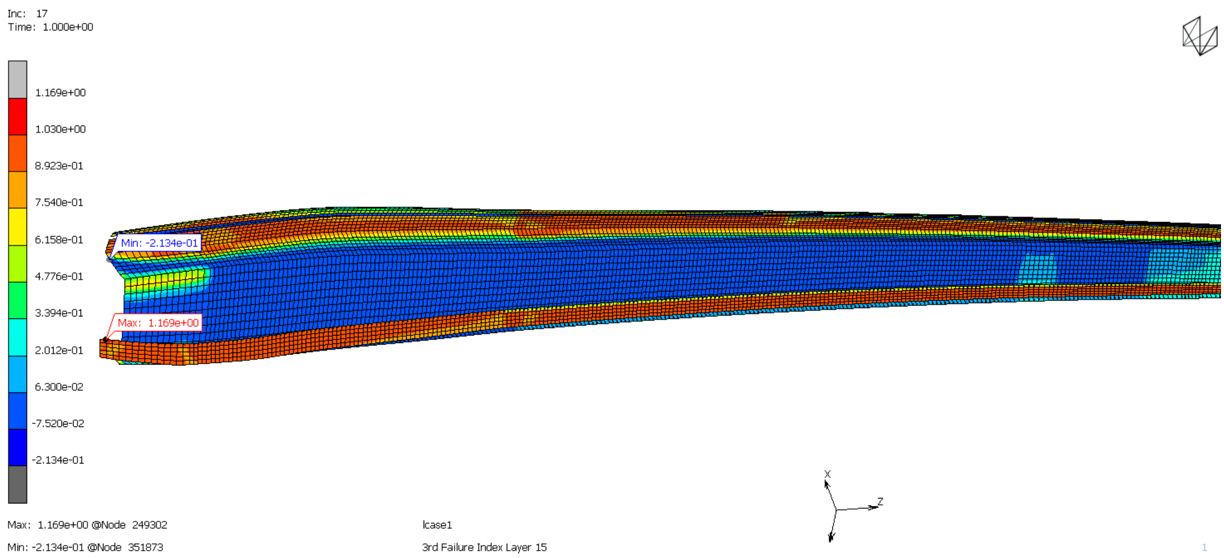

Figure 21. Increase around spar cap- 3. failure index layer 1

Regarding the stress criterion, adhesive separation failure was simulated by applying a cohesive zone model to the pressure side and spar interface. This model shows that adhesive separation failure first starts from the corners of the spar structure and progresses to include the root-transition zone (Figure 22).

When the finite element model, which provides high consistency with modal analyses, was examined with Puck progressive failure analysis, based on the results of this study, it was predicted that the adhesive separation failure that could occur at the pressure side shell-spar interface located in the root-transition region of the blade was critical (Figures 23 and 24) (Batmaz et al., 2021).

When the Glue Breaking criterion is reached, it uses regular Touch contact, which may include friction and other properties, and therefore tunable properties for the Touch contact can be defined here.

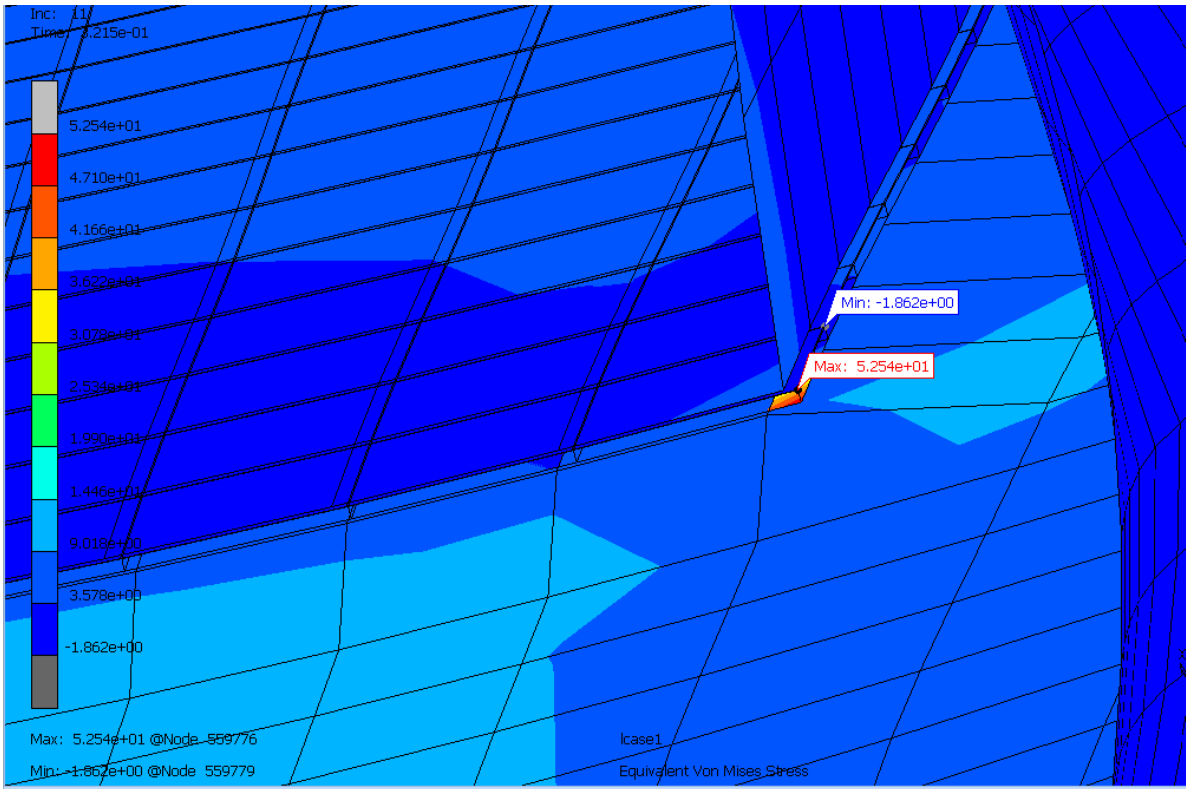

Figure 22. Parts where stress is concentrated

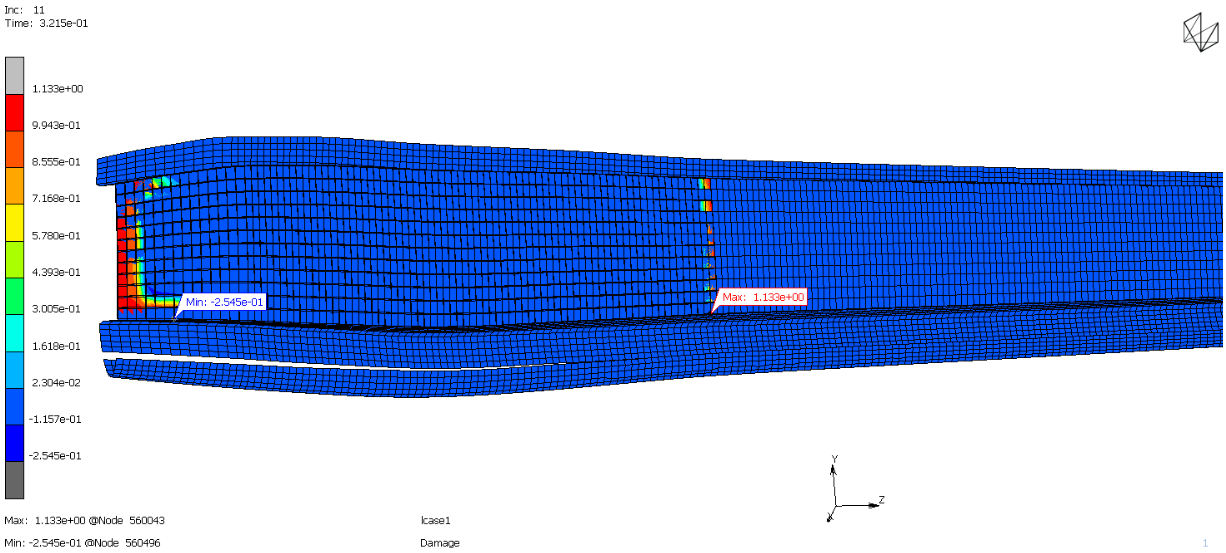

Figure 23. Formation of adhesive failure on the adhesive surface

In the blade model, under the applied load, adhesive separation failure was examined in the region and determined to be critical in the Puck criterion failure analysis results. This examination revealed that it alone did not destroy the blade's structural integrity in terms of breaking index (see Figure 25).

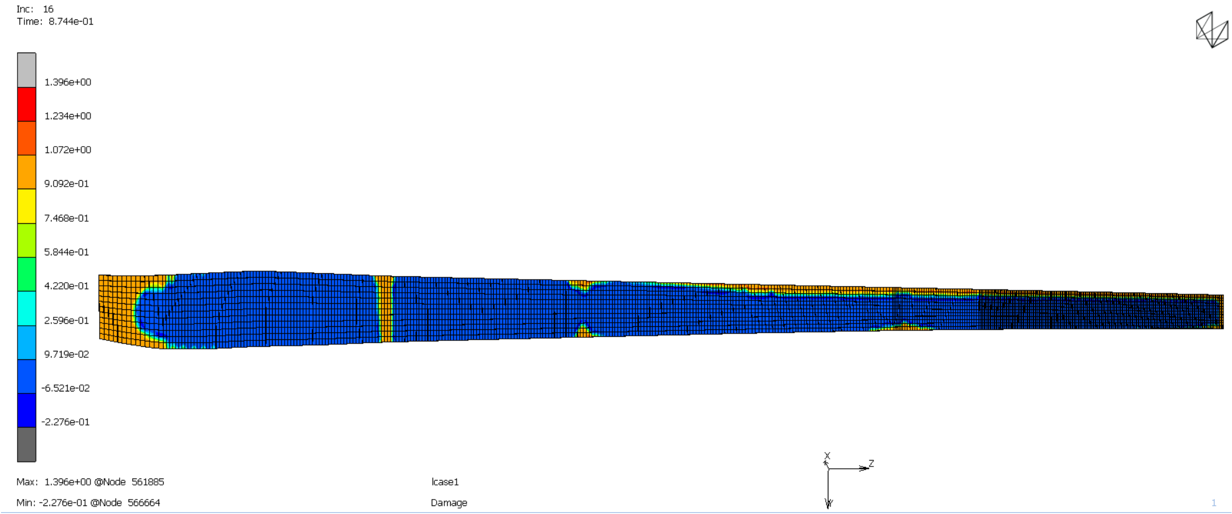

Figure 24. Distribution of final separation failure on the adhesive surface

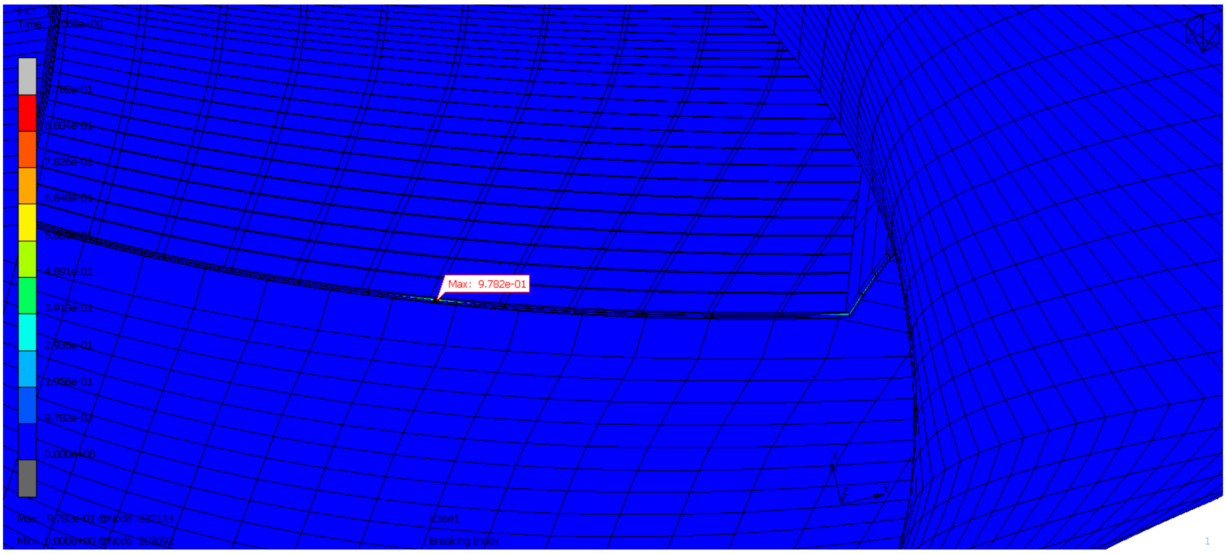

Figure 25. No effect of adhesive separation on structural destruction in terms of breaking index

CZM is a numerical technique that finds practical application in simulating fracture and delamination in materials and structures. This method effectively models the behavior when two composite layers separate. In cohesive zone model analysis, element 149 is an 8-node solid composite element, while 75 is a 4-node shell element. 188, on the other hand, is the 8-node interface element. A series of experiments were conducted to evaluate the VCCT and CZM methods.

The results of these experiments were significant, as they determined the presence of a Glue-breaking effect (see Figures 26 and 27), further validating the effectiveness of cohesive zone modeling.

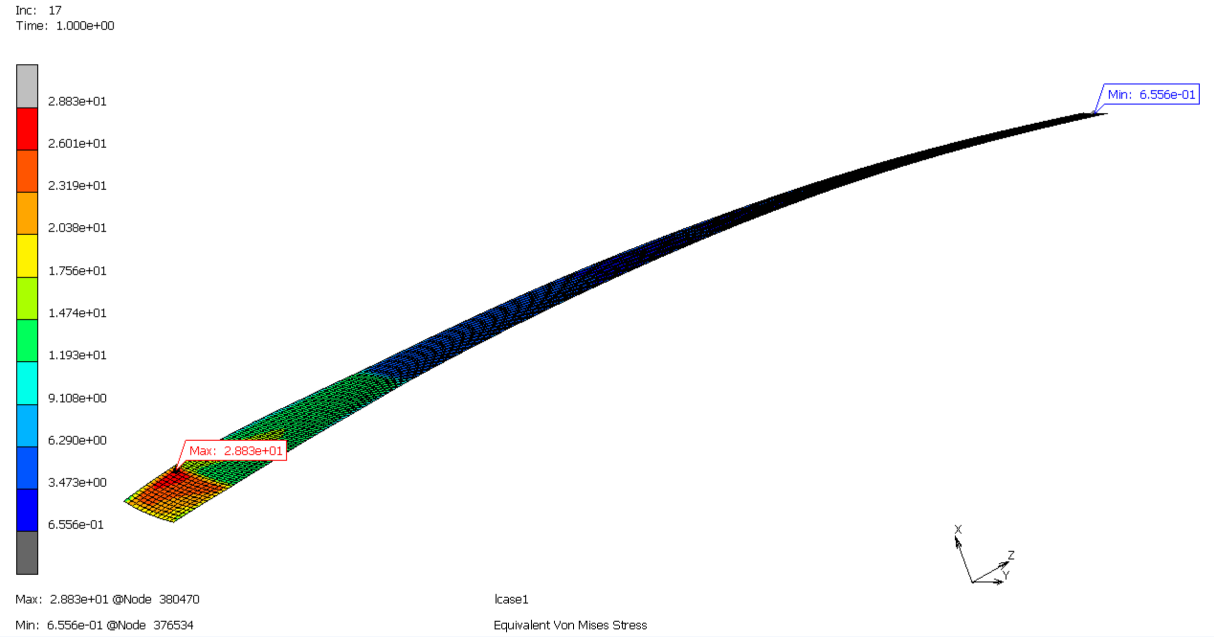

Figure 26. Equivalent von Misses stress in CZM with non-Glue Breaking

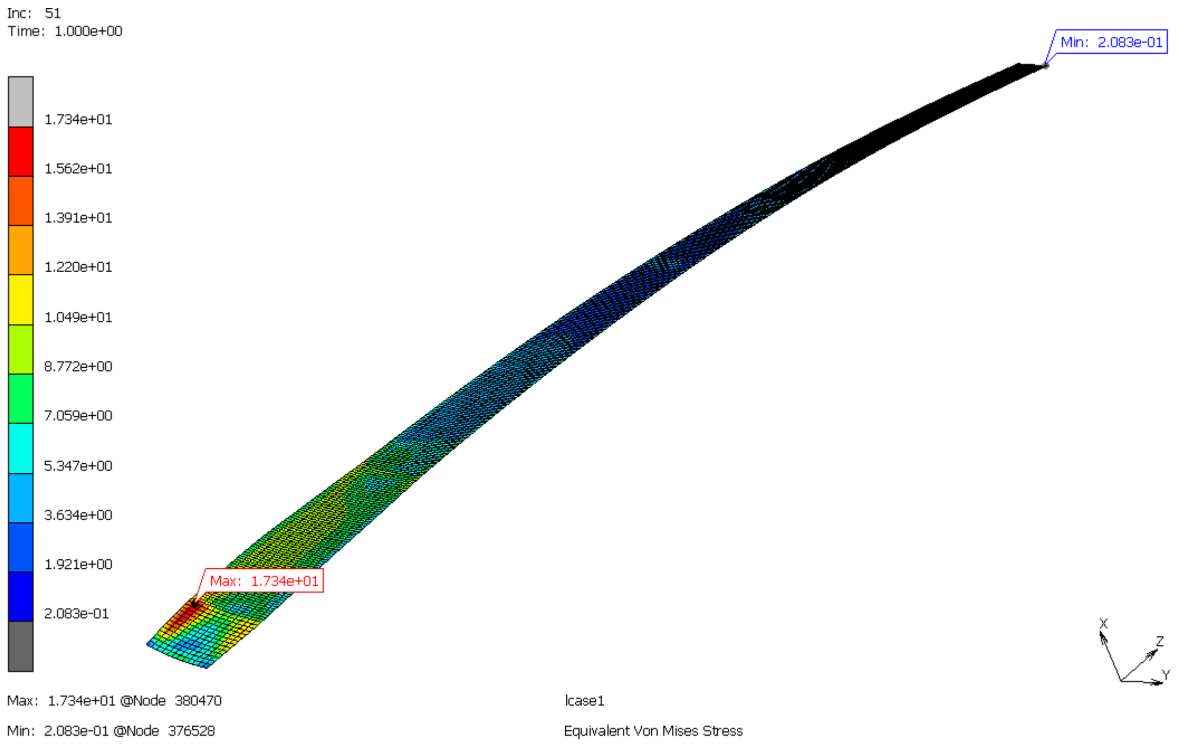

Figure 27. Equivalent von Misses stress in CZM with Glue Breaking

VCCT is a powerful fracture mechanics tool that predicts the crack tip's strain energy release rate (SERR). It can be used with various material models, including linear elastic, elastic-plastic, and cohesive zone models. It is used for crack growth prediction, fracture toughness evaluation, or design optimization of cracked structures. Accuracy is reduced in CZM studies without Glue Breaking, and CZM gives almost the same results as VCCT (see Figures 28 and 29).

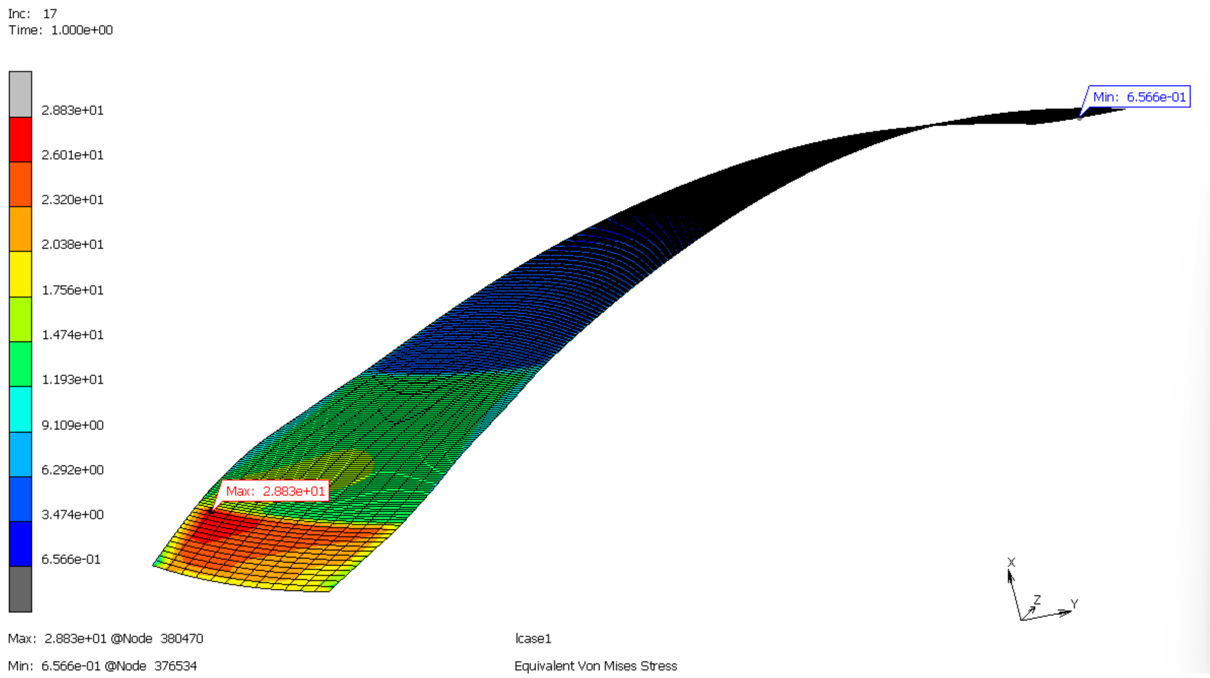

Figure 28. Equivalent von Misses stress in VCCT with non-Glue Breaking

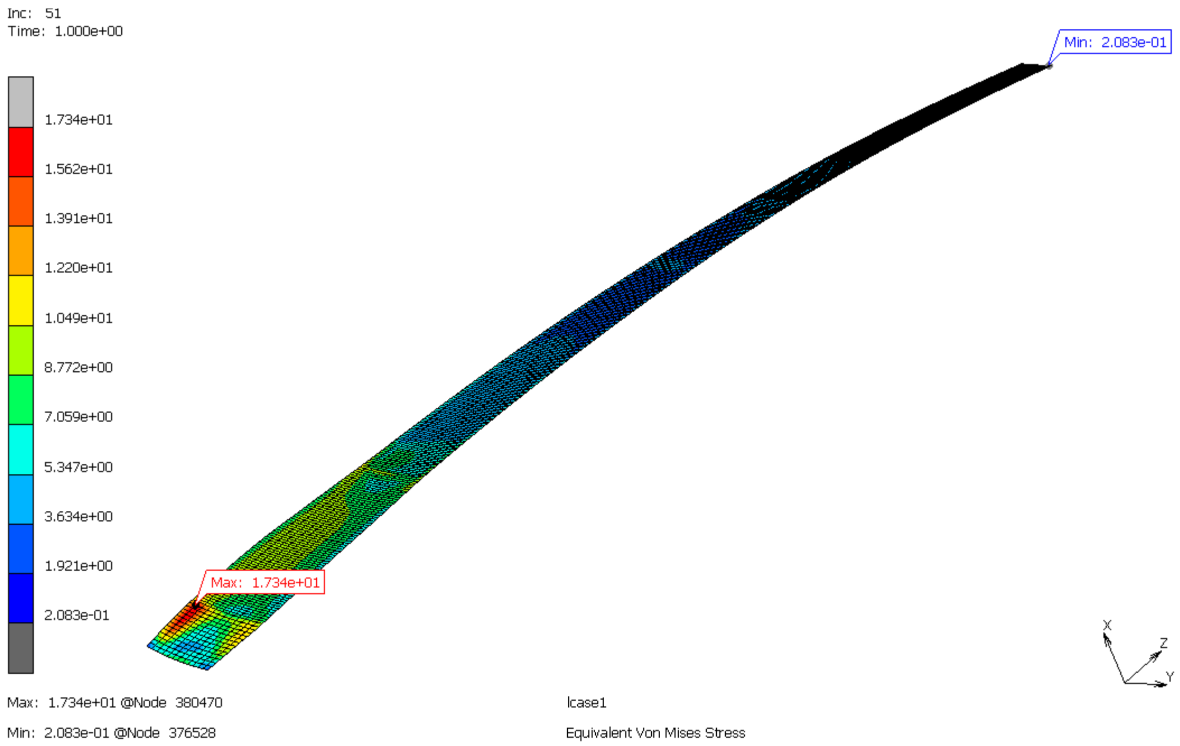

Figure 29. Equivalent von Misses stress in VCCT with Glue Breaking

Crack Initiator is a tool used to identify the initiation of a crack within a structure. No delamination or Turon pattern was used. The critical zone for cracks and structural failure is more likely to be in the area 1 meter further from the tip of the spar cap. The reason why no crack formation is observed in the section chosen as the crack initiation may be compressive stresses (see Figure 30).

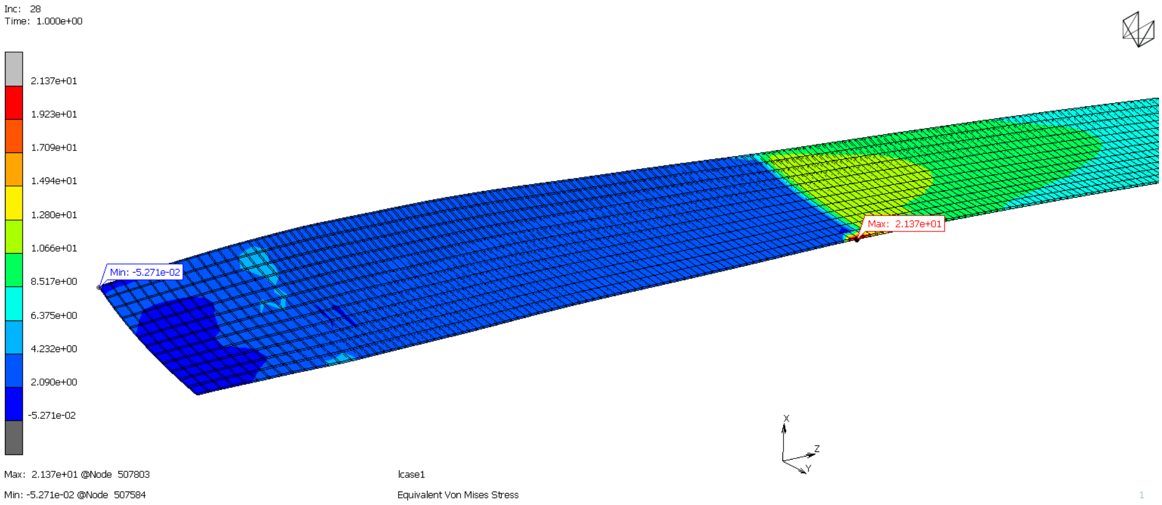

Figure 30. No crack formation and compression

The choice of crack growth model has several consequences on simulation results:

• Crack Propagation Rate: VCCT typically predicts faster crack propagation rates than the sticky zone model because free faces allow cracks to open more easily.

• Stress Distribution: The cohesive zone model provides more uniform stress distributions around the crack tip than VCCT, partly due to residual stresses on bonded crack faces.

• Energy Dissipation: The cohesive zone model considers the energy dissipation during crack growth, while VCCT does not. This can lead to differences in the overall energy balance of the simulation.

• Failure Criteria: The damage criteria for crack propagation in the two models differ. VCCT typically uses a critical stress criterion, whereas the adhesive zone model uses a damage-based criterion.

• Choosing the Right Model**:** The appropriate crack growth model selection depends on the specific material behavior and the desired level of accuracy. VCCT is usually sufficient for brittle materials with minimal interfacial strength. However, the sticky zone model is more accurate for ductile materials with significant residual interfacial strength.

As a result, when the crack mentioned above growth model selection effects were considered, no difference was observed between VCCT and CZM. From these analyses, no crack formation is understood in VCCT. Although there was failure in this region, it was observed that there was no structural destruction. When the interface properties were entered into glue contact in the cohesive region with Glue Breaking, the stress values were obtained more accurately than reference values, as shown in Table 3.

Table 3. Comparison of CZM and VCCT

FEA Method/ Type of Stress (MPa)	CZM		VCCT	
	non-Glue Breaking	with Glue Breaking	non-Glue Breaking	with Glue Breaking
Von Misses	28.83	17.32	28.85	17.34
Normal Stress	-25.05	-11.31	-25.02	-11.30
Shear Stress	10.84	8.30	10.82	8.29

4. Conclusion

There was no crack propagation in the adhesive separation, and the CZM and VCCT results were the same. This means that the VCCT method can be used instead of CZM when examining the adhesive separation with the FEM. The VCCT method does not require the creation of user-defined interface elements required in the CZM method and can also be easily applied to FEM codes; thus, the VCCT method makes the work more accessible and more efficient. Glue Breaking continues as contact when the glue contact effect is removed, and by assigning this feature, more accurate results were obtained. Situations that cause VCCT and CZM values to be the same in a failure analysis study are as follows:

- The extent of failure is minimal: VCCT and CZM may produce different results depending on the extent of failure. If the failure size is small, both methods can ignore the failure and deliver the same results.
- Failure does not significantly affect the material's behavior: VCCT and CZM consider how failure affects the material's behavior. If the failure does not significantly affect the material's behavior, both methods can produce the same results.
- Failure does not disrupt the homogeneity of the material: VCCT and CZM take the homogeneity of the material into account. If the failure does not disrupt the homogeneity of the material, both methods can produce the same results.

In certain cases, technical factors can result in identical VCCT and CZM values. This can occur when the parameters used to calculate these values lead both methods to yield the same results. Here are some specific scenarios where this may happen:

- If there is a small crack on the material surface, VCCT and CZM may overlook the crack and produce the same results.
- In the case of minor delamination within a composite material, VCCT and CZM may disregard the delamination and yield the same results.
- When a material's internal structure exhibits slight deformation, VCCT and CZM may overlook the deformation and produce the same results.

Upon considering the growth model selection effects mentioned above, no distinction was observed between VCCT and CZM as the crack extended. The analyses indicated that no crack formation occurred in VCCT. Despite the failure in this area, there was no structural damage. Introducing the interface properties into the cohesive region with Glue Breaking in the adhesive contact provided stress values that were more accurate than the reference values.

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3

Analysis of Single Degree of Freedom Systems Solved by Taylor, Euler, and Lucas Polynomials

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Abstract

Various polynomial methods employed in solving differential equations are examined. These methods, founded on Taylor polynomials, offer a wide range of applications, from high-order linear differential equations to integro-differential and delay differential equations. The Taylor polynomial approach has been effectively applied in numerous areas, as demonstrated by the work of Sezer and colleagues. In addition to the Taylor polynomial approach, several other polynomial methods have been developed, including the Bernoulli matrix method, Lucas polynomials, and Euler polynomials. These methods offer alternative strategies for solving both linear and nonlinear differential equations, particularly those involving variable delays or nonlinear terms. The Lucas polynomial approach is particularly effective in solving nonlinear differential equations with variable delay and functional integro-differential equations. In the field of mechanical vibrations, polynomial methods have also been applied to solve single degree of freedom systems. Contributions from several researchers have demonstrated the applicability of Euler and Taylor polynomial methods in this field. Moreover, the hybrid use of polynomial methods with collocation techniques has improved computational efficiency and accuracy. For instance, the hybrid Taylor-Lucas collocation method offers a robust solution for high-order pantograph-type delay differential equations. Notably, advancements in polynomial methods play a critical role in the numerical solution of differential equations. These methods not only provide accurate and efficient solutions but also have broad applications across various scientific and engineering disciplines. This study provides a detailed examination of the theoretical foundations and practical implementations of different polynomial methods.

Keywords: Taylor polynomial approach, Lucas polynomials, Euler polynomials, collocation method, differential equations

1. Introduction

Numerical methods for solving differential equations have seen significant development over the years, providing crucial tools for scientists and engineers in various fields. Among these methods, polynomial-based techniques have garnered particular attention due to their versatility and accuracy. This study explores several polynomial methods employed to solve different types of differential equations, including high-order linear differential equations, integro-differential equations, and delay differential equations.

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The foundational work by Sezer and colleagues on the Taylor polynomial approach has paved the way for numerous advancements in the numerical solution of differential equations. The method's application ranges from solving high-order linear Fredholm integro-differential equations (Nas et al., 2000; Yalçınbaş & Sezer, 2000) to addressing complex differential-difference equations (Gülsu & Sezer, 2006a; Sezer, 1996; Sezer & Daşçıoğlu, 2006; Sezer & Daşçıoğlu, 2007; Sezer & Gülsu, 2005). The efficacy of Taylor polynomials in providing approximate solutions has been further demonstrated in works by Gülsu and Sezer (2006b) and Kanwal and Liu (1989), highlighting the method's robustness.

Parallel to the Taylor polynomial approach, other polynomial methods such as the Bernoulli matrix method (Biçer et al., 2021), the Lucas polynomial method (Baykuş Savaşaneril, 2023a; Baykuş Savaşaneril, 2023b; Gümgüm et al., 2018; Gümgüm et al., 2019; Gümgüm et al., 2020), and the Euler polynomial method (Baykuş Savaşaneril, 2023a; Elmacı et al., 2021) have been developed. These methods offer alternative strategies for solving both linear and nonlinear differential equations, often involving variable delays or nonlinear terms. For instance, the Lucas polynomial approach has been effectively used to solve nonlinear differential equations with variable delay (Gümgüm et al., 2019; Gümgüm et al, 2020), as well as functional integro-differential equations (Gümgüm et al., 2018).

In the realm of mechanical vibrations, polynomial methods have also been applied to solve the single degree of freedom (SDOF) system. Notable contributions by Baykuş Savaşaneril (2023a & 2023b) and Kurt and Çevik (2008) have demonstrated the applicability of Euler and Taylor polynomial methods in this area. These methods provide a reliable means to model and analyse the dynamic behaviour of vibrating systems, complementing classical texts on vibration analysis by Inman (2001), Meirovitch (1975), and Rao (2004).

Furthermore, the hybridization of polynomial methods with collocation techniques has enhanced their computational efficiency and accuracy. For example, the hybrid Taylor-Lucas collocation method proposed by Baykuş and Sezer (2017) offers a robust solution for high-order pantograph type delay differential equations with variable delays. This innovative approach underscores the potential of hybrid methods in tackling more complex differential equations.

Overall, the advancements in polynomial methods, as evidenced by the extensive literature, highlight their critical role in the numerical solution of differential equations. These methods not only provide accurate and efficient solutions but also broaden the scope of applications in various scientific and engineering disciplines. The following sections will delve into specific polynomial methods and their applications, providing detailed insights into their theoretical foundations and practical implementations.

In general, an mth order differential equation can be written as

$$\sum_{k=0}^{m} P_k x^{(k)}(t) = f(t), \tag{1}$$

with initial conditions

$$\sum_{k=0}^{m-1} a_{ik} x^{(k)}(t) = \lambda_i \qquad i = 0,1,2,\dots,m-1 \tag{2}$$

where $P_k(t)$ is analytic functions defined on $a \le t \le b$, a_{ik}, λ_i are suitable constants. In the present method,

1. the solution of (1) is expressed in the Taylor polynomial form (Kurt & Çevik, 2008)

$$x(t) = x_N(t) = \sum_{n=0}^{N} a_n T_n(t) \tag{3T}$$

and obtained by determining the Taylor coefficients a_n, $n = 0,1,2,\dots,N$

2. the solution of (1) is expressed in the Lucas polynomial form (Baykuş Savaşaneril, 2023b)

$$x(t) = x_N(t) = \sum_{n=0}^{N} a_n L_n(t) \tag{3L}$$

where $L_n(t)$ are the Lucas polynomials and a_n, $n = 0,1,2,...,N$ are unknown coefficients (Baykuş & Sezer, 2017).

3. the solution of (1) is expressed in the Euler polynomial form (Baykuş Savaşaneril, 2023a)

$$x(t) = x_N(t) = \sum_{n=0}^{N} a_n E_n(t) \tag{3E}$$

where $E_n(t)$ are the Euler polynomials and a_n, $n = 0,1,2,...,N$ are unknown coefficients (Elmacı et al., 2021).

2. Fundamental Matrix Relations

In this study, the viscously damped single degree of freedom system subjected to harmonic excitation (Kurt & Çevik, 2008)

$$M\ddot{x} + C\dot{x} + Kx = F_0 \cos wt \tag{4}$$

with initial conditions

$$x(0) = \lambda_0$$
$$\dot{x}(0) = \lambda_1 \tag{5}$$

will be solved by the Taylor-Lucas-Euler matrix method. In this case, $m = 2$ and the constants $P_2 = M$ $P_1 = C$ $P_0 = K$ in Eq. (1). Assuming the solution $x(t)$ to be defined by the truncated Taylor-Lucas-Euler series, one may put Eq. (3T-3L-3E) into the following matrix form respectively

$$[x_T(t)] = \mathbf{T}(t)\mathbf{A} \tag{6T}$$

$$[x_L(t)] = \mathbf{L}(t)\mathbf{A} \tag{6L}$$

$$[x_E(t)] = \mathbf{E}(t)\mathbf{A} \tag{6E}$$

where

$$\mathbf{T}(t) = \begin{bmatrix} 1 & t & \cdots & t^N \end{bmatrix}, \qquad \mathbf{A} = \begin{bmatrix} a_0 & a_1 & \cdots & a_N \end{bmatrix}^T \tag{7T}$$

$$\mathbf{L}(t) = \begin{bmatrix} L_0(t) & L_1(t) & \cdots & L_N(t) \end{bmatrix}, \quad \mathbf{A} = \begin{bmatrix} a_0 & a_1 & \cdots & a_N \end{bmatrix}^T \tag{7L}$$

$$\mathbf{E}(t) = \begin{bmatrix} E_0(t) & E_1(t) & \cdots & E_N(t) \end{bmatrix}, \quad \mathbf{A} = \begin{bmatrix} a_0 & a_1 & \cdots & a_N \end{bmatrix}^T \tag{7E}$$

The relation between the matrices $\mathbf{T}(t)$, $\mathbf{L}(t)$, $\mathbf{E}(t)$ and their first derivatives $\dot{\mathbf{T}}(t)$, $\dot{\mathbf{L}}(t)$, $\dot{\mathbf{E}}(t)$ can be expressed as (Baykuş & Sezer, 2017; Baykuş Savaşaneril, 2023b)

$$\dot{\mathbf{T}}(t) = \mathbf{T}(t)\mathbf{B} \tag{8T}$$

$$\dot{\mathbf{L}}(t) = \mathbf{T}(t)\mathbf{B}\mathbf{M} \tag{8L}$$

$$\dot{\mathbf{E}}(t) = \mathbf{T}(t)\mathbf{BS} \tag{8E}$$

where

$$\mathbf{B} = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 2 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & N \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \tag{9}$$

If N is odd,

$$\mathbf{M} = \begin{bmatrix} 2 & 0 & \frac{2}{1}\binom{1}{1} & 0 & \cdots & \frac{n-1}{\left(\frac{n-1}{2}\right)}\binom{\frac{n-1}{2}}{\frac{n-1}{2}} & 0 \\ 0 & \frac{1}{1}\binom{1}{0} & 0 & \frac{3}{2}\binom{2}{1} & \cdots & 0 & \frac{n}{\left(\frac{n+1}{2}\right)}\binom{\frac{n+1}{2}}{\frac{n-1}{2}} \\ 0 & 0 & \frac{2}{2}\binom{2}{0} & 0 & \cdots & \frac{n-1}{\left(\frac{n+1}{2}\right)}\binom{\frac{n+1}{2}}{\frac{n-3}{2}} & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 0 & \frac{n}{n}\binom{n}{0} \end{bmatrix} \tag{10}$$

If N is even,

$$\mathbf{M} = \begin{bmatrix} 2 & 0 & \frac{2}{1}\binom{1}{1} & 0 & \cdots & 0 & \frac{n}{\left(\frac{n}{2}\right)}\binom{\frac{n}{2}}{\frac{n}{2}} \\ 0 & \frac{1}{1}\binom{1}{0} & 0 & \frac{3}{2}\binom{2}{1} & \cdots & \frac{n-1}{\left(\frac{n}{2}\right)}\binom{\frac{n}{2}}{\frac{n-2}{2}} & 0 \\ 0 & 0 & \frac{2}{2}\binom{2}{0} & 0 & \cdots & 0 & \frac{n}{\left(\frac{n+2}{2}\right)}\binom{\frac{n+2}{2}}{\frac{n-2}{2}} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 0 & \frac{n}{n}\binom{n}{0} \end{bmatrix} \tag{11}$$

$$\mathbf{S} = \begin{bmatrix} 1 & \frac{1}{2}\binom{2}{1} & \frac{1}{2}\binom{2}{0} & \cdots & \frac{1}{2}\binom{N}{0} \\ 0 & 1 & \frac{1}{2}\binom{2}{0} & \cdots & \frac{1}{2}\binom{N}{1} \\ 0 & 0 & 1 & \cdots & \frac{1}{2}\binom{N}{2} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \end{bmatrix} \tag{12}$$

The second derivatives can be written similarly,

$$\ddot{\mathbf{T}}(t) = \mathbf{T}(t)\mathbf{B}^2 \tag{13T}$$

$$\ddot{\mathbf{L}}(t) = \mathbf{T}(t)\mathbf{B}^2\mathbf{M} \tag{13L}$$

$$\ddot{E}(t) = \mathbf{T}(t)\mathbf{B}^2\mathbf{S} \tag{13E}$$

Substituting (6), (7) and (9) into (4), the matrix form of the left-hand side of (4) is obtained as

$$M\ddot{x} + C\dot{x} + Kx = \sum_{k=0}^{2} P_k \mathbf{T}(t)\mathbf{B}^k\mathbf{A} \tag{14T}$$

$$M\ddot{x} + C\dot{x} + Kx = \sum_{k=0}^{2} P_k \mathbf{T}(t)\mathbf{B}^k\mathbf{MA} \tag{14L}$$

$$M\ddot{x} + C\dot{x} + Kx = \sum_{k=0}^{2} P_k \mathbf{T}(t)\mathbf{B}^k\mathbf{SA} \tag{14E}$$

The matrix representation of the excitation term of (4) can be written in the form

$$|f(t)| = \mathbf{T}(t)\mathbf{F}, \quad f_n = \frac{f^{(n)}(c)}{n!} \tag{15}$$

where

$$\mathbf{F} = \begin{bmatrix} f_0 & f_1 & \cdots & f_N \end{bmatrix}^T \tag{16}$$

The matrix form for the initial conditions (5) can be obtained using (6T-6L-6E) and (8T-8L-8E)

$$\mathbf{U}_{Ti} = \sum_{k=0}^{1} c_{ik}\mathbf{T}(a)\mathbf{B}^k\mathbf{A} = [\lambda_i], \qquad i = 0,1 \tag{17T}$$

$$\mathbf{U}_{Li} = \sum_{k=0}^{1} c_{ik}\mathbf{T}(a)\mathbf{B}^k\mathbf{MA} = [\lambda_i], \qquad i = 0,1 \tag{17L}$$

$$\mathbf{U}_{Ei} = \sum_{k=0}^{1} c_{ik}\mathbf{T}(a)\mathbf{B}^k\mathbf{SA} = [\lambda_i], \qquad i = 0,1 \tag{17E}$$

where c_{ik} represent the coefficients of initial condition equation.

Finally, the matrix representation of the problem is obtained by substituting (14T-14L-14E) and (15) into the fundamental Eq. (4) and making necessary simplifications as

$$\sum_{k=0}^{2} P_k \mathbf{T}(t)\mathbf{B}^k \mathbf{A} = \mathbf{F} \tag{18T}$$

$$\sum_{k=0}^{2} P_k \mathbf{T}(t)\mathbf{B}^k \mathbf{MA} = \mathbf{F} \tag{18L}$$

$$\sum_{k=0}^{2} P_k \mathbf{T}(t)\mathbf{B}^k \mathbf{SA} = \mathbf{F} \tag{18E}$$

which corresponds to a system of $(N+1)$ algebraic equations for the $(N+1)$ unknown Taylor, Lucas, Euler coefficients $a_0, a_1, ..., a_N$ respectively.

3. Matrix solution of the problem

3.1 Particular solution

In order to determine the particular solution of the problem in matrix form, (18T-18L-18E) is written briefly in the form

$$\mathbf{WA} = \mathbf{F} \quad \text{or} \quad [\mathbf{W}; \mathbf{F}] \tag{19}$$

where

$$\mathbf{W}_T = [w_{pq}] = \sum_{k=0}^{2} P_k \mathbf{T}(t)\mathbf{B}^k \qquad p, q = 0, 1, ..., N \tag{19T}$$

$$\mathbf{W}_L = [w_{pq}] = \sum_{k=0}^{2} P_k \mathbf{T}(t)\mathbf{B}^k \mathbf{M} \qquad p, q = 0, 1, ..., N \tag{19L}$$

$$\mathbf{W}_E = [w_{pq}] = \sum_{k=0}^{2} P_k \mathbf{T}(t)\mathbf{B}^k \mathbf{S} \qquad p, q = 0, 1, ..., N \tag{19E}$$

By consequence

$$\mathbf{A} = \mathbf{W}^{-1}\mathbf{F} \tag{20}$$

which yields the desired Taylor coefficients a_n , $n = 0, 1, 2, ..., N$ of the particular solution.

3.2 General solution

To determine the general solution, the matrix form (17T-17L-17E) of the boundary conditions (5) is written as

$$\mathbf{UA} = [\lambda_i] \text{ or } [\mathbf{U}; \lambda_i], \quad i = 0, 1 \tag{21}$$

where

$$\mathbf{U}_{Ti} = \sum_{k=0}^{1} a_{ik} \mathbf{T}(c)\mathbf{B}^k \equiv [u_{i0} \quad u_{i1} \quad \cdots \quad u_{iN}], \qquad i = 0, 1 \tag{22T}$$

$$\mathbf{U}_{Li} = \sum_{k=0}^{1} a_{ik}\mathbf{T}(a)\mathbf{B}^k\mathbf{M} \equiv \begin{bmatrix} u_{i0} & u_{i1} & \cdots & u_{iN} \end{bmatrix} \qquad i = 0,1 \tag{22L}$$

$$\mathbf{U}_{Ei} = \sum_{k=0}^{1} a_{ik}\mathbf{T}(t)\mathbf{B}^k\mathbf{S} \equiv \begin{bmatrix} u_{i0} & u_{i1} & \cdots & u_{iN} \end{bmatrix} \qquad i = 0,1 \tag{22E}$$

Now, to solve the problem, the following augmented matrix (Nas et al., 2000; Sezer & Gülsu, 2005) is constructed by replacing the last 2 rows of $[\mathbf{W};\mathbf{F}]$ of (19) by the 2-row matrix $[\mathbf{U}_i;\lambda_i]$

$$[\tilde{\mathbf{W}};\tilde{\mathbf{F}}] = \left[\begin{array}{cccc|c} w_{00} & w_{01} & \cdots & w_{0N} & f_0 \\ w_{10} & w_{11} & \cdots & w_{1N} & f_0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ w_{N-2,0} & w_{N-2,1} & \cdots & w_{N-2,N} & f_{N-2} \\ u_{00} & u_{01} & \cdots & u_{0N} & \lambda_0 \\ u_{10} & u_{11} & \cdots & u_{1N} & \lambda_1 \end{array}\right] \tag{23}$$

If $\det \tilde{\mathbf{W}} \neq 0$, then one can write

$$\tilde{\mathbf{A}} = (\tilde{\mathbf{W}})^{-1}\tilde{\mathbf{F}} \tag{24}$$

which yields the Taylor-Lucas-Euler coefficients of the general solution. Thus, the fundamental Eq. (4) with initial conditions (5) has a unique solution.

3.3 Homogeneous solution

Since the system is linear, the general solution is the sum of the particular solution plus the homogeneous solution; therefore, the homogeneous solution is determined by taking the difference of the general and particular solutions given in the previous sections.

4. Numerical Application

A spring-mass-damper system with a mass of $M = 10$ kg, damping coefficient of $C = 20$ kg/s and spring stiffness of $K = 4000$ N/m subject to an excitation force of amplitude $F_0 = 100$ N and frequency $\omega = 10$ rad/s is considered with initial conditions $x(0) = 0.01$ m and $\dot{x}(0) = 0$. The matrix operations in this section are performed by using MATLAB 6.5.1 (2003) or Wolfram Mathematica 13.0 software package.

The exact solution is given by Inman (2001).

According to (11), taking $N = 5$

$$\mathbf{F} = \begin{bmatrix} 100 & 0 & -5000 & 0 & 41667 & 0 \end{bmatrix}^T$$

and according to (13) and (14)

$$\mathbf{W}_T = 10\mathbf{B}^2 + 20\mathbf{B} + 4000\mathbf{I} = \begin{bmatrix} 4000 & 20 & 20 & 0 & 0 & 0 \\ 0 & 4000 & 40 & 60 & 0 & 0 \\ 0 & 0 & 4000 & 60 & 120 & 0 \\ 0 & 0 & 0 & 4000 & 80 & 200 \\ 0 & 0 & 0 & 0 & 4000 & 100 \\ 0 & 0 & 0 & 0 & 0 & 4000 \end{bmatrix}$$

$$\mathbf{W}_L = 10\mathbf{T}(t)\mathbf{B}^2\mathbf{M} + 20\mathbf{T}(t)\mathbf{BM} + 4000\mathbf{T}(t)\mathbf{M} = \begin{bmatrix} 8000 & 20 & 8020 & 60 & 8080 & 100 \\ 8000 & 820 & 8188 & 2506.4 & 8763.84 & 4335.04 \\ 8000 & 1620 & 8676 & 5149.6 & 10830.7 & 9604.32 \\ 8000 & 2420 & 9484 & 8181.6 & 14514.9 & 17075.2 \\ 8000 & 3220 & 10612 & 11794.4 & 20204.2 & 28226.1 \\ 8000 & 4020 & 12060 & 16180 & 28440 & 45000 \end{bmatrix}$$

$$\mathbf{W}_E = 10\mathbf{T}(t)\mathbf{B}^2\mathbf{S} + 20\mathbf{T}(t)\mathbf{BS} + 4000\mathbf{T}(t)\mathbf{S} = \begin{bmatrix} 4000 & -1980 & 0 & 970 & 20 & -1950 \\ 4000 & -1180 & -632 & 764.4 & 739.04 & -1556.56 \\ 4000 & -380 & -944 & 275.6 & 1167.52 & -570.48 \\ 4000 & 420 & -936 & -304.4 & 1155.68 & 630 \\ 4000 & 1220 & -608 & -783.6 & 707.36 & 1593.68 \\ 4000 & 2020 & 40 & -970 & -20 & 1950 \end{bmatrix}$$

One may also write (16) for the given boundary conditions as

$$\left[\mathbf{U}_i \;|\lambda_i\right] = \left[\begin{array}{cccccc|c} 1 & 0 & 0 & 0 & 0 & 0 & 0.01 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \end{array}\right]$$

$$\left[\mathbf{U}_i \;|\lambda_i\right] = \left[\begin{array}{cccccc|c} 2 & 0 & 2 & 0 & 2 & 0 & 0.01 \\ 0 & 1 & 0 & 3 & 0 & 5 & 0 \end{array}\right]$$

$$\left[\mathbf{U}_i \;|\lambda_i\right] = \left[\begin{array}{cccccc|c} 1 & -\frac{1}{2} & 0 & \frac{1}{4} & 0 & -\frac{1}{2} & 0.01 \\ 0 & 1 & -1 & 0 & 1 & 0 & 0 \end{array}\right]$$

where $i = 0,1$. Therefore, the augmented matrix (17) becomes

$$\left[\tilde{\mathbf{W}}_T;\tilde{\mathbf{F}}\right] = \left[\begin{array}{cccccc|c} 4000 & 20 & 20 & 0 & 0 & 0 & 100 \\ 0 & 4000 & 40 & 60 & 0 & 0 & 0 \\ 0 & 0 & 4000 & 60 & 0 & 0 & -5000 \\ 0 & 0 & 0 & 4000 & 80 & 200 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0.01 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \end{array}\right]$$

$$\left[\tilde{\mathbf{W}}_L;\tilde{\mathbf{F}}\right]=\left[\begin{array}{cccccc|c} 8000 & 20 & 8020 & 60 & 8080 & 100 & 100 \\ 8000 & 820 & 8188 & 2506.4 & 8763.84 & 4335.04 & 28.3662 \\ 8000 & 1620 & 8676 & 5149.6 & 10830.7 & 9604.32 & -65.3644 \\ 8000 & 2420 & 9484 & 8181.6 & 14514.9 & 17075.2 & 96.017 \\ 2 & 0 & 2 & 0 & 2 & 0 & 0.01 \\ 0 & 1 & 0 & 3 & 0 & 5 & 0 \end{array}\right]$$

$$\left[\tilde{\mathbf{W}}_E;\tilde{\mathbf{F}}\right]=\left[\begin{array}{cccccc|c} 4000 & -1980 & 0 & 970 & 20 & -1950 & 100 \\ 4000 & -1180 & -632 & 764.4 & 739.04 & -1556.56 & 28.3662 \\ 4000 & -380 & -944 & 275.6 & 1167.52 & -570.48 & -65.3644 \\ 4000 & 420 & -936 & -304.4 & 1155.68 & 630 & 96.017 \\ 1 & -\frac{1}{2} & 0 & \frac{1}{4} & 0 & -\frac{1}{2} & 0.01 \\ 0 & 1 & -1 & 0 & 1 & 0 & 0 \end{array}\right]$$

Performing the necessary matrix operations, the particular solutions are determined in the Taylor, Lucas, and Euler forms, as follows:

$$x_{Tp}(t)=10.417t^4-0.2083t^3-1.5594t^2+0.0187t+0.0327$$

$$x_{Lp}(t)=184063-160037L_1(t)-123718L_2(t)+88047.9L_3(t)+31679L_4(t)-20838L_5(t)$$

$$x_{Ep}(t)=-0.0024241+0.1810964E_1(t)+0.7060483E_2(t)+17.4140342E_3(t)$$
$$+0.5897235E_4(t)+8.4282770E_5(t)$$

and the general solution in Taylor polynomial form is

$$x_{Tg}(t)=96.267t^5-140.67t^4-2t^3+3t^2+0.01$$

and the general solution in Lucas polynomial form is

$$xL_g(t)=323.256-313.714L_1(t)-216.497L_2(t)+168.799L_3(t)+54.8743L_4(t)-38.5364L_5(t)$$

and the general solution in Euler polynomial form is

$$x_{Eg}(t)=8.4875382+68.3892671E_1(t)+205.3209880E_2(t)+365.1420451E_3(t)$$
$$+136.9317209E_4(t)+130.9568318E_5(t)$$

The Taylor solution is illustrated in Figure 1 for $N=80$.

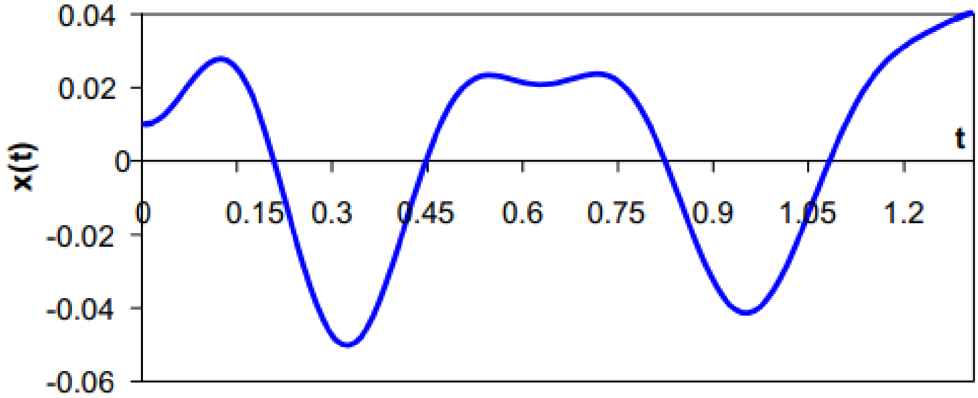

Figure 1. The approximate solution $x_T(t)$ for $N = 80$

Figure 2 illustrates the Euler solution for $N = 30, 50, 100$ and compares it with the exact solution. Table 1 shows the convergence of the Lucas method results to the exact solution.

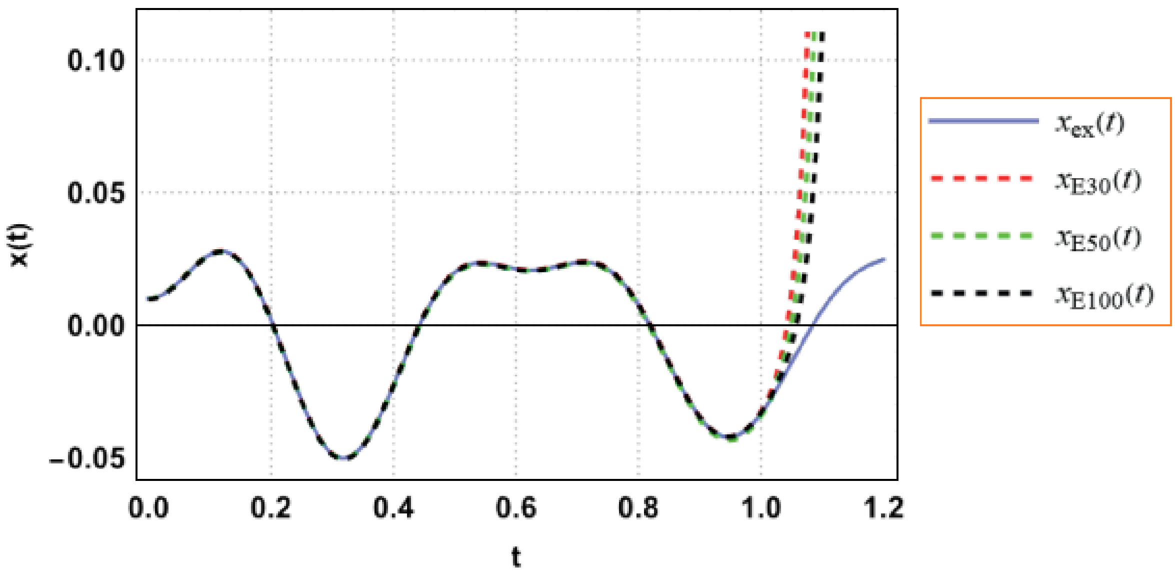

Figure 2. The approximate solutions $x_E(t)$ for $N = 30, 50, 100$ compared with exact solution.

Table 1. Convergence of the Lucas method results to those of exact solution

t	Exact $x(t)$	Present Method (N=5) $x_5(t)$	Present Method (N=30) $x_{30}(t)$	Present Method (N=40) $x_{40}(t)$
0	0,010000000000102	0,010000000033538	0,0099999863996768	0,010000037786085159
0,1	0,026066378588454577	0,02118558662097035	0,02606628462983588	0,02660616339402371
0,2	0,02080749042409633	0,014399161349069003	0,02007760236634558	0,02080733158671263
0,3	-0,04815575105425815	-0,0140164111458152	-0,048157885172134	-0,04815363803797576
0,4	-0,022765129712940937	-0,02837548614445584	-0,022765300714933545	-0,02276530628618173
0,5	0,019920548607770103	-0,00050820151811814807	0,0199181146827926	0,01992104885832965
0,6	0,02129574543613383	0,04627878810885573	0,021294268846607825	0,02129388260227041
0,7	0,023558587433570195	-0,013514385405768658	0,023586714873090386	0,023585425421433096
0,8	0,007668914388655218	-0,4494595130334105	0,007668879581615329	0,007668491685730014
0,9	-0,0346286386751298	-1,723424008541791	-0,03467919216701355	-0,034628015888392925
1	-0,033476404604690305	-4,535364612144179	-0,03263649434444275	-0,03311382979154587

5. Conclusions

Euler and Lucas polynomials exhibit convergence tendencies towards Taylor polynomial-based solutions. When using Euler polynomials, the solutions obtained converge quite well to the Taylor polynomial-based solution up to a certain degree of accuracy, and the accuracy increases as the degree of the polynomial increases. Similarly, Lucas polynomials also show convergence towards Taylor polynomial-based solutions, but there can be significant deviations at lower degrees, such as $N = 5$.

- Euler and Lucas polynomials have different accuracy and convergence characteristics compared to Taylor polynomial-based solutions.
- Both methods yield more accurate results as the polynomial degree increases.
- Graphs and tables are used to illustrate the effectiveness and accuracy of these methods.

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4

On Triangular Pentagonal and Square Pentagonal Numbers

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Abstract

This study investigates the identification of numbers possessing both triangular and pentagonal properties, as well as those exhibiting both square and pentagonal characteristics. Additionally, we have developed a novel method employing Pell equations and matrix algebra to efficiently determine these numbers.

Keywords: Polygonal numbers, triangular numbers, square numbers, pentagonal numbers

1. Introduction

Polygonal numbers are numbers that represent the count of objects arranged in a geometric pattern. These objects are typically points arranged in a pattern according to a specific rule on a plane. For example, triangular numbers represent the points arranged along the sides of a triangle, while pentagonal numbers represent points arranged in a pentagon shape, see Deza & Deza (2012).

A triangular number can be expressed in the form $\frac{n(n+1)}{2}$ for $n \in \mathbb{N}$, which is the sum of the first n terms, and is represented by $S_3(n)$. So,

$$S_3(n) = 1 + 2 + 3 + \cdots + n = \frac{n(n+1)}{2}$$

for $n \geq 1$, (see Deza & Deza, 2012; Gebeş, 2024).

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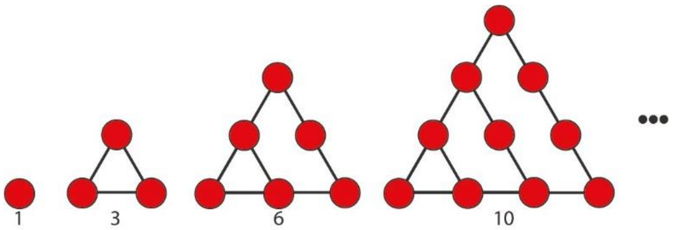

Figure 1. The first four triangular numbers

Also, a square number can be expressed in the form n^2 for $n \in \mathbb{N}$. It is the sum of the first n terms $1, 3, 5, \dots, 2n-1$ and is represented by $S_4(n)$. That is,

$$S_4(n) = 1 + 3 + 5 + \cdots + 2n - 1 = n^2$$

for $n \geq 1$, (see Deza & Deza, 2012; Gebeş, 2024).

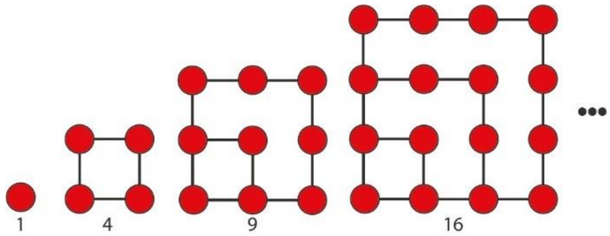

Figure 2. The first four square numbers

Furthermore, a pentagonal number can be expressed in the form $\frac{n(3n-1)}{2}$ for $n \in \mathbb{N}$. It is the sum of the first n terms $1, 4, 7, \dots, 3n-2$ and is represented by $S_5(n)$. Thus,

$$S_5(n) = 1 + 4 + 7 + \cdots + 3n - 2 = \frac{n(3n-1)}{2}$$

for $n \geq 1$, (see Deza & Deza, 2012; Gebeş, 2024).

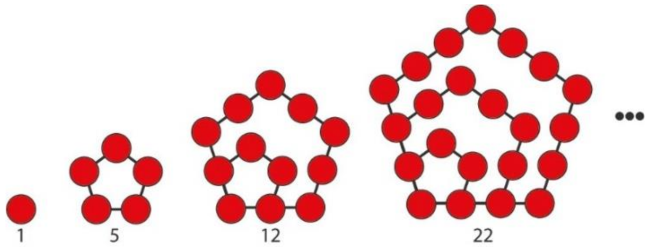

Figure 3. The first four pentagonal numbers

Multi polygonal numbers are numbers that can be terms of more than one polygonal number at the same time. For example, the number 210 is a triangular number because it can be written as $\frac{20 \cdot 21}{2}$. It is also a pentagonal number because it can be written as $\frac{12 \cdot (3 \cdot 12 - 1)}{2}$. Therefore, the number 210 is a multi polygonal (i.e., triangular pentagonal) number because it is both a triangular and a pentagonal number at the same time. Similarly, the number 9801 is a square number because it can be written as 99^2. It is also a pentagonal number because it can be written as $\frac{81 \cdot (3 \cdot 81 - 1)}{2} = \frac{81 \cdot 242}{2}$. Thus, the number 9801 is a multi polygonal (i.e., square pentagonal) number because it is both a square and a pentagonal number at the same time. For more information about this subject, one can consult (Deza & Deza, 2012; Gebeş, 2024; Emin, 2023; OEIS, 2024).

2. Preliminaries

Pell equations are equations of the form $x^2 - dy^2 = k$, where d is not a perfect square. If $k = 1$, then this Pell equation is called the classical Pell equation, and this equation always has an integer solution. But when $k \neq 1$, this Pell equation may not always have an integer solution. The smallest positive integer solution of the Pell equation $x^2 - dy^2 = k$ is called its fundamental solution and is denoted by (x_1, y_1) or $x_1 + y_1\sqrt{d}$. The other positive integer solutions of the Pell equation $x^2 - dy^2 = 1$ are produced with the help of this fundamental solution and denoted by (x_n, y_n) or $x_n + y_n\sqrt{d}$. Indeed, if (x_1, y_1) is the fundamental solution of the Pell equation $x^2 - dy^2 = 1$, then the n^{th} solution of this equation is given by

$$x_n + y_n\sqrt{d} = \left(x_1 + y_1\sqrt{d}\right)^n \tag{1}$$

for $n \geq 1$, (see Rosen, 1984; Borwein et al., 2014; Keskin & Duman, 2019).

Theorem 1. Let s be the period length of continued fraction expansion of $\sqrt{d}$. When s is even, the positive solutions of the Pell equation $x^2 - dy^2 = 1$ are $(x, y) = (p_{ts-1}, q_{ts-1})$, $t = 1, 2, 3, \ldots$. When s is odd, the positive solutions of the Pell equation $x^2 - dy^2 = 1$ are $(x, y) = (p_{2ts-1}, q_{2ts-1})$, where $t = 1, 2, 3, \ldots$ p and q are integers. Additionally, $\frac{p}{q}$ is a convergent continued fraction of $\sqrt{d}$ (Emin, 2023; Rosen, 1984; Borwein et al., 2014; Keskin & Duman, 2019).

Note that the numerators and denominators of the k^{th} convergent of a continued fraction expansion of $\sqrt{d}$ is

$$\frac{p_k}{q_k} = [a_0; a_1, a_2, \ldots, a_k] = a_0 + \cfrac{1}{a_1 + \cfrac{1}{a_2 + \cfrac{\cdots}{\cdots + a_k}}}. \tag{2}$$

Lemma 1. The continued fraction expansion of $\sqrt{3}$ is $[1;\ \overline{1,2}]$ and the period length of the continued fraction expansion of $\sqrt{3}$ is $s = 2$.

Proof.

$$\sqrt{3} = 1 + \left(\sqrt{3} - 1\right) = 1 + \cfrac{1}{\cfrac{1}{\sqrt{3} - 1}} = 1 + \cfrac{1}{\cfrac{\sqrt{3} + 1}{2}}$$

$$= 1 + \cfrac{1}{1 + \cfrac{\sqrt{3} - 1}{2}}$$

$$= 1 + \cfrac{1}{1 + \cfrac{1}{\cfrac{2}{\sqrt{3} - 1}}}$$

$$= 1 + \cfrac{1}{1 + \cfrac{1}{\sqrt{3} + 1}}$$

$$= 1 + \cfrac{1}{1 + \cfrac{1}{2 + \left(\sqrt{3} - 1\right)}}.$$

Thus, $\sqrt{3} = [1;\ \overline{1,2}]$ and so, the period length of continued fraction expansion of $\sqrt{3}$ is $s = 2$.

Lemma 2. The continued fraction expansion of $\sqrt{6}$ is $[2;\ \overline{2,4}]$ and the period length of the continued fraction expansion of $\sqrt{6}$ is $s = 2$.

Proof.

$$\sqrt{6} = 2 + \left(\sqrt{6} - 2\right) = 2 + \cfrac{1}{\cfrac{1}{\sqrt{6} - 2}} = 2 + \cfrac{1}{\cfrac{\sqrt{6} + 2}{2}}$$

$$= 2 + \cfrac{1}{2 + \cfrac{\sqrt{6} - 2}{2}}$$

$$= 2 + \cfrac{1}{2 + \cfrac{1}{\cfrac{2}{\sqrt{6} - 2}}}$$

$$= 2 + \cfrac{1}{2 + \cfrac{1}{\sqrt{6} + 2}}$$

$$= 2 + \cfrac{1}{2 + \cfrac{1}{4 + \left(\sqrt{6} - 2\right)}}.$$

Thus, $\sqrt{6} = [2;\ \overline{2,4}]$ and so, the period length of continued fraction expansion of $\sqrt{6}$ is $s = 2$.

Lemma 3. The fundamental solution of the Pell equation $x^2 - 3y^2 = 1$ is $(x_1, y_1) = (2, 1)$.

Proof. From Theorem 1, Lemma 1 and Eq. (2), one can see that $s = 2$ is even, and the fundamental solution of the Pell equation $x^2 - 3y^2 = 1$ is $(x_1, y_1) = (p_{1.s-1}, q_{1.s-1}) = (p_{2.1-1}, q_{2.1-1}) = (p_1, q_1)$, where $\frac{p_1}{q_1} = a_0 + \frac{1}{a_1} = 1 + \frac{1}{1} = 2.$ Hence, $(x_1, y_1) = (p_1, q_1) = (2, 1)$. Indeed, the smallest positive integers is 1, and if we take $y = 1$, then we get $x^2 - 3 \cdot 1^2 = 1$, so we have $x = 2$.

Lemma 4. The fundamental solution of the Pell equation $x^2 - 3y^2 = -2$ is $(X_1, Y_1) = (1, 1)$.

Proof. The smallest positive integers is 1, and if we take $Y_1 = 1$, then we get $X_1^2 - 3 \cdot 1^2 = -2$, so we have $X_1 = 1$.

Lemma 5. The fundamental solution of the Pell equation $x^2 - 6y^2 = 1$ is $(x_1, y_1) = (5, 2)$.

Proof. From Theorem 1, Lemma 2, and Eq. (2), one can see that $s = 2$ is even, and the fundamental solution of the Pell equation $x^2 - 6y^2 = 1$ is $(x_1, y_1) = (p_{1.s-1}, q_{1.s-1}) = (p_{2.1-1}, q_{2.1-1}) = (p_1, q_1)$, where $\frac{p_1}{q_1} = a_0 + \frac{1}{a_1} = 2 + \frac{1}{2} = \frac{5}{2}$. Hence, $(x_1, y_1) = (p_1, q_1) = (5, 2)$.

3. Triangular Pentagonal Numbers

Triangular pentagonal numbers are numbers that are simultaneously triangular and pentagonal. In this section, we investigate which numbers are both triangular and pentagonal. We also developed a method to find these numbers with the help of Pell equations and matrix algebra, (see Gebeş, 2024).

First, let us equate the triangular numbers $S_3(v)$ with the pentagonal numbers $S_5(u)$. So, we have

$$S_3(v) = S_5(u) \Rightarrow \frac{1}{2}v(v+1) = \frac{1}{2}u(3u-1). \tag{3}$$

If both sides of the equation (3) are multiplied by 24, then the equation

$$(6u-1)^2 - 3(2v+1)^2 = -2 \tag{4}$$

is obtained. If we take $x = 6u - 1$ and $y = 2v + 1$, then we have the Pell equation

$$x^2 - 3y^2 = -2. \tag{5}$$

Now we can present the following theorem, which provides a method to find all positive integer solutions of the Pell equation $x^2 - 3y^2 = -2$.

Theorem 2. Let (x_1, y_1) and (X_1, Y_1) be the fundamental solutions of the Pell equations $x^2 - 3y^2 = 1$ and $x^2 - 3y^2 = -2$, respectively. Then all positive integer solutions of the Pell equation $x^2 - 3y^2 = -2$ are given by

$$\begin{pmatrix} X_n \\ Y_n \end{pmatrix} = \begin{pmatrix} x_1 & dy_1 \\ y_1 & x_1 \end{pmatrix}^{n-1} \begin{pmatrix} X_1 \\ Y_1 \end{pmatrix} \tag{6}$$

for $n \geq 1$ where (X_n, Y_n) is the n^{th} solution of $x^2 - 3y^2 = -2$ (Gebeş, 2024).

Proof. We will use mathematical induction on n to prove this theorem. We know from Lemma 3 and Lemma 4 that the fundamental solutions of the Pell equations $x^2 - 3y^2 = 1$ and $x^2 - 3y^2 = -2$ are $(x_1, y_1) = (2, 1)$ and $(X_1, Y_1) = (1, 1)$, respectively.

For $n = 1$, we get

$$\begin{pmatrix} X_1 \\ Y_1 \end{pmatrix} = \begin{pmatrix} x_1 & dy_1 \\ y_1 & x_1 \end{pmatrix}^{0} \begin{pmatrix} X_1 \\ Y_1 \end{pmatrix} = \begin{pmatrix} X_1 \\ Y_1 \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

which is the fundamental solution of $x^2 - 3y^2 = -2$, that is, $(X_1, Y_1) = (1, 1)$.

Now we suppose that (X_{n-1}, Y_{n-1}) is the $(n-1)^{th}$ solution of $x^2 - 3y^2 = -2$. That is, $X_{n-1}^2 - 3Y_{n-1}^2 = -2$. From equation (6) we have

$$\begin{pmatrix} X_n \\ Y_n \end{pmatrix} = \begin{pmatrix} 2 & 3 \\ 1 & 2 \end{pmatrix}^{n-1} \begin{pmatrix} 1 \\ 1 \end{pmatrix} = \begin{pmatrix} 2 & 3 \\ 1 & 2 \end{pmatrix} \begin{pmatrix} 2 & 3 \\ 1 & 2 \end{pmatrix}^{n-2} \begin{pmatrix} 1 \\ 1 \end{pmatrix} = \begin{pmatrix} 2 & 3 \\ 1 & 2 \end{pmatrix} \begin{pmatrix} X_{n-1} \\ Y_{n-1} \end{pmatrix} = \begin{pmatrix} 2X_{n-1} + 3Y_{n-1} \\ X_{n-1} + 2Y_{n-1} \end{pmatrix}$$

So, we get $X_n = 2X_{n-1} + 3Y_{n-1}$ and $Y_n = X_{n-1} + 2Y_{n-1}$. Substituting these values into the Pell equation $x^2 - 3y^2 = -2$, then, we get

$$\begin{aligned} X_n^2 - 3{Y_n}^2 &= (2X_{n-1} + 3Y_{n-1})^2 - 3(X_{n-1} + 2Y_{n-1})^2 \\ &= (4X_{n-1}^2 + 12X_{n-1}Y_{n-1} + 9Y_{n-1}^2) - 3(X_{n-1}^2 + 4X_{n-1}Y_{n-1} + 4Y_{n-1}^2) \\ &= X_{n-1}^2 - 3Y_{n-1}^2 \end{aligned}$$

$= -2.$

Thus, (X_n, Y_n) is the n^{th} solution of $x^2 - 3y^2 = -2$.

The Corollary, which follows from Theorem 2 and will help us find the solutions of the Pell equation $x^2 - 3y^2 = -2$ in a more practical way, is given below:

Corollary 1. Let (X_{n-1}, Y_{n-1}) and (X_n, Y_n) be consecutive solutions of the Pell equation $x^2 - 3y^2 = -2$. Then the recurrence relations

$X_n = 2X_{n-1} + 3Y_{n-1}$ and $Y_n = X_{n-1} + 2Y_{n-1}$

hold for all $n \geq 2$ (Gebeş, 2024).

From Lemma 4 and Corollary 1, we can find some solutions of the Pell equation $x^2 - 3y^2 = -2$. So,

$(X_1, Y_1) = (1, 1)$,

$$\left.\begin{aligned} X_2 = 2X_1 + 3Y_1 \Rightarrow X_2 = 5 \\ Y_2 = X_1 + 2Y_1 \Rightarrow Y_2 = 3 \end{aligned}\right\} \Rightarrow (X_2, Y_2) = (5, 3),$$

$$\left.\begin{aligned} X_3 = 2X_2 + 3Y_2 \Rightarrow X_3 = 19 \\ Y_3 = X_2 + 2Y_2 \Rightarrow Y_3 = 11 \end{aligned}\right\} \Rightarrow (X_3, Y_3) = (19, 11),$$

$$\left.\begin{aligned} X_4 = 2X_3 + 3Y_3 \Rightarrow X_4 = 71 \\ Y_4 = X_3 + 2Y_3 \Rightarrow Y_4 = 41 \end{aligned}\right\} \Rightarrow (X_4, Y_4) = (71, 41),$$

$$\left.\begin{aligned} X_5 = 2X_4 + 3Y_4 \Rightarrow X_5 = 265 \\ Y_5 = X_4 + 2Y_4 \Rightarrow Y_5 = 153 \end{aligned}\right\} \Rightarrow (X_5, Y_5) = (265, 153),$$

$$\left.\begin{aligned} X_6 = 2X_5 + 3Y_5 \Rightarrow X_6 = 989 \\ Y_6 = X_5 + 2Y_5 \Rightarrow Y_6 = 571 \end{aligned}\right\} \Rightarrow (X_6, Y_6) = (989, 571).$$

In equation (4), $x = 6u - 1$ and $y = 2v + 1$ are taken as equalities. With the help of these equalities, it can be determined which terms of the triangular number sequences $S_3(v)$ and the pentagonal number sequence $S_5(u)$ are equal to each other.

Using relations $x = 6u - 1$ and $y = 2v + 1$, we have $u_n = \frac{x_n+1}{6}$ and $v_n = \frac{y_n-1}{2}$. From these two equations, the sequence $(1, 1), \left(\frac{10}{3}, 5\right), (12,20), \left(\frac{133}{3}, 76\right), (165, 285), \ldots$ is obtained, and it is seen that not all terms of this sequence are integers. Then, to find the terms of the sequence (u_n, v_n) that are all positive integer solutions of the equation $S_5(u) = S_3(v)$ in (3), the solutions with even indices are considered.

The Corollary given below will indicate for which (u_n, v_n) terms the equation $S_5(u) = S_3(v)$ is satisfied.

Corollary 2. Let u and v be positive integers, and let (X_n, Y_n) be a solution of the Pell equation $x^2 - 3y^2 = -2$. Then $S_5(u) = S_3(v)$ if and only if u_n and v_n are given by

$(u_n, v_n) = \left(\frac{X_{2n}+1}{6}, \frac{Y_{2n}-1}{2}\right)$

for all $n \geq 1$ (Gebeş, 2024).

From Corollary 2, some terms of the sequence (u_n, v_n) are $(1,1)$, $(12,20)$, $(165,285)$, $(2296,3976)$, $(31977,\ 55385)$, ..., respectively, (see OEIS, 2024).

4. Square Pentagonal Numbers

Square pentagonal numbers are numbers that are simultaneously square and pentagonal. In this section, we investigate which numbers are both square and pentagonal. We also developed a method to find these numbers with the help of Pell equations and matrix algebra.

First, let us equate the square numbers $S_4(v)$ with the pentagonal numbers $S_5(u)$. So, we have

$$S_4(v) = S_5(u) \Rightarrow v^2 = \frac{1}{2}u(3u-1). \tag{7}$$

If both sides of the equation (7) are multiplied by 24, then the equation

$$(6u-1)^2 - 6(2v)^2 = 1 \tag{8}$$

is obtained. If we take $x = 6u - 1$ and $y = 2v$, then we have the Pell equation

$$x^2 - 6y^2 = 1. \tag{9}$$

Now we can find all positive integer solutions of the Pell equation $x^2 - 6y^2 = 1$. From Eq. (1) and Lemma 5, we can obtain some solutions of $x^2 - 6y^2 = 1$. $(x_1, y_1) = (5, 2)$, and so

$$x_2 + y_2\sqrt{6} = \left(5 + 2\sqrt{6}\right)^2 = 49 + 20\sqrt{6} \Rightarrow (x_2, y_2) = (49, 20),$$

$$x_3 + y_3\sqrt{6} = \left(5 + 2\sqrt{6}\right)^3 = 485 + 198\sqrt{6} \Rightarrow (x_3, y_3) = (485, 198),$$

$$x_4 + y_4\sqrt{6} = \left(5 + 2\sqrt{6}\right)^4 = 4801 + 1960\sqrt{6} \Rightarrow (x_4, y_4) = (4801, 1960),$$

$$x_5 + y_5\sqrt{6} = \left(5 + 2\sqrt{6}\right)^5 = 47525 + 19402\sqrt{6} \Rightarrow (x_5, y_5) = (47525, 19402),$$

$$x_6 + y_6\sqrt{6} = \left(5 + 2\sqrt{6}\right)^6 = 470449 + 192060\sqrt{6} \Rightarrow (x_6, y_6) = (470449, 192060),$$

$$x_7 + y_7\sqrt{6} = \left(5 + 2\sqrt{6}\right)^7 = 4656965 + 1901198\sqrt{6} \Rightarrow (x_7, y_7) = (4656965, 1901198).$$

In Eq. (8), $x = 6u - 1$ and $y = 2v$ are taken as equalities. Using these equalities, we can determine which terms of the square number sequences $S_4(v)$ and the pentagonal number sequence $S_5(u)$ are equal to each other.

Using relations $x = 6u - 1$ and $y = 2v$, we have $u_n = \frac{x_n+1}{6}$ and $v_n = \frac{y_n}{2}$. From these two equations, the sequence $(1,1), \left(\frac{25}{3}, 10\right), (81,99), \left(\frac{2401}{3}, 980\right), (7921, 9701), \ldots$ is obtained, and it is seen that not all terms of this sequence are integers. Then, to find the terms of the sequence (u_n, v_n) that are all positive integer solutions of the equation $S_5(u) = S_4(v)$ in Eq. (7), the solutions with odd indices are considered.

The Corollary given below will indicate for which (u_n, v_n) terms the equation $S_5(u) = S_4(v)$ is satisfied.

Corollary 3. Let u and v positive integers, and let (x_n, y_n) be a solution of the Pell equation $x^2 - 6y^2 = 1$. Then $S_5(u) = S_4(v)$ if and only if u_n and v_n are given by

$$(u_n, v_n) = \left(\frac{x_{2n-1} + 1}{6}, \frac{y_{2n-1}}{2}\right)$$

for all $n \geq 1$.

From Corollary 3, some terms of the sequence (u_n, v_n) are $(1, 1)$, $(81, 99)$, $(7921, 9701)$, $(776161, 950599)$, $(76055841, \ \ 93149001)$, ..., respectively, (see OEIS, 2024).

We can find another way to determine all solutions of the Pell equation $x^2 - 6y^2 = 1$ by using matrix algebra. The theorem that explains how to find all solutions of the Pell equation $x^2 - 6y^2 = 1$ using matrix algebra is as follows:

Theorem 3. Let (x_1, y_1) be the fundamental solutions of the Pell equations $x^2 - 6y^2 = 1$. Then all positive integer solutions of the Pell equation $x^2 - 6y^2 = 1$ are given by

$$\begin{pmatrix} x_n \\ y_n \end{pmatrix} = \begin{pmatrix} x_1 & 6y_1 \\ y_1 & x_1 \end{pmatrix}^{n-1} \begin{pmatrix} x_1 \\ y_1 \end{pmatrix} \tag{10}$$

for $n \geq 1$ where (x_n, y_n) is the n^{th} solution of $x^2 - 6y^2 = 1$.

Proof. We will use mathematical induction on n to prove this theorem. We know from Lemma 5 that the fundamental solutions of the Pell equation $x^2 - 6y^2 = 1$ is $(x_1, y_1) = (5, 2)$.

For $n = 1$, we get

$$\begin{pmatrix} x_1 \\ y_1 \end{pmatrix} = \begin{pmatrix} x_1 & 6y_1 \\ y_1 & x_1 \end{pmatrix}^{0} \begin{pmatrix} x_1 \\ y_1 \end{pmatrix} = \begin{pmatrix} x_1 \\ y_1 \end{pmatrix} = \begin{pmatrix} 5 \\ 2 \end{pmatrix}$$

which is the fundamental solution of $x^2 - 6y^2 = 1$, that is, $(x_1, y_1) = (5, 2)$.

Now we suppose that (x_{n-1}, y_{n-1}) is the $(n-1)^{th}$ solution of $x^2 - 6y^2 = 1$. That is, $x_{n-1}^2 - 6y_{n-1}^2 = 1$. From Eq. (10) we have

$$\begin{pmatrix} x_n \\ y_n \end{pmatrix} = \begin{pmatrix} 5 & 12 \\ 2 & 5 \end{pmatrix}^{n-1} \begin{pmatrix} 5 \\ 2 \end{pmatrix} = \begin{pmatrix} 5 & 12 \\ 2 & 5 \end{pmatrix} \begin{pmatrix} 5 & 12 \\ 2 & 5 \end{pmatrix}^{n-2} \begin{pmatrix} 5 \\ 2 \end{pmatrix} = \begin{pmatrix} 5 & 12 \\ 2 & 5 \end{pmatrix} \begin{pmatrix} x_{n-1} \\ y_{n-1} \end{pmatrix} = \begin{pmatrix} 5x_{n-1} + 12y_{n-1} \\ 2x_{n-1} + 5y_{n-1} \end{pmatrix}.$$

So, we get $x_n = 5x_{n-1} + 12y_{n-1}$ and $y_n = 2x_{n-1} + 5y_{n-1}$. Substituting these values into the Pell equation $x^2 - 6y^2 = 1$, then, we get

$$\begin{aligned} {x_n}^2 - 6{y_n}^2 &= (5x_{n-1} + 12y_{n-1})^2 - 6(2x_{n-1} + 5y_{n-1})^2 \\ &= (25x_{n-1}^2 + 120x_{n-1}y_{n-1} + 144y_{n-1}^2) - 6(4x_{n-1}^2 + 20x_{n-1}y_{n-1} + 25y_{n-1}^2) \\ &= x_{n-1}^2 - 6y_{n-1}^2 \\ &= 1. \end{aligned}$$

Thus, (x_n, y_n) is the n^{th} solution of $x^2 - 6y^2 = 1$.

The Corollary, which follows from Theorem 3 and will help us find the solutions of the Pell equation $x^2 - 6y^2 = 1$ in a more practical way, is given below:

Corollary 4. Let (x_{n-1}, y_{n-1}) and (x_n, y_n) be consecutive solutions, and let (x_1, y_1) be the fundamental solution of the Pell equation $x^2 - 6y^2 = 1$. Then the recurrence relations are given by

$x_n = 5x_{n-1} + 12y_{n-1}$ and $y_n = 2x_{n-1} + 5y_{n-1}$

for all $n \geq 2$.

From Lemma 5 and Corollary 4, we can find some solutions of the Pell equation $x^2 - 6y^2 = 1$. So,

$(x_1, y_1) = (5, 2)$,

$$\left.\begin{aligned} x_2 = 5x_1 + 12y_1 \Rightarrow x_2 = 5 \cdot 5 + 12 \cdot 2 = 49 \\ y_2 = 2x_1 + 5y_1 \Rightarrow y_2 = 2 \cdot 5 + 5 \cdot 2 = 20 \end{aligned}\right\} \Rightarrow (x_2, y_2) = (49, 20),$$

$$\left.\begin{array}{r}x_3 = 5x_2 + 12y_2 \Rightarrow x_3 = 5\cdot 49 + 12\cdot 20 = 485\\ y_3 = 2x_2 + 5y_2 \Rightarrow y_3 = 2\cdot 49 + 5\cdot 20 = 198\end{array}\right\} \Rightarrow (x_3, y_3) = (485, 198),$$

$$\left.\begin{array}{r}x_4 = 5x_3 + 12y_3 \Rightarrow x_4 = 5\cdot 485 + 12\cdot 198 = 4801\\ y_4 = 2x_3 + 5y_3 \Rightarrow y_4 = 2\cdot 485 + 5\cdot 198 = 1960\end{array}\right\} \Rightarrow (x_4, y_4) = (4801, 1960),$$

$$\left.\begin{array}{r}x_5 = 5x_4 + 12y_4 \Rightarrow x_5 = 5\cdot 4801 + 12\cdot 1960 = 47525\\ y_5 = 2x_4 + 5y_4 \Rightarrow y_5 = 2\cdot 4801 + 5\cdot 1960 = 19402\end{array}\right\} \Rightarrow (x_5, y_5) = (47525, 19402),$$

$$\left.\begin{array}{r}x_6 = 5x_5 + 12y_5 \Rightarrow x_6 = 5\cdot 47525 + 12\cdot 19402 = 470449\\ y_6 = 2x_5 + 5y_5 \Rightarrow y_6 = 2\cdot 47525 + 5\cdot 19402 = 192060\end{array}\right\} \Rightarrow (x_6, y_6) = (470449,192060),$$

$$\left.\begin{array}{r}x_7 = 5x_6 + 12y_6 \Rightarrow x_7 = 5\cdot 470449 + 12\cdot 192060 = 4656965\\ y_7 = 2x_6 + 5y_6 \Rightarrow y_7 = 2\cdot 470449 + 5\cdot 192060 = 1901198\end{array}\right\} \Rightarrow (x_7, y_7) =$$
$(4656965, 1901198)$,

Theorem 4. Let (x_{n-2}, y_{n-2}), (x_{n-1}, y_{n-1}), and (x_n, y_n) be consecutive solutions, and let (x_1, y_1) be the fundamental solution of the Pell equation $x^2 - 6y^2 = 1$. Then the recurrence relations are given by

$x_n = 10x_{n-1} - x_{n-2}$ and $y_n = 10y_{n-1} - y_{n-2}$

for all $n \geq 3$.

Proof. We will use the Eq. (10) to prove this theorem. We know from Lemma 5 that the fundamental solutions of the Pell equations $x^2 - 6y^2 = 1$ is $(x_1, y_1) = (5, 2)$. From Eq. (10) we have

$$\begin{pmatrix} x_n \\ y_n \end{pmatrix} = \begin{pmatrix} 5 & 12 \\ 2 & 5 \end{pmatrix}^{n-1} \begin{pmatrix} 5 \\ 2 \end{pmatrix}$$

for all $n \geq 1$. If the matrix $\begin{pmatrix} 5 & 12 \\ 2 & 5 \end{pmatrix}$ is taken as *M*, that is, $M = \begin{pmatrix} 5 & 12 \\ 2 & 5 \end{pmatrix}$, then the Eq. (10) becomes

$$\begin{aligned} \begin{pmatrix} x_n \\ y_n \end{pmatrix} &= \begin{pmatrix} 5 & 12 \\ 2 & 5 \end{pmatrix}^{n-1} \begin{pmatrix} 5 \\ 2 \end{pmatrix} \\ &= \begin{pmatrix} 5 & 12 \\ 2 & 5 \end{pmatrix} \begin{pmatrix} 5 & 12 \\ 2 & 5 \end{pmatrix}^{n-2} \begin{pmatrix} 5 \\ 2 \end{pmatrix} \\ &= M \begin{pmatrix} 5 & 12 \\ 2 & 5 \end{pmatrix}^{n-2} \begin{pmatrix} 5 \\ 2 \end{pmatrix} \\ &= M \begin{pmatrix} x_{n-1} \\ y_{n-1} \end{pmatrix}. \end{aligned} \tag{11}$$

If the characteristic equation of *M* is taken into account, we get

$$\begin{aligned} |M - \lambda I_2| = 0 &\Rightarrow \begin{vmatrix} 5-\lambda & 12 \\ 2 & 5-\lambda \end{vmatrix} = 0 \\ &\Rightarrow \lambda^2 - 10\lambda + 1 = 0 \end{aligned}$$

for $\lambda \in \mathbb{R}$. If M is substituted for λ in the above equation, we have $M^2 - 10M + I_2 = 0$, and thus $M^2 = 10M - I_2$. We now utilize Eq. (11) that

$$\begin{aligned} \begin{pmatrix} x_n \\ y_n \end{pmatrix} &= M \begin{pmatrix} x_{n-1} \\ y_{n-1} \end{pmatrix} \\ &= M \cdot M \begin{pmatrix} x_{n-2} \\ y_{n-2} \end{pmatrix} \end{aligned}$$

$$= M^2 \begin{pmatrix} x_{n-2} \\ y_{n-2} \end{pmatrix}$$

$$= (10M - I_2) \begin{pmatrix} x_{n-2} \\ y_{n-2} \end{pmatrix}$$

$$= 10M \begin{pmatrix} x_{n-2} \\ y_{n-2} \end{pmatrix} - \begin{pmatrix} x_{n-2} \\ y_{n-2} \end{pmatrix}$$

$$= 10 \begin{pmatrix} x_{n-1} \\ y_{n-1} \end{pmatrix} - \begin{pmatrix} x_{n-2} \\ y_{n-2} \end{pmatrix}$$

$$= \begin{pmatrix} 10x_{n-1} - x_{n-2} \\ 10y_{n-1} - y_{n-2} \end{pmatrix}.$$

Thus, we obtain that

$x_n = 10x_{n-1} - x_{n-2}$ and $y_n = 10y_{n-1} - y_{n-2}$.

for all $n \geq 3$. Hence, the proof is completed.

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5

What Citizens Urgently Want from City Authorities: Insights from Türkiye

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Abstract

Cities are dynamic entities comprising various urban functions, each with its own importance. Evaluating the success or failure of city authorities in managing these functions involves assessing indicators from different frameworks, such as sustainability, liveability, resilience, and global competitiveness. Despite these competing functions and needs, there often exists a gap between resource allocation and citizen expectations. Through an online survey, this study examines residents' most important urban services across a section of Turkish cities. It focuses on understanding the level of priority residents place on urban services and therefore provide directions for the appropriate investment options to improve urban life. The study reveals that health, urban transport, safety, housing conditions and sanitation and waste management are the top 5 most important urban services required by residents. The findings offer insights for city managers globally regarding where to invest resources to meet residents' growing expectations. Additionally, this study contributes to urban planning discourse by enriching discussions on urban management within the planning discipline.

Keywords: City management, performance indicators, quality of life, sustainability, Türkiye

1. Introduction

Rapid urbanisation, or the influx of people into urban areas has widely been held liable for the unrelenting urban problems bedevilling towns and cities around the world (Ranasinghe et al., 2016). The mounting pressure on the available urban infrastructure tends to give credence to this view even though beyond this, a counter argument suggests that the lack of (adequate) investment in urban areas is at the core of the problems witnessed in our towns and cities especially in an era when urbanisation can hardly be avoided. Given the inevitability of rising urban populations and the constraints on available resources, the critical challenge for city managers is to optimize the allocation of these limited

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resources to maximize benefits for residents. The benefits here so-called refer to a number of both local and global goals. They range from sustainability goals (Webster, 1998) to improvement in quality of life of the people (Afroj et al., 2021). In addition to that, liveability and resilience of cities have emerged lately to become important considerations for city managers in building liveable and resilient cities that are capable of withstanding adverse economic and environmental conditions. Resilience of cities is said to be the ability of cities to respond to or recover from crises in a timely manner such that residents to do not feel the full extent of these crises.

To adequately measure the performance of municipalities or urban communities in achieving these stated urban management functions, various indicators have been put forth. The ISO has been the leading organisation in this regard which has so far presented various performance indicators for cities particularly the ISO 37101 and ISO 37123 which report on standards related to management systems for communities and indicators for resilient cities respectively. Generally, indicators are subjective or objective measures used in determining the extent of a state or condition of any entity. For general acceptability, these indicators need to be transparent, testable and scientifically tenable (Moussiopoulos et al., 2010). Urban functions that need to be subjected to these indicators include, housing, transportation, health, sanitation, utility services, environmental protection, sports and recreation, land use planning, social welfare and security among others (Ranasinghe et al., 2016). It must be noted that some of these functions are performed by both the central and local government authorities at varying degrees of responsibilities whereas others are exclusive to either of the two levels of government as determined by the respective legislations of the countries involved.

For improved city management, several studies have been conducted in this regard. Using some selected neighbourhoods in Dhaka North City Corporation Area as case studies, Afroj et. al. (Afroj et al., 2021) evaluated the level of quality of services rendered to the residents of the study areas. Their work enquired into the satisfaction levels of household heads in the area to provide an insight into the general view of residents in the city. In Sri Lanka, a perception survey was conducted to determine a shortlist of urban management criteria and indicators which were then evaluated using the Full Permutation Polygon Synthetic Indicator (Ranasinghe et al., 2016). The work concluded that municipalities still have a long way to go in order to be able to perform their functions as expected of them by the residents (Ranasinghe et al., 2016). Other works also concentrated on how best municipalities could utilise their resources to enhance the welfare of citizens (Moghaddam et al., 2011). Yet some works focused on the smartness of cities and how that contributes to the effective management of those cities. It was observed that, cities that were considered smarter were found to exhibit effective management practices and their citizens were also much involved in civic life (Hajduk, 2018). Considering the rising competition of cities in the area of green and smart development, Zong et. al. (2019) proposed an evaluation guide for assessing these indices.

In Türkiye, works related to urban services have been undertaken in past. In many of these studies, the main focus had been on evaluating municipal service satisfaction of residents using different municipalities as case studies (see for instance: Bostancı & Erdem, 2019; Göküş & Alptürker, 2011; İnce & Şahin, 2011; Yücel et al., 2012). Quite different from previous works, in addition to determining the priorities of residents with respect to urban services, this work goes on to determine the most impactful urban services using multiple regression analyses. This way, the services with the potential to make significant differences in residents' lives are identified. This is expected to guide urban managers in their decisions regarding improvement of people's overall satisfaction with life in the city. To do this, an online questionnaire survey was spread to urban residents across some major Turkish cities including İstanbul, Ankara and İzmir invited to respond to relevant questions related to the topic. Details of this account can be found in the methods section of this work.

This work proceeds as follows. What follows next is a brief review of the literature which presents the current state of the discussions on urban management. The third section presents the methods adopted for this study which has been explained in detail. The third section provides the results and further discussions as supported by the results from the data. The fourth section has the conclusion where a wrap up of the investigation is presented along with suggestions for future research prospects on this topic. The limitations of the study have also been presented in the conclusion.

2. Literature Review: Urban Management

Urban management is concerned with a set of functions that interact to ensure that the present and future needs of residents are met. These needs can be simplified as residents' wellbeing which are met when these functions lead to the physical, social and economic development of the urban area. These functions are often carried out at different levels of government such as local and/or central governments. Because the future of humanity remains the city, it becomes even more necessary for urban managers to implement resident-centred approaches to the management of urban areas as it is said to enhance urban productivity as well as improve living conditions especially of the urban poor (Bwala et al., 2022). Also, because urban management directly relates to activities affecting the urban area, urban management practices are often linked to a number of urban phenomena which also explains the growing interest in its research by urban planners. Findings from this work are therefore expected to contribute significantly to policies related to urban management as well as to the urban studies literature.

Debates on urban management are varied and diverse. They are often centred around urban governance and policy, urban planning and design and infrastructure and public services (Pierre, 1999). Others include smart cities and technology (Meijer & Bolívar, 2016; Angelidou, 2015; Yiğitcanlar, 2015), sustainability and resilience (Elmqvistet al., 2019; Asprone & Manfredi, 2015), community participation and social equity and urban health and wellbeing (Schrock et al., 2015; Rice & Hancock, 2016; Nakamura, 2014). The diversity of scholarship related to the urban management help shape our understanding of towns and cities and how to develop them in a sustainable way. For instance, Pierre (Pierre, 1999) presents an argument that, governance models at the local level are not value neutral but are a reflection of political views. Here, it is understood that the manner in which an urban area is managed directly reflects the political ideologies of the managing authorities (Pierre, 1999). These ideologies are often demonstrated through regime and governance theories that include managerialism and neoliberalism (Pierre, 1999). In other contexts, these ideologies are also demonstrated through the strategies adopted in urban development (Sharma, 2014). Urban governance that is shaped by neoliberal ideologies where priorities are on efficiency and profit-seeking have been found to be detrimental to issues of social justice and equity (Pierre, 1999). In contexts where urban governance is shaped by ad hoc and piecemeal approach to urban development as demonstrated by Sharma (2014), there is often the risk of having less integrated urban development which is inimical to sustainable development.

This study contributes to the current discourse on urban management within the context of infrastructure and urban services. It seeks to present the urban services that are of utmost importance to urban residents. This is because effective urban management requires that infrastructure and services are sufficient to meet the needs of the urban population (Deichmann et al., 2003). In dealing with the infrastructure and service needs of developing countries' urban spaces, Choguill (1996) has proposed 10 principles. Among these includes the recognition of the two interdependent circuits that exists in developing country cities namely, formal and informal. In this context infrastructure such as water, sanitation, transportation and waste management that are within the informal setting are expected to be upgraded to reach the standards of those enjoyed in the formal residential settings. Poor urban service delivery has also been attributed to low investments in those services (Sridhar & Reddy, 2010). Apart from public investments in urban services, others have also maintained that private participation in urban service delivery is an avenue for improved services in the urban area (Koppenjan & Enserink, 2009).

And owing to the mounting pressures on local and central governments to meet the needs of the urban population, it is clear that a separate study is carried out to examine and determine the topmost priorities of urban residents amidst the several competing urban needs that have to be met. This is where this study comes in. The next section discusses the methods adopted in reaching this goal.

3. Methods

An online survey was conducted to assess the urgent urban services most anticipated by residents across various cities in Türkiye, including İstanbul, Ankara, İzmir, and other medium and small-sized cities. The survey was designed to gather insights into the preferences and expectations of residents regarding urban services provided by local authorities. Participants were recruited through online survey form powered by Google Forms. The online questionnaire was left open between 24 December 2023 and 05 February 2024 with the last response date recorded on 02 February 2024. The form was designed to contain questions pertinent to the study objectives. Because this research involved the participation of humans, an ethical approval was obtained from the Middle East Technical University Ethical Committee with a protocol number, 0078-ODTUİAEK-2024.

The online questionnaire consisted of three sections. The first section contained questions that elicited from respondents, their biographical data such as their cities and districts of residence, the number of years they have stayed in those places, their employment statuses, their income and age ranges and the highest level of education completed. The section part of the questionnaire consisted of questions related to the urban living. In this section, respondents were provided with a series of statements (15 of them) to which they were asked to rate from 1 to 5 on a Likert scale where 1 signifies "*strongly disagree*" and 5 implies "*strongly agree*" with 2, 3 and 4 implying "*disagree*", "*indifference*" and "*agree*" respectively. The statements included "*I'm satisfied with the health services in the city*", "*I'm satisfied with the urban transport services in the city*", "*I'm satisfied with the sanitation services in the city*" among a host of other urban services which were determined from the literature particularly the ISO 37101 and ISO 37123 which provide indicators for measuring sustainable cities and resilient cities respectively.

We acknowledge that these services are provided by both local and central governments with some strictly limited to either of these levels of government in Türkiye. This was necessary to identify and determine the exact urban services expected by residents regardless of the government authority responsible for provision of such services. In this way, we avoided the possibility of seemingly evaluating the performance of either local or central government. Apart from affording the opportunity to respondents to freely answer questions without being influenced by their political affiliations, a mixture of these services without isolating only local or central government-provided services would also mean that the findings would be relevant to other cities beyond Türkiye since some services may be provided by different governmental levels in different countries. It is worthy of note that in Türkiye, mayors of metropolitan and municipal areas are elected on partisan lines with all three major metropolitan areas (İstanbul, Ankara and İzmir) currently being led by the opposition party (to central government) at the time of the survey.

Table 1. Reliability test

Item analyses from SPSS Output				
Scale Statistics	Mean	Variance	SD	N
	46.64	176.196	13.274	15
Items Statistics		Mean	SD	N
I am satisfied with the health services in the city		3.22	1.24	171
I am satisfied with the sanitation and waste management services in the city		3.09	1.26	171
I am satisfied with the urban transport services in the city		3.08	1.306	171
I am satisfied with the open and green spaces in the city		2.95	1.231	171
I am satisfied with my work/education/retirement life in the city		2.90	1.161	171
I am satisfied with the social activities (summer concerts etc) in the city		3.01	1.205	171
I am satisfied with the safety and security services in the city		3.13	1.359	171
I am satisfied with living in the city		3.18	1.21	171

I am satisfied with the drainage infrastructure in the city			3.11	1.19	171
I am satisfied with the electricity services in the city			3.46	1.223	171
I am satisfied with the potable water supply services in the city			3.32	1.272	171
I feel valuable living in the city			2.96	1.224	171
I am satisfied with the services I receive from public offices in the city			2.91	1.182	171
I am satisfied with the education services in the city			3.17	1.117	171
Overall, I am satisfied with the urban services in gen. in the city			3.16	1.126	171

Item-Total Statistics	**Scale Mean if Item Deleted**	**Scale Variance if Item Deleted**	**Corrected Item-Total Correlation**	**Squared Multiple Correlation**	**Cronbach's Alpha if Item Deleted**
I am satisfied with the health services in the city	43.42	155.139	0.632	0.49	0.932
I am satisfied with the sanitation and waste management services in the city	43.56	154.613	0.638	0.579	0.932
I am satisfied with the urban transport services in the city	43.57	154.353	0.62	0.432	0.933
I am satisfied with the open and green spaces in the city	43.69	154.921	0.645	0.556	0.932
I am satisfied with my work/education/retirement life in the city	43.74	155.863	0.655	0.551	0.931
I am satisfied with the social activities (summer concerts etc.) in the city	43.64	157.021	0.587	0.465	0.933
I am satisfied with the safety and security services in the city	43.51	150.487	0.716	0.585	0.930
I am satisfied with living in the city	43.47	153.203	0.719	0.612	0.930
I am satisfied with the drainage infrastructure in the city	43.53	155.627	0.645	0.625	0.932
I am satisfied with the electricity services in the city	43.19	153.671	0.693	0.683	0.930
I am satisfied with the potable water supply services in the city	43.33	153.669	0.663	0.675	0.931
I feel valuable living in the city	43.68	152.653	0.729	0.664	0.929
I am satisfied with the services I receive from public offices in the city	43.73	154.798	0.68	0.596	0.931
I am satisfied with the education services in the city	43.47	154.874	0.722	0.617	0.930
Overall, I am satisfied with the urban services in general in city	43.48	152.051	0.824	0.738	0.927

Reliability Statistics	**Cronbach's Alpha**				**No of Items**
	0.935				15

The third section measured the most urgent urban services from the point of view of respondents. This was achieved by asking respondents to award points between 1 and 10 to the listed urban services where a higher (closer to 10) point indicates the urgency of a service and lower (closer to 1) indicates less urgency. In the same section, respondents were also asked to rank the top 7 urban services from the list of services provided. This enabled us to identify the most urgent urban services that residents of cities demand from authorities. Because this survey was administered on residents of Turkish cities, the language of the survey was the Turkish language, framed in ways that are consistent with the basic understanding of the average urban resident. This was done to ensure that the internal consistency of the questions, particularly those that measured the satisfaction level of residents with urban services is high. In the reliability test we conducted, a Cronbach alpha of 0.935 was obtained (see, Table 1), which indicates that there was high internal consistency in the responses to the statements posed to respondents. The results emanating from this questionnaire and subsequent interpretations can therefore be said to be retain some high level of validity.

To comply with ethical standards, the survey was open to non-disabled individuals aged between 18 and 65 years as research on subject individuals outside of this group would require a special ethical approval. The responses and consequent analyses of results obtained from this survey should therefore be understood with these limitations in mind. Online surveys are often less attractive in quantitative research due to their vulnerability to bias arising from unequal chance of access to the survey by all persons within the target population due to reasons such as lack of internet access and/or smart phones. Also, it is also acknowledged that online surveys could also suffer from a possible sampling bias arising from unequal chances of participation as chances of access mainly depended on the degree of connections to the researchers. This is because, the links surveys are often shared over various platforms and only those on such platforms tend to have the highest chances of seeing and accessing them. It is without doubt that this survey was also vulnerable to these limitations. However, the limitations due to lack of access to the internet and/or smartphones are expected to have a very minimum impact on the results give that Türkiye has a very high literacy rate exceeding 96% of the entire population along with widespread internet penetration of up to 95.5% of households as at the end of 2023 (TÜİK, 2023).

Additionally, through our use of innovative ways to remedy these possible sources of bias, the link to the online survey questionnaire was shared directly to all first-degree contacts of the researchers (without any discrimination despite any hiatus in communication between us up to that point) over the main social media platforms as direct messages and were invited to participate. Frequent reminders were sent in this regard. Also, these contacts were also encouraged to also share the links further to their first-degree contacts and so on. Even though the literature on online surveys seems to suggest that online surveys are more convenient, this did not seem to be the case here as some contacts were noted to have been reluctant in sharing the link further. Others were also very reluctant to click on the links given their fear of possible cyber-attacks. And as a result, for a period of about 6 weeks, we could only retrieve 171 responses. Even though this number meets the minimum sample size[1] for this study given that we worked with a confidence interval of 95% and a margin of error of between 8%, it is still worthy of noting these bottlenecks encountered in this work. Future studies are therefore encouraged to prepare adequately in this regard if they intend to use this approach to data collection for their research.

Despite the difficulties outlined above, the responses obtained portrayed a fair representation of the major cities in Türkiye particularly, İstanbul, Ankara and İzmir along with other important medium and small sized cities of Anatolian Türkiye (Table 2). Also, our use of online survey for this study afforded us an opportunity to obtain responses from a wider geographical spread across the country to reach places we would otherwise not have been able to reach (see, Figure 1). Despite the apparent susceptibility to bias, our samples show a fair level of representativeness when statistics were compared to their corresponding population parameters such as gender and city of residence (Table 2 and Table 3). Table 2 provides a comparison between, the percentages of respondents residing in the various cities represented to the total responses obtained for this variable on the one hand and on the other hand, the percentages of the populations of the cities represented to the total population of all the represented cities. Table 3 also provides the distribution of respondents who took part in the survey where the gender

[1] The sample size calculation was done on the website https://www.calculator.net/sample-size-calculator.html

distribution can be seen to be 48% for female and 52% percent for male which also fairly represents both the national average and for the represented cities of 49% (female) and 51% (male) and 50% and 50% respectively. This made it possible to embark on further statistical analyses that could be generalised to the larger urban areas in the country.

Table 2. Cities of respondents

No	Cities	Frequency	% of Total Responses	% of Population 2023
1	Afyonkarahisar	1	1%	1%
2	Ankara	17	10%	11%
3	Antalya	2	1%	5%
4	Aydın	2	1%	2%
5	Burdur	1	1%	1%
6	Bursa	2	1%	6%
7	Denizli	1	1%	2%
8	Diyarbakır	2	1%	3%
9	Erzurum	2	1%	1%
10	Eskişehir	1	1%	2%
11	Gaziantep	1	1%	4%
12	İstanbul	84	50%	28%
13	İzmir	16	9%	8%
14	Kahramanmaraş	1	1%	3%
15	Kayseri	5	3%	4%
16	Kocaeli	11	7%	1%
17	Malatya	1	1%	3%
18	Manisa	1	1%	2%
19	Rize	1	1%	1%
20	Sakarya	3	2%	2%
21	Samsun	2	1%	3%
22	Şanlıurfa	1	1%	4%
23	Şırnak	8	5%	1%
24	Trabzon	1	1%	1%
25	Uşak	1	1%	1%
26	Zonguldak	1	1%	1%
	Total	169	100%	100%

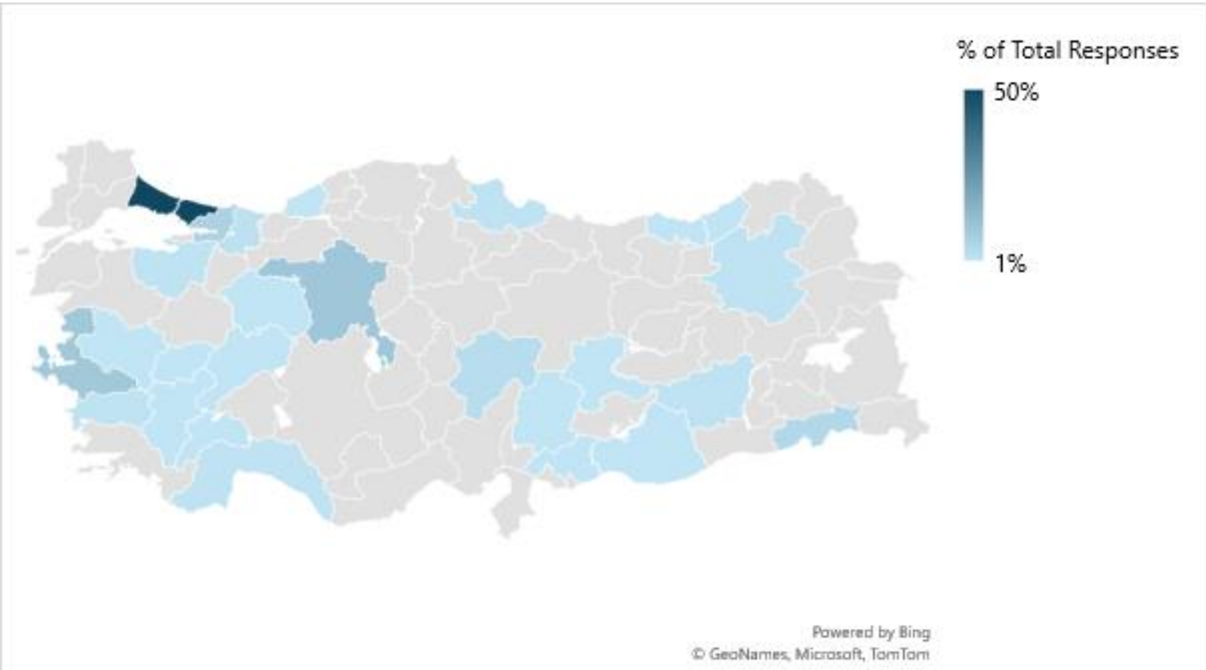

Figure 1. Geographical distribution of respondents

It is therefore worthy of note that the online survey methodology employed in this research, despite its inherent limitations as acknowledged, provided valuable insights into the urgent urban service preferences of residents in various cities across Türkiye, offering a foundation for informed decision-making by local authorities and urban planners.

4. Results

In this section, two main forms of results are provided. The first is descriptive data that mainly comprise of factual observations and responses. They include the cities of respondents, gender, employment status, age group, income group and education level. The other group of responses include those that relate to respondents' views and perceptions of what is being asked. Various forms of inferential statistical analyses are conducted here to draw insights from this and make meaningful interpretation of the results regarding the urban services that of utmost importance to the resident population of cities in Türkiye.

5. Descriptive Statistics

Table 3 provides details of the distribution of respondents in this study. In conducting research, particularly through surveys, a crucial aspect is comprehending the demographic profile of the participants. Such insights not only illuminate the characteristics of the sample population but also offer valuable context for interpreting the collected data. In this section, we delve into a detailed description of the data collected from an online survey aimed at gauging the expectations and preferences of residents regarding urgent urban services across various cities in Türkiye. The gender distribution has already been discussed in the preceding section. This section throws more light on the other components of the samples obtained such as age, education, and income among other biographical distributions of the sample.

First and foremost, we explore the age distribution of the survey participants. Out of a total of 171 respondents, the majority fall within the age brackets of 18 to 35 years, comprising 72% of the sample. This skew towards younger age groups is indicative of the digital nature of the survey, aligning with the widespread adoption of online platforms among the younger populace. However, it is noteworthy that there is representation across all age groups, albeit with diminishing percentages in the higher brackets, emphasizing the inclusivity of the survey across different generations.

Moving on to the income range of the participants, a diverse spectrum emerges, reflecting the economic heterogeneity within the sample. The largest segment falls within the income bracket of 0 to 30,000 Turkish Lira[1], constituting 75% of the respondents. Interestingly, there is a notable drop in participation beyond the 50,000 lira income threshold, suggesting potential disparities in access to digital platforms among higher-income earners or perhaps indicating a smaller proportion of individuals in that income bracket within the broader population. The predominance of income earners within the 0 – 30000 lira can also be attributed to the significant participation of persons who identify as students (31%) and so this group can reasonably be said to earn very little (such as bursaries or pocket money) or no income.

Employment status offers further insights into the occupational landscape of the respondents. Half of the participants identify as employed, followed by a substantial cohort of students comprising 31%. This distribution underscores the significance of including students in surveys concerning urban services, as they represent a demography with vested interests in shaping the future of their cities. Additionally, the presence of retirees, unemployed individuals, and homemakers highlights the diversity of circumstances among respondents, enriching the survey with varied perspectives.

[1] Respondents were requested to indicate their monthly income for December 2023. This is the income earned by people before the increases which took effect from January 2024. As at the close of business week on December 29, 2023, the exchange rate was 1 USD = 29.476 TRY (see, https://www.exchange-rates.org/exchange-rate-history/usd-try-2023).

Table 3. Distribution of respondents

Descriptive Statistics	Frequency	Percentage
Gender	**170**	**100%**
Female	82	48%
Male	88	52%
Age Group	**171**	**100%**
18-25	44	26%
26-35	79	46%
36-45	23	13%
46-55	18	11%
56-65	7	4%
Income Range (in Turkish Lira)	**171**	**100%**
0-12000	56	33%
12001-20000	34	20%
20001-30000	37	22%
30001-40000	17	10%
40001-50000	14	8%
50001-60000	6	4%
Over 60000	7	4%
Employment Status	**171**	**100%**
Employed	85	50%
Employer	18	11%
Housewife	5	3%
Retired	5	3%
Unemployed	5	3%
Student	53	31%
Highest Education Completed	**171**	**100%**
Basic School	5	3%
High School	27	16%
Associate degree	6	4%
Undergraduate	81	47%
Graduate	52	30%
Cities of Residence	**169**	**100%**
İstanbul	84	50%
Ankara and İzmir	33	20%
Other Cities	52	31%
Nationality	**167**	**100%**
Republic of Türkiye	124	74%
Other Nationality	43	26%

The sample also comprised of persons from wide spectrum of professions (see Figure 2) such as engineering and planning (comprising, engineers, architects, surveyors, urban planners and airplane pilot) constituting about a third (29%) of those who stated their professions and excluding students (which is 72% of the entire sample). Other professional groups within the sample include those working in education (including higher education and child development) who also constitute almost a fifth (18%) of those who declared their profession. Business and accounting (including banking and finance, sales, import and export, consultancy services, insurance and freelancing) took the largest proportion of professionals within the sample at 29%. The rest were grouped as “Others”, and this group is also very diverse but could not fit into any of the above. This group comprised professionals such as lawyers, medical doctors, masseuse, psychologists, welders and herdsmen altogether constituting 22% of the sample. The diversity of professionals within the sample thoroughly reflects the composition of urban residents which further strengthens the composition of the sample and the findings drawn therefrom.

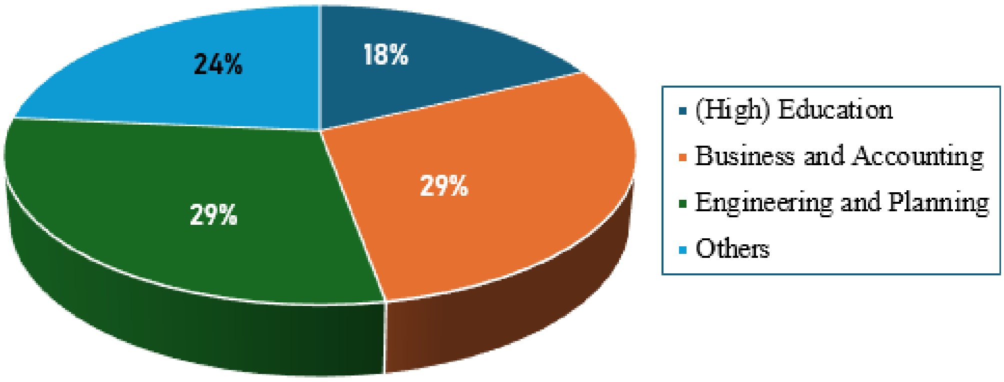

Figure 2. Professional composition of respondents

Education level serves as another crucial dimension in understanding the demographics of the participants. Nearly half of the respondents hold bachelors (undergraduate) degrees, while graduate degree (master's and above) holders constitute 30% of the sample. This prevalence of higher education attainment underscores the significance of conducting online surveys in a context where digital literacy and access to higher education intersect. Moreover, the inclusion of individuals with basic school education or high school diplomas underscores the accessibility of the survey across different educational backgrounds.

Geographically, the survey captures responses from various cities across Türkiye, with İstanbul emerging as the predominant location for respondents, representing half of the sample. Ankara, İzmir, and other cities contribute to the remainder, showcasing a diverse representation that extends beyond the major urban centres (for details see, Figure 1 and Table 2). Such geographic diversity enriches the survey findings by incorporating perspectives from residents across different regions, each with its unique urban challenges and priorities. Further discussions have also been done in previous sections.

Lastly, the nationality distribution provides insights into the cultural diversity within the sample. While the majority (74%) of respondents are citizens of the Republic of Türkiye, a notable proportion identifies with other nationalities, comprising 26% of the sample. This diversity underscores the cosmopolitan nature of Türkiye's urban landscape, where residents from various nationalities coexist and contribute to the socio-economic fabric of the country.

In conclusion, a comprehensive understanding of the demographic profile of survey participants is indispensable for contextualizing and interpreting the collected data effectively. The insights gleaned from age, income, employment status, education level, geographical distribution, and nationality enrich the survey findings, offering nuanced perspectives on the expectations and preferences of residents regarding urgent urban services in Türkiye. Moving forward, such demographic analyses serve as foundational pillars for informed decision-making and policy formulation aimed at enhancing the quality of urban life for all residents.

6. Discussions and Further Analyses

In this section, the main subject of the study discussed. Findings regarding the main urban preferences of respondents have been presented. Further statistical analyses including inferential statistics have been done to draw insights from the findings for policy and scholarly contributions.

Tables 4 and 6 provide some valuable insights into the priorities and expectations of individuals regarding various urban services in Türkiye. The tables represent the responses of residents regarding their rating of services according to the priority they placed on them. Even though the two tables seek to measure the same variable, the approach adopted for each was different. The aim is to reinforce evidence regarding the priorities of urban residents with respect to urban services. The out of Table 4 was drawn from the ratings of respondents of each urban service on a scale of 1 to 10 with 10 representing highest priority and 1 representing lowest priority. The ratings presented are the mean ratings for each of the urban service which were subsequently ranked from highest to lowest. Accordingly, safety and security services emerged the highest rated urban service deserving of attention. Health and urban transport services also found their way into the top 5 most rated urban services using this approach.

Table 4. Ranking of urban services according to rating out 10

Rank	Urban Services	Priority Level
1	Safety and Security	7.28
2	Health Services	7.22
3	Potable Water Supply	7.21
4	Urban Transport Services	7.16
5	I am satisfied with living in the city	7.02
6	Electricity Services	7.01
7	Sanitation and waste management services	6.92
8	Work/Educ/Retirement Life	6.89
9	Open and Green Spaces	6.75
10	Housing Condition	6.73
11	Drainage Systems	6.72
12	Social Support	6.60
13	Social Activities	6.02

Knowing that it is possible for respondents to place similar weight on more than one service, respondents were further asked to rank (Table 5) the top 7 of the services they have rated. This prevented a situation where the same rate or rank is given to more than one service as only one service could be ranked for each rank. For instance, for each respondent, more than one urban service could not be placed at say rank 1 or rank 2 etc. For the avoidance of doubt, rank 1 indicates first priority, rank 2 for second priority in that order. It was clearly stated on the survey questionnaire that the same ranks offered to more than one urban service would not be included in the analyses. And so, responses that had such multiple rankings were removed which led to the use of only about 50% to 52% (there were some omissions even for those who abided by this instruction) of the responses obtained, as these were the ones that abided by this provision. It was not possible to restrict respondents to this instruction as such feature was not available on the online form used. Future studies seeking to go by this are therefore encouraged to consider this in their choice of survey forms.

That said, the responses for this question proved significant for the analysis conducted on this. As can be seen on Table 5, the various urban services considered in this study occupy the rows whereas the different ranks occupy the columns. For each urban service, there are two rows, one on top of the other. The figures on the top are the frequencies. The frequencies indicate the number of respondents who have selected a particular urban service for the associated rank. To ensure that each rank is different from the other, weights (4 to 10) were assigned to each rank with the highest weight assigned to Rank 1 and the lowest assigned to Rank 7. These weights were then multiplied by the respective frequencies to arrive at the figures on the bottom rows which we refer to as weighted frequencies. The sum of each weighted frequency gave the composite points which were then ranked from the highest to the lowest to arrive at the composite ranking of the urban services considered in this study (Table 6 and Figure 3). This provided better insights into the urban priorities of residents as this took into consideration all the ranks associated with each urban service.

Regardless of the differing results, some intersecting urban services were noted for each of the two approaches used in this study. Even though the direct rating approach suggests that the topmost urban service for residents is safety and security, this urban service is placed at number 3 on the list determined by the composite ranking system (Table 6), indicating its overall importance. This underscores the priority of residents in feeling safe in their communities and the need to keep a required standard of law enforcement, crime prevention and public safety. The high ranking of health services reflects the significance placed on access to quality healthcare facilities and services. This highlights the importance placed by residents on the need to maintain a well-functioning and well-equipped hospitals, clinics, and healthcare infrastructure to cater for the healthcare needs of residents. This same urban service also features at the top of the list of the composite ranking table (Table 6). Figure 3 only provides a graphical representation of what Table 6 contains. This was emphasised by a respondent (#128) who benefited from the only open-ended question that sought to elicit the overall views of respondents regarding the topic under study. This respondent is a female living in Kocaeli for the past 44 years and a housewife with an associate degree level education background who emphasised the need for better sanitation and health services when she stated that "*Hopefully, our provinces and municipalities will be much cleaner and more developed, and our health sector will improve*".

Table 5. Frequency table for ranked urban services

Urban Services	**Rank 1**	**Rank 2**	**Rank 3**	**Rank 4**	**Rank 5**	**Rank 6**	**Rank 7**	**Total Value**	**Overall Rank**
Health Service Delivery	29	11	11	4	8	7	5		
	290	99	88	28	48	35	20	608	1st
Sanitation and Waste Management Services	2	13	11	3	9	9	6		
	20	117	88	21	54	45	24	369	5th
Urban Transport Services	10	10	16	11	11	6	7		
	100	90	128	77	66	30	28	519	2nd
Parks, Open and Green Spaces	5	6	4	11	7	8	3		
	50	54	32	77	42	40	12	307	7th
Work/Educ/Retirement Life	4	7	7	10	11	5	9		
	40	63	56	70	66	25	36	356	6th
Social Activities		5	3	3	3	4	8		
	0	45	24	21	18	20	32	160	13th
Housing Condition	9	8	9	8	2	9	7		
	90	72	72	56	12	45	28	375	4th
Safety and Security	14	11	7	15	9	5	8		
	140	99	56	105	54	25	32	511	3rd
Life Satisfaction	4	5	4	1	9	7	6		
	40	45	32	7	54	35	24	237	9th
Drainage Infrastructure	0	1	3	9	3	6	6		
	0	9	24	63	18	30	24	168	12th
Electricity Infrastructure	3	4	4	0	8	8	6		
	30	36	32	0	48	40	24	210	10th
Potable Water Infrastructure	2	3	6	7	8	10	10		
	20	27	48	49	48	50	40	282	8th
Social Support	4	4	4	5	1	4	6		
	40	36	32	35	6	20	24	193	11th

Adequate housing is a basic human need, and the priority assigned to housing conditions indicates a concern for housing affordability, quality, and availability. This highlights the importance of addressing housing shortages, improving housing standards, and ensuring affordable housing options for residents. This being among the top 5 urban priorities of residents (Figure 3) came as no surprise due to the current housing crisis which has been intensified by the unfortunate February 6, 2023 earthquakes in southern Türkiye where millions of housing units got destroyed (TMMOB, 2023) which added to the already existing housing problems in the country. Also, the expected earthquake in Marmara Sea, which is expected to impact heavily on İstanbul and other surrounding cities such as Kocaeli and Bursa has also intensified people's need for much improved housing conditions which is explained to mean the regeneration of the existing stock in these cities and beyond. This is very instructive for urban managers in determining where to invest their resources to earn the approval of their residents. This was highlighted by some respondents in the only open-ended question in the questionnaire which allowed respondents to highlight areas that were of special interest to them. In this regard, Respondent #150 who is a male living in İstanbul for the past 19 years with high school education pointed out the need for safe and secure buildings when he emphasised that, "*The buildings can be made safer and more secured…*".

Another (#154) who is also a male living in İstanbul for 15 years bemoaned the escalating rent when he mentioned that "*the rent is too high. Social support should be provided…*".

Table 6. Composite ranking of urban services using frequencies

Urban Services	**Rank 1**	**Rank 2**	**Rank 3**	**Rank 4**	**Rank 5**	**Rank 6**	**Rank 7**	**Composite Points**	**Overall Rank**
Health service delivery	290	99	88	28	48	35	20	608	1st
Urban transport services	100	90	128	77	66	30	28	519	2nd
Safety and security	140	99	56	105	54	25	32	511	3rd
Housing condition	90	72	72	56	12	45	28	375	4th
Sanitation and waste management services	20	117	88	21	54	45	24	369	5th
Work/educ/retirement life	40	63	56	70	66	25	36	356	6th
Parks, open & green spaces	50	54	32	77	42	40	12	307	7th
Potable water infrastructure	20	27	48	49	48	50	40	282	8th
Life satisfaction	40	45	32	7	54	35	24	237	9th
Electricity infrastructure	30	36	32	0	48	40	24	210	10th
Social support	40	36	32	35	6	20	24	193	11th
Drainage infrastructure	0	9	24	63	18	30	24	168	12th
Social activities	0	45	24	21	18	20	32	160	13th

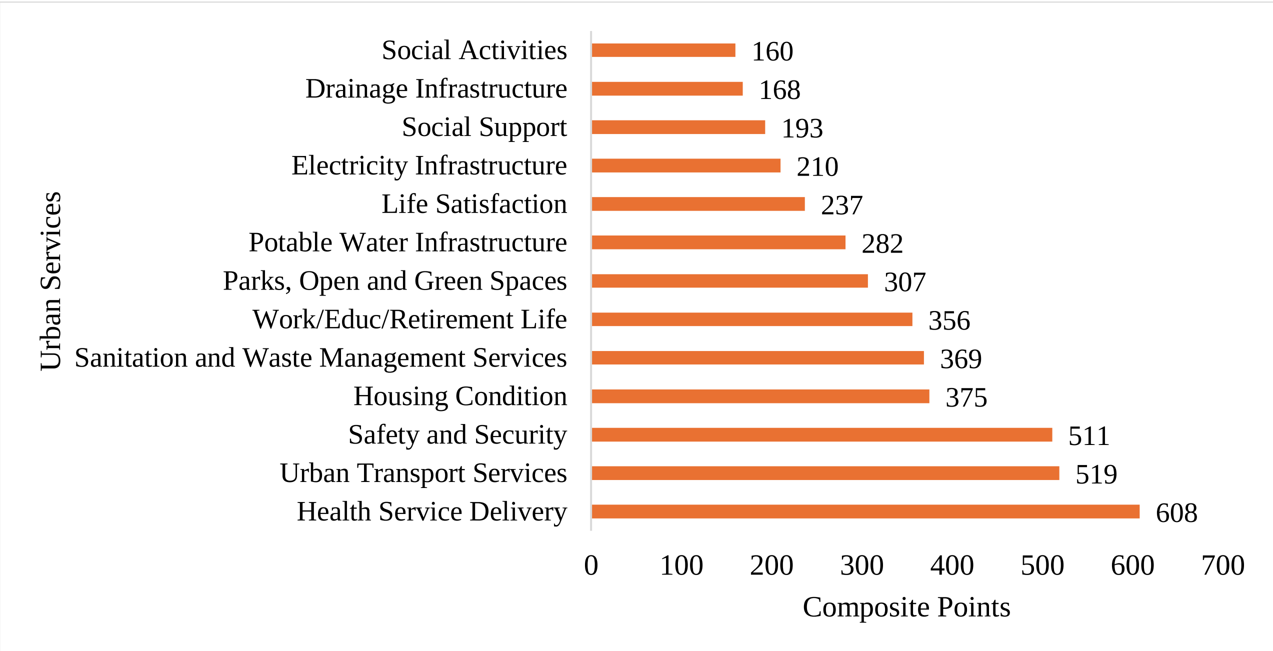

Figure 3. Composite ranking of urban services

Even though it can be said that access to clean and safe drinking water is a fundamental requirement for residents, as indicated by the high priority assigned to potable water supply on the ratings table (see Table 4), the composite scale which can be said to be more robust presents a different outcome which puts safe drinking water right at the middle of the ranking at number 8. This does not in any way underestimate the importance of potable water supply to the population. Even though at the moment Turkish urban centres do not experience major potable water supply problems, the risk of this continues to linger on due to the effect of climate change which is altering the precipitation patterns (Nicholas et al., 2016; Dagbegnon & Vijay, 2016). The need to invest in dams and other water infrastructure has been a major call by the Turkish president His Excellency R. T. Erdogan in recent years (Bayar, 2023; TRT Haber, 2023). The identification of this major urban service as a priority of residents underscores the importance of investing in water treatment facilities and ensuring reliable water supply systems.

Urban transportation has retained its place within the top 5 most urgent urban services for both rankings. Efficient and accessible urban transport systems are crucial for facilitating mobility and connectivity within cities. The high priority given to urban transport services provides a hint about the importance residents place on urban transportation. This was further emphasised by respondents when a number of them indicated their frustrations with transport services. For instance, Respondent 8 who is a male resident of İstanbul for 44 years indicated that "*Projects that can solve urban traffic congestion should be developed ...*". Another respondent (#110) who is a male resident of Kocaeli for 40 years with a postgraduate qualification also pointed out that, "*Urban transportation facilities have increased. However, there is not enough information about the transportation route at the stops…*". In emphasising the need for improvement of transport services, another respondent (#164) also from İstanbul who is still an undergraduate student stated that, "*The city is very crowded especially during peak hours of morning and evening there's too much trouble getting access to public transport…*".

Just like the rest of the other urban services studied in this work, no specific aspects of each service were asked. Respondents were allowed to make their own evaluation and make that reflect in their responses. And so, it needs to be noted that, urban transport services should be understood to mean all the infrastructure and services that come together to provide a seamless urban transport experience to residents. They include among others, mass transit and traffic management. Judging from the mean satisfaction level of respondents (Table 1), urban transport can be said to be just above the neutral position of 3 (3.08 out of 5)[1] indicating that there is more room for improvement within this urban service. It also indicates a demand for improved public transportation options and infrastructure development.

The emphasis on life satisfaction indicates a holistic approach to urban planning, recognising that residents' overall well-being is influenced by various factors beyond basic services. This underscores the importance of creating inclusive and liveable communities that promote residents' happiness and fulfilment. Like the rest of the other services, further studies that identify the exact components or influencing factors that led to respondents' evaluation could be pursued to shed more light on this. However, it can be retained that, urban living affects people's satisfaction with their lives and a satisfactory group of urban services has a major role to play in improving people's satisfaction with their lives. The same is true for the need to improve people's life depending on their status of either being employed, still schooling or retired. This category encompasses various aspects of daily life, including employment opportunities, educational resources, and retirement provisions. Special packages targeting these categories of people could be developed and implemented in this regard.

Other urban services cannot be overlooked regardless of their relatively low rankings. Access to open and green spaces is vital for promoting physical and mental well-being (Abass et al., 2024), recreational activities, and environmental conservation. Also, efficient drainage systems are essential for preventing flooding, managing stormwater runoff, and protecting urban infrastructure. Continuous investments in these areas are also indispensable urban life. Social support services play a crucial role in fostering community resilience, addressing social inequalities, and providing assistance to vulnerable populations. There is therefore a need for social welfare programs, support networks, and community services to promote social cohesion and inclusivity. While social activities (summer concerts, funfairs etc) may not rank as high in priority compared to other urban services, they remain significant for promoting social interaction, cultural enrichment, and community engagement. This suggests a potential opportunity for enhancing social programming and cultural initiatives to meet residents' leisure and recreational needs.

7. Further discussions based on inferential statistics

It has to be noted that the previously discussed evaluations of urban services by respondents do not necessarily indicate a "need" occasioned by the "absence" of these services. Whereas in some cases, this may be the case, in other cases, they indicate a "need" occasioned by the "fear" of "losing" what is currently available. In telling exactly which services are in shortfall and which ones are in adequacy,

[1] A 5-point Likert scale was used there. Because "3" reflected a neutral position, values below this indicate dissatisfaction and those above it indicate satisfaction.

respondents were further asked to score the existing services out of a maximum score of 10. Table 7 presents the mean scores of the services evaluated. Services with lower scores indicate those whose provisions are below the expectations of residence the least, housing conditions being the least of them.

Table 7. Mean scores of existing urban services

Urban Services	**Mean Scores**
Housing Conditions	4.94
Work/Educ/Retirement Life	5.37
Life Satisfaction	5.46
Social Activities	5.49
Parks, Open and Green Spaces	5.71
Health Service Delivery	5.73
Drainage Infrastructure	5.84
Social Support	5.85
Urban Transport Services	5.86
Safety and Security	5.86
Sanitation and Waste Management Services	5.96
Potable Water Infrastructure	6.11
Electricity Infrastructure	6.24

Respondents were also asked to give a general evaluation of the entire urban services by way of scoring out of 100 with the mean score being 66.1. A one-way between subjects ANOVA[1] was performed with levels of satisfaction (*strongly disagree, disagree, indifferent, agree and strongly agree*) as the independent variable, and the scores given to the respective urban services as dependent variable (Table 8). This helped to make more sense of the individual means of these scores as they were compared between those of the different groups identified from the responses to the statements seeking to identify their various levels of satisfaction with the services. The aim was to confirm if indeed any significant differences exist between people's levels of satisfaction with a service and their actual scoring of the same service.

From Table 8, we report that significant differences exist in the levels of satisfaction (*strongly disagree, disagree, indifferent, agree and strongly agree)* and the corresponding scores given to urban services such as health service delivery at $F(4,166) = 25.429$, $p < 0.001$, sanitation and waste management services at $F(4,166) = 24.218$, $p < 0.001$, urban transport at $F(4,166) = 22.670$, $p < 0.001$, safety and security at $F(4,166) = 19.813$, $p < 0.001$, work, education or retirement life at $F(4,166) = 16.819$, $p < 0.001$, parks, green and open spaces at $F(4,166) = 8.945$, $p < 0.001$ and the overall scores for the entire urban services at $F(2,166) = 30.211$, $p < 0.001$. A post hoc (Dunnet T3)[2] analysis revealed a decreasing mean for each of the urban services as one moves from the category of strongly disagree to strongly agree. For instance, in the case of health services, those who strongly disagree with their levels of satisfaction with is service (n=18, M=1.61, SD=1.195) gave a significantly lower score than those who disagree (n=33, M=4.64, SD=2.608), those indifferent (n=42, M=5.38, SD=2.141), those who agree (n=49, M=7.29, SD=2.082) and those who strongly agree (n=29, M=7.41, SD=3.053). Similar findings were observed for the rest of the urban services on Table 8 that have not been reported here. The null hypothesis that no such significant differences exist in the scores given and their respective satisfaction levels is therefore rejected.

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[1] This test was chosen because of its proven robustness even in the light of a violation of normality assumption (Blanca et al., 2017). As such, the normality test was not conducted since it would have no impact on the choice of this test. Parametric tests are generally considered more robust otherwise its non-parametric counterpart in Kruskal-Wallis H Test would have been conducted.

[2] This post hoc test was preferred because it provided an in-depth comparison between the groups. Stated differently, it returned results for among other things, the mean differences and significant levels for each individual group compared with each of the other groups.

Table 8. One-way ANOVA output from SPSS for satisfaction levels and scores

Score of Health Service	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	550.772	4	137.693	25.429	**0.000**
Within Groups	898.853	166	5.415		
Total	1449.626	170			
Score of Sanitation and waste management services	**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Between Groups	424.054	4	106.013	24.218	**0.000**
Within Groups	726.66	166	4.377		
Total	1150.713	170			
Score of Urban Transport	**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Between Groups	471.498	4	117.875	22.67	**0.000**
Within Groups	863.133	166	5.2		
Total	1334.632	170			
Score of Safety and Security	**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Between Groups	435.804	4	108.951	19.813	**0.000**
Within Groups	912.827	166	5.499		
Total	1348.632	170			
Score of Work/Educ/Retirement Life	**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Between Groups	322.369	4	80.592	16.819	**0.000**
Within Groups	795.421	166	4.792		
Total	1117.789	170			
Score of Parks and Green Spaces	**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Between Groups	213.378	4	53.344	8.945	**0.000**
Within Groups	990.002	166	5.964		
Total	1203.38	170			
Overall Evaluation	**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Between Groups	19085.362	2	9542.681	30.211	**0.000**
Within Groups	52433.928	166	315.867		
Total	71519.29	168			

To further understand whether or not the differences in the mean scores awarded to the different urban services were significantly different from each other based on the locations of respondents, a one-way between subjects ANOVA was performed with cities of respondents (*İstanbul, Ankara and İzmir and other cities*) as the independent variable, and the scores given to the respective urban services as dependent variable (Table 9).

We found that the cities in which people lived influenced the scores they awarded to; their current life in terms of work life or school life or retirement life at $F(2,166) = 3.572$, $p < 0.05$, their housing conditions at $F(2,166) = 6.354$, $p < 0.05$ and their life satisfaction in general at $F(2,166) = 4.007$, $p < 0.05$. Housing conditions for instance had lower mean scores for İstanbul (*n*=84, *M*=4.31, *SD*=2.816) than for Ankara and İzmir (combined) at (*n*=33, *M*=4.97, *SD*=2.215) and the other cities combined at (*n*=52, *M*=5.98, *SD*=2.646). On the other hand, cities of residence did not significantly impact the scores given to the urban transport system, health services, sanitation and waste management and safety and security services. This indicates a commonality of the situation across the surveyed cities. In general, these services were poorly rated which means that all the cities require similar levels of attention in the improvement of these services.

Table 9. One-way ANOVA output from SPSS for cities of residence and scores

Urban Services		Sum of Squares	df	Mean Square	F	Sig.
Score of Current Urban Transport	Between Groups	2.4	2	1.2	0.152	0.859
	Within Groups	1307.68	166	7.878		
	Total	1310.08	168			
Score of Current Health Service	Between Groups	2.667	2	1.333	0.158	0.854
	Within Groups	1401.66	166	8.444		
	Total	1404.33	168			
Score of Current Sanitation	Between Groups	18.451	2	9.225	1.377	0.255
	Within Groups	1112.54	166	6.702		
	Total	1130.99	168			
Score of Current Work/Educ/Retirement Life	Between Groups	45.568	2	22.784	3.572	**0.03**
	Within Groups	1058.87	166	6.379		
	Total	1104.44	168			
Score of Current Housing Conditions	Between Groups	89.718	2	44.859	6.354	**0.002**
	Within Groups	1171.9	166	7.06		
	Total	1261.62	168			
Score of Current Safety and Security	Between Groups	14.205	2	7.103	0.896	0.41
	Within Groups	1315.88	166	7.927		
	Total	1330.08	168			
Score of Current Life Satisfaction	Between Groups	58.505	2	29.252	4.007	**0.02**
	Within Groups	1211.71	166	7.299		
	Total	1270.21	168			

8. Predictors of Overall Satisfaction with Urban Services

Using data on the relative satisfaction levels of respondents with the different urban services, we identified the services that predict a person's overall satisfaction with urban services across Turkish cities using multiple regression analysis. Two regression models were developed with the output variable being "overall, I am satisfied with the urban services in this city (OSuS)" and the independent variables being "I am satisfied with the health services in the city (SwHeaS)", "I am satisfied with the urban transport services in the city (SwUTran)", "I am satisfied with safety and security services in the city (SwSafsec)" and "I am satisfied with the sanitation and waste management services in the city (SwSan)". As previously indicated, the responses to these statements represent ordinal measures and therefore can be used for multiple linear regression analysis like we have done. These four variables were chosen for the regression analyses because they were found to be among the top 5 most important urban services in the views of respondents (Table 4 and Table 6). Two models were developed using these variables.

Model 1

Model 1 comprised of the 3 variables, SwHeaS, SwUTran and SwSafsec as independent variables and OSUS as the dependent variable. In model 1, the independent variables, “SwHeaS”, “SwUTran” and “SwSafsec” significantly predict a person’s overall satisfaction with urban services (OSuS) in Turkish cities at $F(3, 167) = 58.355$, $p < 0.0001$ with $R^2 = 0.512$. This indicates that 51.2% of variations in a person’s overall satisfaction with urban services were attributable to these 3 urban services. Having understood that these variables together significantly impact on people’s overall satisfaction with urban services, we found it necessary to detect the individual impacts that these 3 variables have on OSuS. Before going further with this analysis, we put forward the following three alternative hypotheses;

H1: SwHeaS has a predictive effect on OSuS.
H2: SwUTran has a predictive effect on OSuS.
H3: SwSafsec has a predictive effect on OSuS.

To test the above hypotheses, we report their individual coefficients, t-values and p-values as obtained from the regression out from SPSS. Accordingly, the independent variable, “*SwHeaS*” was found to have a significant positive impact on a person’s overall satisfaction with urban services (B = 0.192, t = 3.162, $p = 0.002$). The independent variable, “*SwUTran*” has significant positive impact on a person’s overall satisfaction with urban services (B = 0.267, t = 4.898, $p = 0.0001$). And finally, the independent variable, “*SwSafsec*” has significant positive impact on a person’s overall satisfaction with urban services (B = 0.304, t = 5.667, $p = 0.0001$). This indicates that all three alternative hypotheses are supported (Table 10).

Table 10. Impacts of urban services on overall satisfaction with urban services - Model 1

Hypotheses	**Regression weights**	**B**	**t**	**p - value**	**Results**
H1	SwHeaS ---> OSuS	0.192	3.162	0.002*	Supported
H2	SwUTran ---> OSuS	0.267	4.898	0.0001*	Supported
H3	SwSafsec ---> OSuS	0.304	5.667	0.0001*	Supported

R^2 0.513
F(3, 167) 58.355
*p < 0.05

Thus, following the general regression equation, $\mathbf{Y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + \ldots + b_nx_n + e}$, the following regression equation is presented for this model;

OSuS = 0.773 + 0.192SwHeaS + 0.267SwUTran + 0.304SwSafsec + e

Model 2

In Model 2, an additional variable (SwSan) was introduced into the previous equation. This marginally increased the overall regression variation (R-squared) to 0.543, indicating a 54.3% contribution of the four variables to the total variations in the regression model. In effect, the overall model remains significant in its predictive effect on OSuS at $F(4, 166) = 49.076$, $p < 0.0001$. However, in determining the individual impacts of the four variables, it was noted that the introduction of the new variable caused a previous variable, SwHeaS to lose its significance at 0.05 significance level (Table 11). A number of reasons could be attributed to this situation. First, the inclusion of SwSan may have corrected a possible case of variable bias in the first model by its exclusion of SwSan. Secondly, the changes in degrees of freedom and the (re)distribution of variance may have contributed to this. The addition of SwSan can therefore be said to have resulted in a more comprehensive model.

Table 11. Impacts of urban services on overall satisfaction with urban services – Model 2

Hypotheses	**Regression weights**	**B**	**t**	***p* - value**	**Results**
H1	SwHeaS ---> OSuS	0.113	1.778	0.077**	Unsupported
H2	SwUTran ---> OSuS	0.222	4.054	0.0001*	Supported
H3	SwSafsec ---> OSuS	0.268	5.028	0.0001*	Supported
H4	SwSan ---> OSuS	0.204	3.299	0.001*	Supported

R^2 0.543
$F(4, 166)$ 49.076
**supported only at 0.10 significance level.
*$p < 0.05$.

Consequently, the following regression equation is presented:

OSuS = 0.647 + 0.113SwHeaS + 0.222SwUTran + 0.268SwSafsec + 0.204SwSan + e

9. Conclusion

In conclusion, this study provides valuable insights into the priorities and expectations of urban residents regarding various urban services in Türkiye. Through a comprehensive analysis of the survey data, key areas of focus have been identified, ranging from essential infrastructure to quality of life and social services. At the top of residents' priorities are health services, urban transport, safety and security, housing and sanitation in that order. The regression analyses performed using four of these variables demonstrated the positive impacts they have on people's overall satisfaction with urban services, signifying the relevance of these services to what residents' regard as the most important services in the urban area. Managers of urban areas can therefore take a cue or two from these analyses in their decision-making process regarding the specific areas where attention is needed most.

It is important to also acknowledge the main limitation of using an online form for data collection. While online surveys offer accessibility and cost-effectiveness, they may introduce biases due to self-selection and limited representation of certain demographic groups, potentially impacting the generalisability of the findings. Nevertheless, the results of this study remain valid and significant for both policy and urban studies scholarship. Despite the inherent limitations of the survey method, the large sample size and diverse representation across different cities in Türkiye enhance the robustness of the findings. By capturing the perspectives of a wide range of residents, the study provides valuable insights that can inform urban planning decisions, policy formulation, and resource allocation strategies aimed at addressing the needs and priorities of urban communities.

Looking ahead, future research in this area could explore longitudinal studies to track changes in urban service priorities over time and assess the effectiveness of policy interventions. Additionally, comparative studies across different countries or regions could offer insights into variations in urban service preferences and the impact of socio-cultural factors. Moreover, qualitative research methods such as interviews and focus groups could complement quantitative surveys by providing in-depth understanding of residents' experiences, perceptions, and aspirations related to urban services. Overall, by addressing these considerations and continuing to refine research methodologies, future studies can contribute to a deeper understanding of urban dynamics and support the development of more inclusive, sustainable, and resilient cities.

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6

The Effect of ECAP Processing on the Mechanical Properties of Aluminum Alloys

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Abstract

Equal-channel angular pressing (ECAP) is a severe plastic deformation (SPD) application that aims to enhance the mechanical properties of the material by subjecting it to shear stress under high pressure through die cavities with equal diameters intersecting each other at different angles. This study examined the application of ECAP to aluminum alloys that commonly used in industrial applications. The results were evaluated, and studies involving the effects of ECAP operating parameters (channel angle, temperature, pressing speed, number of passes, and the route) were included. Comparative evaluation of the results was conducted to guide further studies. In summary, a general increase in micro hardness values and improvements in the mechanical properties of the materials were observed. This strengthening is also supported with the Hall-Petch equation, which states that grain refinement in crystal grain structures leads to an increase in hardness.

Keywords: Equal channel angular pressing (ECAP), aluminum alloys, microstructure, mechanical properties, Hall-Petch equation

1. Introduction

Severe Plastic Deformation (SPD) technique is an application that involves plastic deformation of materials under high pressure to improve their mechanical properties. As a result of the application, crystal structure orientations and grain shrinkage occur in the internal structures of the materials and micro/nano sized grains can be obtained. SPD methods are widely employed in research due to their effectiveness in improving material strength and performance: (i) High-Pressure Torsion (HPT) (Langdon, 2013; Xu et al., 2015), (ii) Equal-Channel Angular Pressing (ECAP) (Küçükömeroğlu, 2010; Patil et al., 2015), (iii) Accumulative Roll-Bonding (ARB) (Jamaati & Toroghinejad, 2010; Kim et al., 2009), (iv) Cyclic Extrusion and Compression (CEC), (v) Constrained Groove Pressing (CGP) (K et al., 2023). Figure 1 illustrates the historical progress of SPD.

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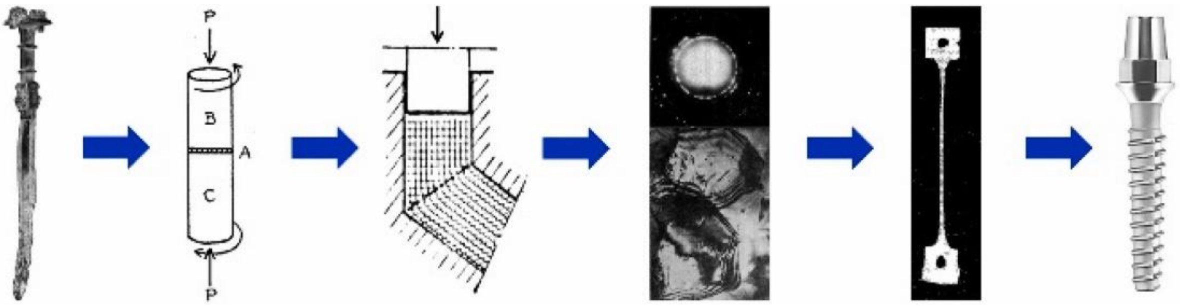
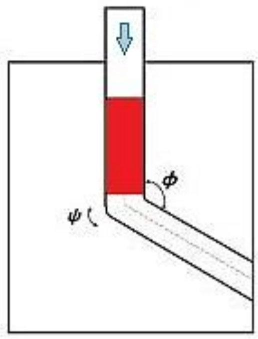


Figure 1. Schematic of the historical progress of SPD. From left to right: Sword making by repeated forging and folding; principles of HPT; principles of ECAP; formation of Ultra-Fine Grained (UFG) structure by HPT processing; high strain rate superplasticity in an aluminum alloy processed by ECAP; and commercialization of ECAP-processed titanium for implants. (Edalati et al., 2022)

ECAP was first implemented and developed by Segal (1977) and his team at the Minsk Institute in the Soviet Union in the 1970s and 1980s. ECAP is an severe plastic deformation application that aims to improve the mechanical properties of the material while maintaining its ductility by subjecting it to shear stress under high pressure through equal diameter mould cavities cutting each other at different angles. Figure 2 shows representation and equivalent plastic strain of the ECAP method (Segal, 1999). Although this subject has not reached a sufficient level in commercial and industrial applications due to its limited application dimension, it has attracted the attention of material science researchers in terms of obtaining materials with superior material and mechanical properties. In the literature, it is seen that these studies are widespread on titanium and its alloys, copper and its alloys, aluminium and its alloys (Féron, 2007; Gao et al. 2020; Atan, 2022; Küçükömeroğlu, 2010; Sato et al., 2008).



$$\bar{\varepsilon}_{ECAP} = \frac{N}{\sqrt{3}}\left[2\cot\left(\frac{\varphi+\psi}{2}\right) + \psi \csc\left(\frac{\varphi+\psi}{2}\right)\right]$$

Figure 2. Representations and equivalent plastic strain of the ECAP method (Segal, 1977).
N: number of passes, φ: channel angle, ψ: corner angle

The most visible effect of SPD, particularly in metallic materials, is the enhancement of mechanical properties such as strength and hardness, mainly due to the grain refinement effect and the Hall-Petch mechanism (Küçükömeroğlu, 2010; Segal, 1977).

The main objective of SPD is to deform the material by applying excessive force, thereby refining the granular microstructure and consequently improving the mechanical and functional properties. The ability to deform plastically depends on the ability of the dislocation to move (see Figure 3). The movement of dislocations is restricted as a result of the re-formation of small granular structures and a stronger material is obtained (Callister & Rethwisch, 2020).

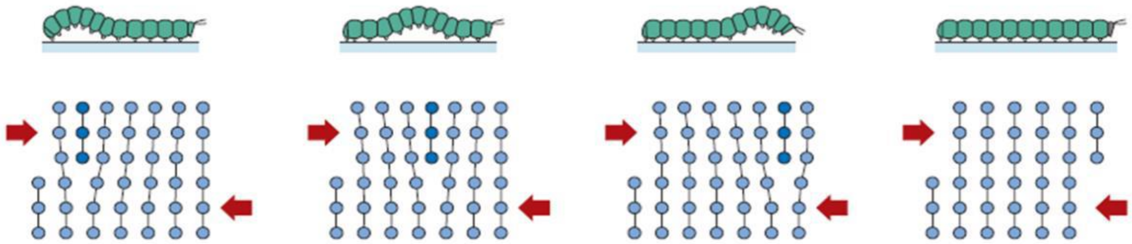


Figure 3. Similarity between caterpillar and dislocation movement (Callister & Rethwisch, 2020)

There is a remarkable relationship between the internal structure of materials and their mechanical properties. This relationship can also be explained by the Hall-Petch equation (Eq. 1), which expresses the increase in mechanical strength of materials with the shrinkage of the grains forming the microstructure.

$$\sigma_y = \sigma_0 + \frac{k}{\sqrt{d}} \tag{1}$$

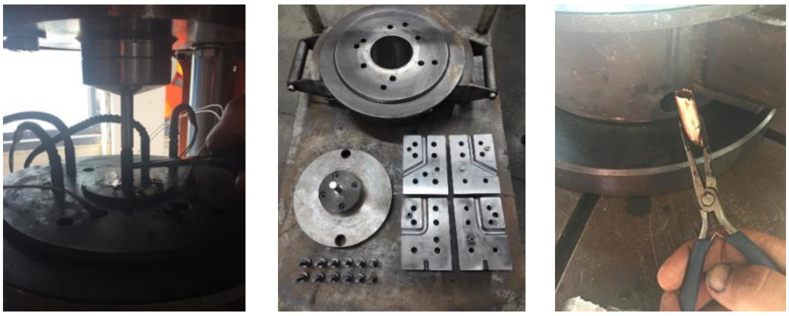
where, σ_y is the yield strength of the material, σ_0 is the material's intrinsic strength (resistance to dislocation motion in the absence of grain boundaries), k is the strengthening coefficient, and d is the average diameter of the grains in the material.

Aluminum alloys stand out among non-ferrous metals for their lightness, strength, high toughness and corrosion resistance. These properties are critical for a wide range of applications from aerospace to automotive. The formability of aluminium alloys varies considerably depending on their composition. For example, alloys containing pure aluminium and magnesium generally have better formability, while those containing copper or zinc have higher strength (Çetin et al., 2024; Féron, 2007; Malla et al., 2024; Shu & Ahmad, 2011).

In this study, researches on the effects of the application parameters of ECAP, one of the severe plastic deformation methods, on the mechanical properties of aluminum alloys and their results were evaluated.

2. ECAP Applications and Parameters

ECAP is the process of subjecting the specimen to shear stress under high pressure through mould cavities of equal diameter cutting each other at different angles as shown in Figure 4. The most characteristic feature of ECAP is that it can be subjected to plastic deformation with high stresses by repeated deformation with multiple passes without cross-sectional change.



(a) (b) (c)

Figure 4. ECAP process: (a) Pressing, (b) ECAP channels, and (c) a sample subjected to shear stress

The ECAP press, the ECAP mould and the samples to be treated are the main components of the ECAP process and need to be precisely designed and prepared. The parameters affecting the ECAP process are: (i) pressing pressure; (ii) angles of the mould channels; (optimum angles φ = 90°, ψ = 15°) (Agwa et al., 2016); (iii) surface quality of the channels; (iv) pressing speed (mm/sec); (v) punch (selection of suitable material and size to avoid buckling); (vi) Lubricant applied to the sample and die channels (Frint et al., 2017); (vii) ECAP application temperature (maintaining a higher temperature facilitates the ECAP process but has an adverse effect on grain size reduction) (Yamashita et al., 2000); (viii) the number of passes required to achieve a homogeneous microstructure (Saravanan et al., 2006). The rotation of the sample around its axis in specific directions (route) before each repetition of the process (Azushima et al., 2008; Venkatachalam et al., 2010).

In the literature, the application of three primary pressing routes or combinations thereof (A, B, C, BA, BC) is a common occurrence, as illustrated in Figure 5. The ECAP process allows for the utilisation of diverse route types, contingent on the principle of rotating the sample around its axis at varying angles prior to each pass (Sato et al., 2008; Wang et al., 2017; Venkatachalam et al., 2010).

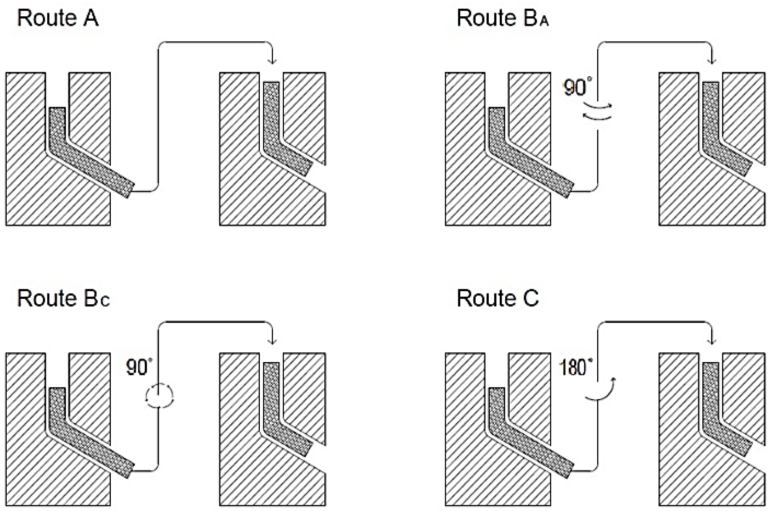


Figure 5. ECAP process routes

In the ECAP process, the defined routes for rotating the sample are as follows: Route A applies the ECAP process repeatedly without rotating the sample. Route B alternates the rotation of the sample by ±90° around its axis. Route BC involves rotating the sample by +90° after each pass, and Route C requires a 180° rotation of the sample around its axis. The BC and A routes have been identified as the most effective paths for achieving significant microstructural grain refinement (Furukawa et al., 1998; Langdon, 2013).

3. Effect of ECAP Parameters in Mechanical Properties

The key parameters of the ECAP process, including the number of passes, the selection of the pressing path, the geometry of the die, and the processing temperature, exert a significant influence on both the degree of grain refinement and the resulting mechanical properties of the material. The number of passes has a direct impact on the level of deformation imparted to the material. In general, the application of multiple passes results in the formation of finer grain structures and an improvement in mechanical strength. The selection of the pressing route, which determines the direction and sequence of deformation, affects the uniformity of the shear stress and the distribution of dislocations within the material. Moreover, the die geometry, which defines the angle and shape of the channels, influences the shear force and flow characteristics during pressing. The processing temperature plays a crucial role, influencing the flow behavior of the material and grain refinement kinetics. Higher temperatures facilitate easier deformation, but can also lead to undesirable grain coarsening if not carefully controlled. Therefore, optimizing these parameters is essential to tailor the ECAP process to achieve the desired material properties and performance characteristics.

3.1. Channel Angle

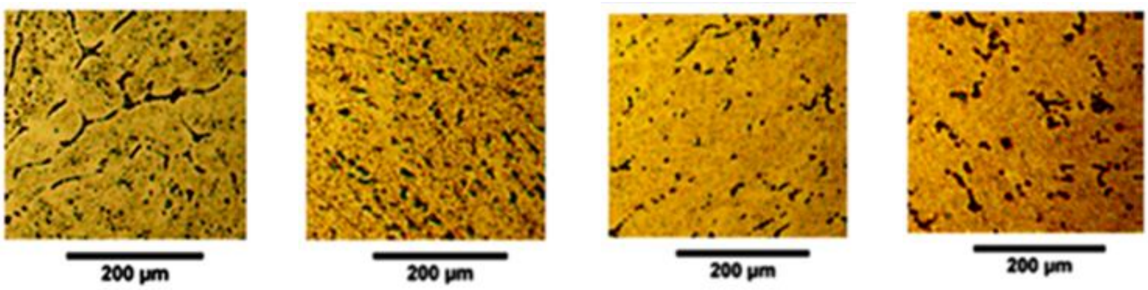
Serban et al. (2013) investigated the impact of die channel angles on the performance of 6063-T1 aluminum alloys processed through ECAP. They examined the effects of different die channel angles and the number of passes on equivalent strain and mechanical properties. The study involves die channel angles of 90°, 100°, and 110°, with a fixed total equivalent strain and varying numbers of passes. For each pass, equivalent strain values are computed and found as approximately 1.05, 0.89, and 0.77, respectively.

Eq. (2) is used to calculate equivalent strain:

$$\varepsilon_N = N \times \frac{1}{\sqrt{3}}\left[2\cot\left(\frac{\phi}{2}+\frac{\psi}{2}\right)\right] + \psi\,\mathrm{cosec}\left(\frac{\phi}{2}+\frac{\psi}{2}\right) \tag{2}$$

where N is the number of passes, ϕ is the channel angle, and ψ is the corner angle.

Optical microscope images of samples processed with different die channel angles and numbers of passes are shown in Figure 6. These images reveal that an increase in die channel angle leads to a less regular microstructure with larger grain sizes. The material processed with smaller die channel angles exhibits a more homogeneous and refined microstructure.



Raw (unprocessed) sample ε_N=0 | ECAPed sample on 90° Channel angle N=6, ε_N=6.30 | ECAPed sample on 100° Channel angle N=7, ε_N=6.23 | ECAPed sample on 110° Channel angle N=8, ε_N=6.16

Figure 6. Optical microscopy images (Serban et al., 2013)

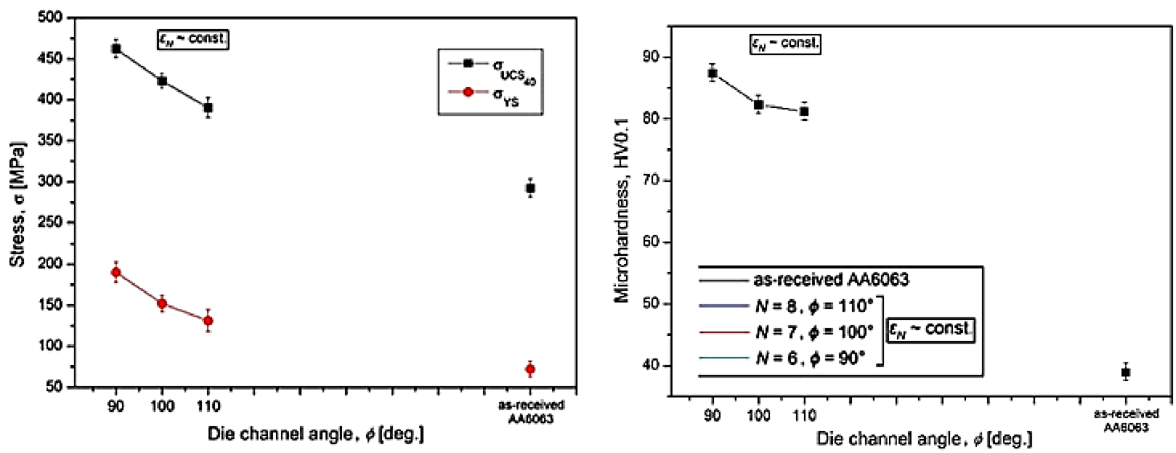


Figure 7. (a) Change in yield compressive strength values depending on channel angle, (b) Change of microhardness values depending on the channel angle (Serban et al., 2013)

The effects of die channel angle on strength value are illustrated in Figure 7(a). It shows the variation of compressive strength with die channel angle. The compressive strength of the unprocessed sample is 292 MPa. The strength values of the processed samples are as follows: with a 90° die and six passes, the strength increases by approximately 58% to 462 MPa; with a 100° die and seven passes, the strength increases by about 45% to 423 MPa; and with a 110° die and eight passes, the strength increases by approximately 33% to 390 MPa. Figure 7(b) demonstrates the variation of microhardness with die channel angle. Similar trends were observed in yield strength and microhardness.

The study shows that the microstructure is finer and more homogeneous when a 90° die channel angle is used, indicating a proportional relationship between die channel angle and microstructure refinement. Additionally, all samples show approximately similar accumulated equivalent strain values, but those processed with smaller die channel angles exhibit superior microstructural homogeneity.

The research highlights the significant impact of die channel angles on the mechanical properties and microstructure of 6063-T1 aluminum alloys processed through ECAP. Smaller die channel angles result in a more refined and homogeneous microstructure and enhanced mechanical properties.

3.2. Temperature

Gupta et al. (2022) studied cylindrical samples of Al-6063 by ECAPed using the route BC at two different temperatures: room temperature and a temperature of 250°C. They examined the change on the microstructure and hardness properties of the samples deformed after the first, third, and sixth passes. The results given in Figure 8 shows that hardness increased up to 85 HV after six passes at room temperature, with a notable 83% increase after just one pass at this temperature. This shows that the effect of ECAP is much greater at lower temperatures.

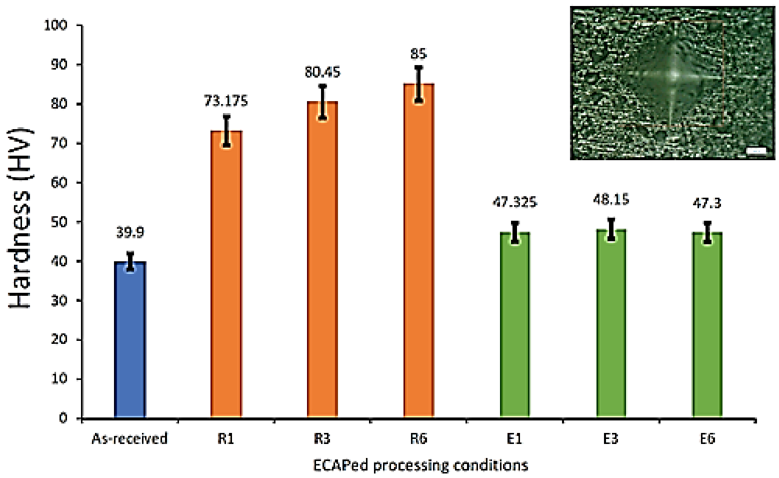


Figure 8. Hardness value at different level; blue shows initial hardness, and orange and green column shows hardness of ECAPed processed samples at room temperature and at 250°C, respectively. In the corner indentation of hardness test on ECAPed sample (Gupta et al., 2022)

In contrast, EBSD analysis of a sample processed at 250°C revealed that low-angle grain boundaries constituted 91.06% of the sample, while high-angle grain boundaries making up only 8.9% after one pass. The researchers reported that the elevated processing temperature had a significant impact on both hardness and microstructure (Figure 9).

The researchers observed that after the first pass, almost all the grains were either equiaxed or elongated, with accumulation occurring at the grain boundaries at room temperatures, leadin to a rapid increase in hardness. Recrystallization began when the die temperature was increased to 250°C, which was accompanied by a decrease in hardness.

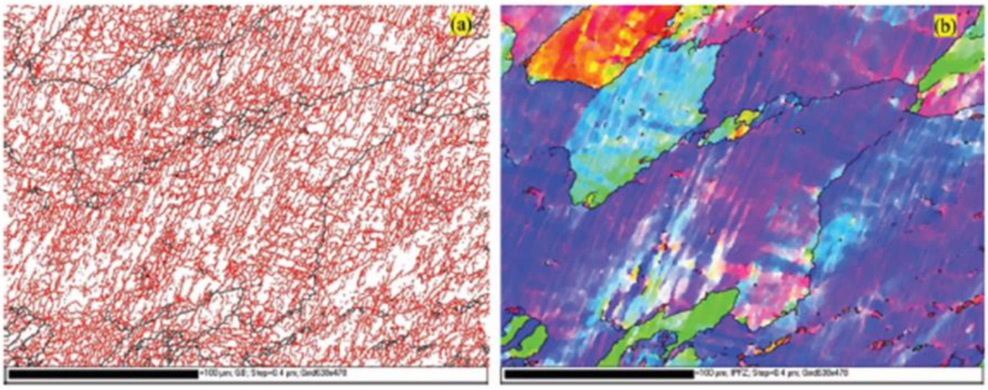


Figure 9. EBSD images of ECAPed sample with one pass at elevated temperature: (a) grain orientation map, (b) inverse pole figure (Gupta et al., 2022)

3.3. Route

Gao et al. (2020) investigated the impact of rotational paths during the ECAP process of AL6063 aluminum alloys. In their study, processing was conducted at room temperature using a die angle of 120° (ψ=30°) with rotational paths A, BA, BC, BC-UD2, and C as shown in Figure 10.

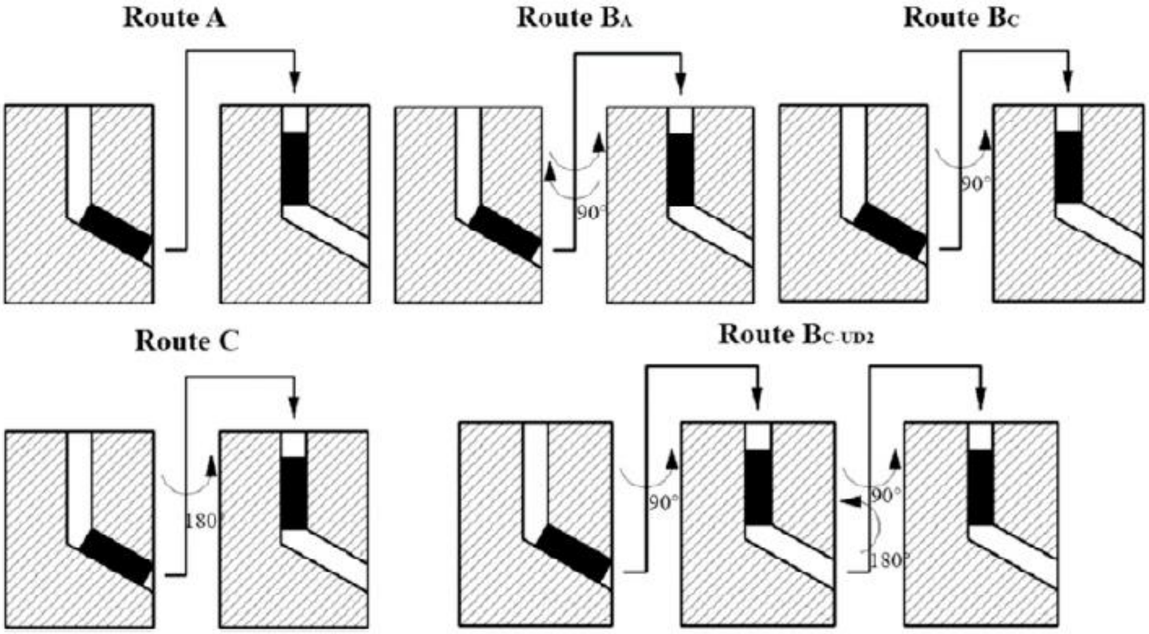


Figure 10. Routes used in the study

The microstructures of paths C and BC are illustrated in Figure 11. The specimens processed with path C exhibit a smaller average grain size compared to those processed with path BC. This reduction in grain size is correlated with an improvement in the mechanical properties of the material, as supported by the Hall-Petch relationship.

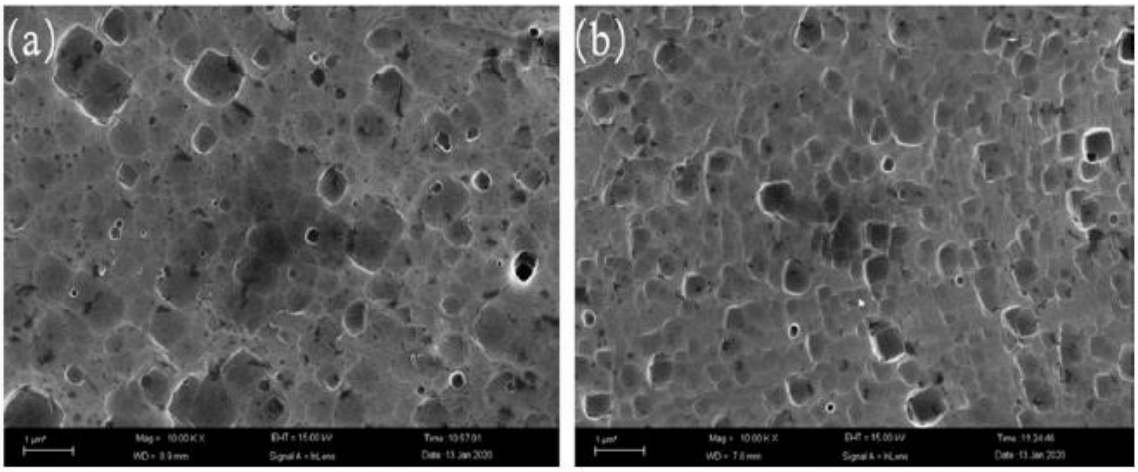


Figure 11. Microstructure of AA6063 material after the ECAP process: (a) Path B, (b) Path C (Gao et al., 2020)

The tensile properties and hardeness values of samples are given in Table 1. The greatest increase in tensile strength was observed in the BC and C routes. The BA and BC routes exhibited the highest level of ductility. The BC route resulted in both an increase in the strength of the material and the maintenance of its ductility.

Table 1. Tensile properties and hardness of AA6063 alloy after cold ECAP (Gao et al., 2020)

Processing route	Ultimate tensile stress (MPa)	Total elongation (%)	Modulus of elasticity (MPa)	Hardness average (HV)	Hardness STD
As-rolled	209.00	0.29	1066.92	70.00	-
1P	250.73	0.10	1066.92	98.95	8.43
2P	341.05	0.11	1203.15	96.62	7.95
A-4P	351.10	0.09	1219.16	94.13	5.65
B_A-4P	342.30	0.13	1044.81	126.24	7.04
B_C-4P	373.04	0.12	1187.08	94.03	5.11
B_{C-UD2}-4P	366.20	0.11	1199.10	92.22	2.42
C-4P	381.84	0.11	1295.53	110.42	7.96

3.4. Number of Passes

In a study performed by Serban et al. (2012), the influence of the number of passes in the ECAP process on 6063-T1 aluminium alloys was investigated. The study employed a die channel angle of 90° (ψ=20°), processed at room temperature with a pressing speed of 10 mm/s, and applied a rotational path designated as BC. The research encompassed a total of nine passes, with each pass representing one, three, six, or nine ECAP passes, respectively.

The ultimate compressive strength exhibits a progressive increase with each additional pass, starting at 165 MPa in the as-received material (0 passes). The strength increases by 13%, reaching 187 MPa, after one pass. With three passes, the strength increases by 27%, reaching 210 MPa. After six passes, the ultimate compressive strength increases by 51%, reaching 250 MPa. By nine passes, the strength has risen by over 70% compared to the as-received material, reaching 282 MPa (see Figure 12).

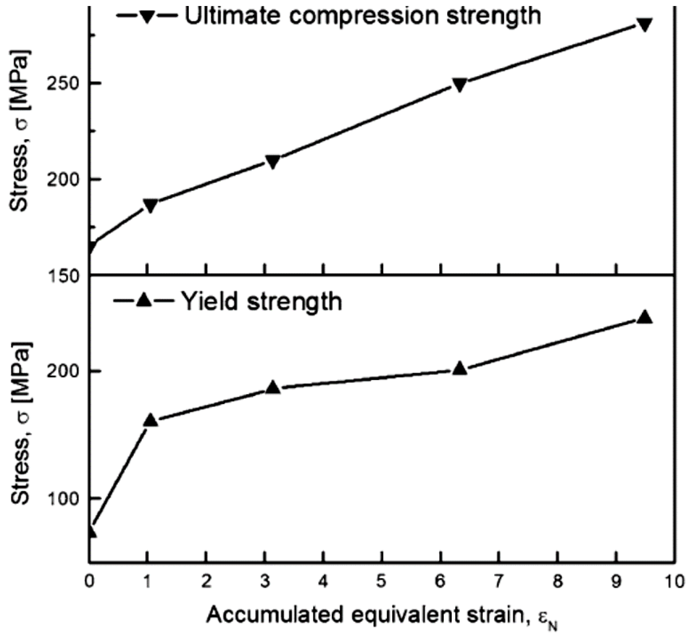


Figure 12. Effect of ECAP pass number on yield and compressive strength values (Serban et al., 2012)

A similar trend is observed for yield strength and hardness as seen in Figure 13(a). The mechanical properties of the AA6063 aluminium alloy exhibits a total increase of 103% in microhardness as a consequence of the ECAP processing. Additionally, it is demonstrated in Figure 13(b) that all mechanical properties improved with the increase in the number of passes.

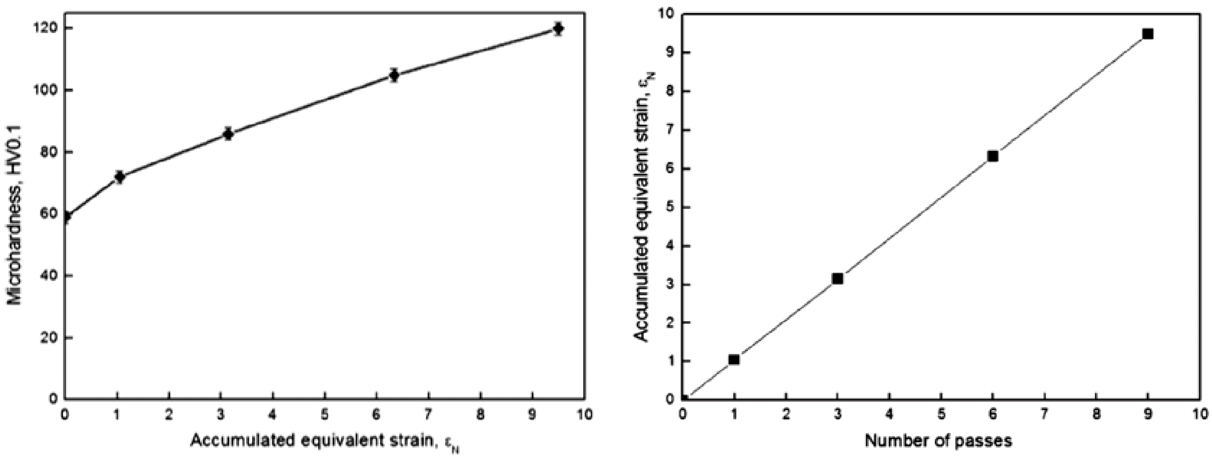


Figure 13. (a) Impact of ECAP on microhardness values, (b) Accumulated equivalent strain

4. Results

The effects of selected ECAP parameters are presented as dimensionless values in a single figure (Figure 14). These parameters include channel angle on yield strength and hardness, room temperature on hardness, elevated temperature on hardness, ECAP path on tensile strength and hardness, and ECAP pass numbers on maximum compressive stress and hardness. The dimensionless values are calculated by taking the ratio of the values obtained from the ECAP process to the corresponding values of the unprocessed (raw) sample.

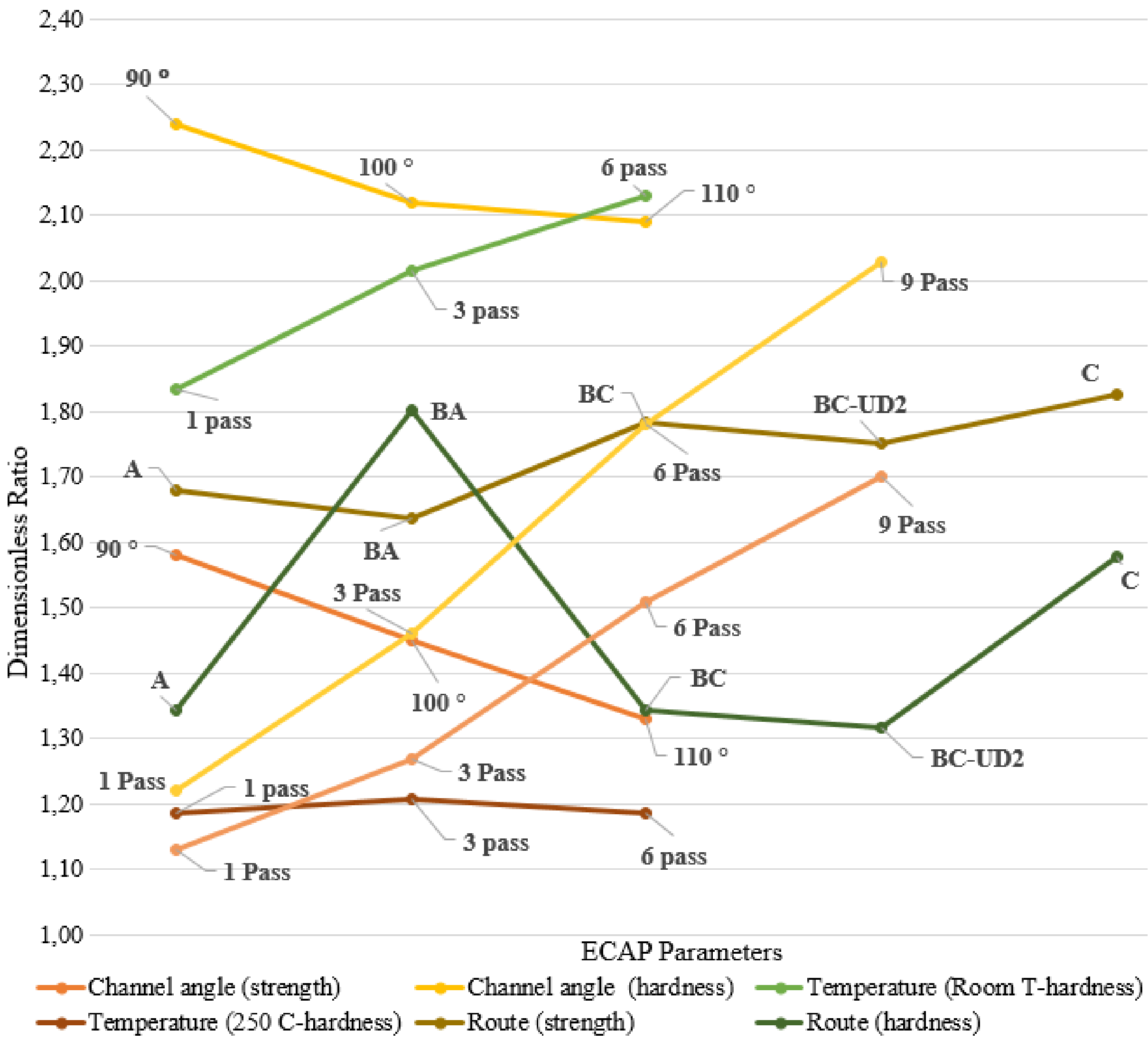


Figure 14. Dimensionless values of ECAP parameter effects

5. Conclusion

This study investigated the application of Equal Channel Angular Pressing (ECAP) on aluminum alloys, focusing on how varying parameters such as channel angle, temperature, pressing speed, number of passes and pressing route affect the mechanical properties and microstructure of the material. The findings show that ECAP is a highly effective severe plastic deformation technique to improve the mechanical properties of aluminum alloys widely used in industrial applications.

An important result of this research is the observed increase in microhardness and mechanical strength at different ECAP parameters. As predicted by the Hall-Petch equation, a significant correlation was observed between grain refinement and increased mechanical properties. In particular, the reduction in grain size resulting from the ECAP process led to significant increases in yield strength and microhardness.

The study revealed several critical insights:

Channel Angle: The die channel angle significantly influences the microstructure and mechanical properties of aluminum alloys. Smaller channel angles (e.g., 90°) resulted in a more refined and homogeneous microstructure, leading to higher compressive strength and microhardness compared to larger angles.

Temperature: Processing at lower temperatures yielded a substantial increase in hardness and a finer microstructure due to the suppression of grain growth. Conversely, higher temperatures facilitated easier deformation but also led to grain coarsening, which negatively impacted hardness.

Route: The selection of the processing route played a vital role in determining the material's final properties. Routes BC and C were particularly effective in achieving a balance between strength and ductility, with route BC showing the highest improvements in both tensile strength and ductility.

Number of Passes: An increase in the number of ECAP passes led to a progressive enhancement in both yield and compressive strength, as well as microhardness. The results indicated that the mechanical properties could be significantly improved with additional passes, highlighting the potential of ECAP for achieving desired material characteristics.

Overall, the findings of this study provide a comprehensive understanding of how different ECAP parameters influence the mechanical properties and microstructure of aluminum alloys. These insights can guide future research and industrial applications in optimizing the ECAP process for enhanced material performance.

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7

The Role of Autophagy in Abiotic Stress Tolerance in Vegetable Crops

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Abstract

There is an urgent need to develop crops that are resilient to the effect of climate change. One way to achieve this is to explore the abiotic tolerance capabilities of existing genetic materials that are found in gene banks around the world. These will help to determine the efficiency of the genetic materials for use in climate-smart breeding and genetic engineering programs. By so doing, we might be able to get ahead of the current food production deficit and put an end to widespread hunger. Autophagy is a mechanism in eukaryotic cells that is used for maintaining the integrity of the cells against pathological materials and other stress factors. This study reviews the role of autophagy-related genes and their proteins in different pathways to plant response under abiotic stress conditions. Autophagy is well-studied in model plants such as Arabidopsis and tobacco, however, this study presents an assessment of autophagy in vegetable crops such as pepper and tomato. Abiotic stress tolerance pathways, together with related genes and enzymes, in these vegetable crops were also evaluated. Aside from the use of phenotypic and molecular marker assays, this study gives a new basis for the use of autophagic activity assays in the evaluation of plant tolerance to abiotic stress. The novel perspectives provided in this review will serve as a source of relevant information to scientists who are interested in the improvement of plant quantitative and qualitative traits.

Keywords: Climate change, autophagy, plant biotechnology, abiotic stress, plant genetic resources, PGR

1. Introduction

Plant genetic resources (PGR) is described as the diverse genetic pools including landraces, prim-itive cultivars, varieties obtained from traditional agriculture, wild relatives of crop plants (including those considered as weed by farmers) and special genetic stocks, including elite and current breeder's lines and mutants (Brockhaus & Oetmann, 1996; IPGRI, 1993). These genetic clusters of diverse botanical and agricultural traits are perpetually under threat due to adverse effects of climate change. The situation is even made worse due to the narrow genetic base of some crop plants which deprives them of the necessary traits that could ensure their adaptability to harsh environmental conditions. Deforestation, industrialization, increase in global population, biotic stress factors and bio-terrorism are also some of

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the other factors that threatens the supply of plant genetic material for crop improvement (Balvanera et al., 2006).

Climate change in particular has been described as the ‘virus’ of nature (Elbehri et al., 2011), a situation that must be addressed with every sense of urgency in order to curtail widespread hunger and poverty. According to the most recent United Nations Food and Agriculture Organization (FAO) report on global food insecurity, in 2021 about 828 million people are affected by hunger globally. There has been an increase of about 46 million in this figure since 2020 and 150 million since the outbreak of the COVID-19 pandemic (UN FAO, 2022). There have also been future estimations of about 670 million people (8 percent of global population) who will still be dealing with the issue of hunger in 2030 (UN FAO, 2022). There has also been an estimated requirement of 70 percent increase, over the current level of production, in world agricultural food production to meet the food demands of 9.2 billion people who are estimated to be on earth by the year 2050.

Plant genetic resources have a crucial role to play in increasing global food security, reducing poverty, and protecting the environment for sustainable development. PGRs are the only source of plant ge¬netic variation found in nature. They provide valuable traits needed for tackling the challenges of adapting crop varieties to rapidly changing agroecological environment (Sahu et al., 2023). These genetic resources are also essential in developing environment-specific crops in places where foreign planting material needs to be introduced to a new environment. Also, some genotypes which are currently less regarded as useful materials for breeding may become useful in the future due to the consistently evolving climate. They might also provide rare and important resistant traits during period of unprecedented disease outbreaks (Campbell et al., 2008).

Therefore, the impact of climate change can be overcome through the cultivation of crop varieties which are adaptable to various environmental stresses. These special crops have to be collected, analyzed and identified either for direct use in cropping systems or as a source of plant genetic resources.

One way to analyze and evaluate plant genetic material is to understand the mechanism that is responsible for inducing trait for which those plants are desired. One such mechanism in plant is Autophagy. Autophagy can be described as the removal of damaged proteins from plant intracellular environment. Autophagy is one of the ubiquitous and highly conserved protein degradation systems in eukaryotic cells (Yoshimoto et al., 2010). During the autophagy process, proteins and organelles that are considered damage and no longer useful for cellular function are enveloped by a double-membrane vesicle called autophagosome and then transported into vacuoles for breakdown (Johansen & Lamark, 2011; Liu & Bassham, 2012). In this review, we evaluate the importance of research findings so far on the workings of the autophagy mechanism in crop plants under various abiotic stress conditions. We gave deep insights and perspective on how the information we currently have on this topic can stimulate future research.

2. Autophagy as a Mechanism for Sustainability of Cellular Function in Vegetable Crops

Autophagy, also known as self-eating, can be described as an evolutionary process that is highly conserved in eukaryotic cells. This cellular process involves the degradation of cellular components (organelles, protein complexes, and macromolecules) (Marshall & Vierstra 2018). The degradation process is followed by a sequestration process whereby the degraded organelles are clustered in autophagic vesicles that are later moved to the vacuole, by the intracellular transport mechanism, for breakdown. In the absence of stress factors (Biotic and Abiotic), autophagy performs a housekeeping function by degrading unwanted cytoplasmic material and maintaining cellular homeostasis (Liu & Bassham 2012). However, under stress conditions (biotic and abiotic), the synthesis and activity of autophagy related proteins (ATG proteins) are up regulated, and they enable the recycling of damaged or non-essential cellular material (Su et al, 2020).

Three different types of autophagy have been identified in plants, this autophagy forms are described based on the mode of degradation and sequestration by a double membrane intracellular transport structure called autophagosome. These forms of autophagy include micro-autophagy, macro-autophagy, and mega-autophagy (Van Doorn & Papini, 2013).

2.1. Micro-autophagy

This involves the direct packaging of the unwanted cellular material into the vacuole for degradation through the invagination or protrusion of the vacuolar membrane (Sienko et al., 2020). In plants, micro-autophagy has been reported to play an important role in anthocyanin aggregates (Chanoca et al., 2015). Another author has also reported the involvement of micro-autophagy in the degradation progress of damaged chloroplast. The degradation has been described as chlorophagy (Nakamura et al., 2018).

2.2. Macro-autophagy

This has been described as the well-studied type of autophagy in plants. It involves a process in which double membrane structures called autophagosomes are formed. After their formation autophagosomes fuse with vacuoles to degrade unwanted cellular materials (Feng et al., 2014). A study has found more than 40 ATG proteins to be involved in the biological process of macro-autophagy (Marshall & Vierstra 2018).

2.3. Mega-autophagy

Compared to the other types of mega-autophagy is a more direct type of autophagy. In this type, the tonoplast membrane ruptures and then releases the vacuolar hydrolases straight into the cytoplasm, where it degrades cytoplasmic materials (Hatsugai et al., 2004; Nakatogawa, 2020). Mega-autophagy often occurs during apoptosis (programmed cell death) or in response to disease causing pathogens (Marshall & Vierstra, 2018).

In plants, autophagy is involved in various biological processes such as development, nutrient recycling, and metabolic activities induced by biotic and abiotic stresses (Liu & Bassham, 2012). Autophagy is necessary for the sustainability of so many life processes in plants. Vegetable crops are produced in stages which included germination of seeds: at these stages growth inhibiting hormones that have ensured the safe storage of the seeds by preventing germination while in storage must be broken down for germination to take place. This process is quite catabolic and involves the production of so many damaged cellular materials. Quite a few studies have been done on the function of autophagy in vegetable crops under stress conditions. Some ATG proteins and their regulators have also been identified to play a major role in this function. Below is a summary of various examples in pepper and tomato plants.

3. Stress in Plants

3.1. Drought Stress

Drought stress is combated in crops by the expression of ATG genes. The genes are responsible for the production of necessary proteins needed for the sustenance of life in plants during drought or low irrigation conditions. For instance, drought stress increases the expression of ATG2 in peppers (Zhai et al., 2016). In tomatoes overexpressing HsfA1a, a heat shock protein regulator, and the silencing of ATG10 and ATG18f reduces the possibility of autophagosome formation and autophagy mediated tolerance to heat shock (Wang et al., 2015). Conversely, the overexpression of MdATG18a (an autophagy related gene which was first cloned form apple Malus domestica) in tomatoes ensures the degradation of stress drought induced proteins, limits oxidative damage, and thereby improves tolerance to drought conditions (Sun et al., 2018). A previous study has also shown that mitochondrial alternative oxidase (AOX) may regulate autophagy through mitochondrial reactive oxygen species (ROS) during drought stress in tomatoes (Zhu et al., 2018).

3.2. Heat Stress

With the rapidly increasing rate of global warming in recent years, extreme high temperatures occur frequently in most climates of the world (IPCC, 2013). It is estimated that a unit degree rise in temperature could lower the yield of crops by up to 10% (Lobell et al., 2011). Issues concerning yield reduction are of great concern to food security, thus heat stress becomes a major threat to crop production and global effort against hunger.

High temperature negatively affects plants' growth and development by inducing protein denaturation, misfolding, aggregation and oxidation (Hemantaranjan et al., 2014). There are two types of mechanisms in living organisms that have been evolutionarily developed to alleviate the damage caused by heat stress. This mechanism includes effectively preventing the proteins from being damaged and efficiently removing the damaged proteins (Dokladny et al., 2015). These two mechanisms ensure that the intracellular environment remains nontoxic.

At temperatures above the plant's threshold for carrying out physiological processes, it is unsustainable and toxic to accumulate large amounts of oxidized and insoluble proteins. Therefore, at this temperature, plants can get rid of these toxic proteins by initiating the process of autophagy to improve plant tolerance and sustainability of physiological processes. In this case, ATG gene is up regulated in various plants, and more autophagosomes are accumulated to combat the adverse effect of heat stress on cellular functioning (Zhai et al., 2016; Zhou et al., 2014; Cheng et al., 2016).

In plants, heat shock proteins (HSPs) are regarded as the major metabolic pathway executors which protect proteins under heat stress. They are also referred to as molecular chaperones (Liu et al., 2012).

3.3. Cold Stress

Unlike in the case of heat stress, few studies have reported on the regulation of cold stress by autophagy in plants (Wang et al., 2022). In tomatoes, it has been reported that BRs (Brassinosteroids) and the positive regulator BZR1 causes autophagy and the accumulation of the selective autophagy receptor NBR1 under cold stress (Julkowska & Testerink 2015). However, the link between the cell's ability to remove damaged proteins and tolerance to cold stress in plants is still not clear and remains to be studied.

3.4. Salt Stress

When concentration of NaCl is high in plant tissue there is reduction in photosynthetic rate, also energy consumption becomes excessive, and accumulation of excess reactive oxygen species (ROS) takes place (Yue et al., 2018). Autophagy serves essentially as a regulator of cellular homeostasis. It is also involved in the pathway of plant salt tolerance. A study has demonstrated that spermidine (Spd), a kind of polyamine, is responsible for the activation of ATG gene expression and formation of autophagosome in cucumbers under salt stress conditions (Leary et al., 2018).

4. Applications for Enhancing and Stimulating Autophagy

Plant growth regulators offer a direct approach to inducing autophagy. For instance, the exogenous spraying of aerosols containing melatonin solution has been proven to improve heat tolerance in tomatoes. This may have been possible because melatonin increases the expression of ATGs and the formation of autophagic vesicles at high temperatures. This process helps to degrade the denatured proteins produced under heat stress (Wang et al., 2019). Also, in another study (Hartman et al., 2021) Ethylene is found to be capable of inducing the expression of ATG genes and increasing ROS levels to promote the adaptation to flooding and hypoxia stress in soybeans and tomatoes (Chen et al., 2017).

Another application in agriculture involves the use of hormone regulators to regulate the autophagy activity of pathogens and pests thereby reducing disease transmission directly. This is a very practical means and effective means of improving tolerance to diseases in crops.

In addition, with the various recent and rapid development in nanotechnology, it is also possible to use titanium dioxide (TiO_2) and zinc oxide (ZnO) nanoparticles in the regulation of plant autophagy (Balážová et al., 2020, Islam et al., 2016).

All the methods mentioned above are capable of ensuring feasibility in the application of autophagy in agricultural crop production. Moreover, with ongoing and future developments, gene editing technology can also be used for manipulating and inducing the process of autophagy.

5. Conclusion and Perspectives for Future Studies

Autophagy has been around for so long and its role in maintaining homeostasis in plants is well-known. However, there is need for more studies to analyze how this mechanism works under stress conditions. Also, it will be interesting to know the functionality of autophagy in cells of plants that are under combined stress factors. This is essential since in fact stresses occur in combination and not in isolation has been presented in most studies. For instance, during periods of high temperature in arid areas the plant is also exposed to drought due to excessive rate of evapotranspiration. Also, systematic analysis of ATGs in crop plant response to abiotic stress is limited. The design of molecular markers to map the region of the plant chromosome where ATG genes are located will go a long way in ensuring the success of studies that are carried out on the classification of plants based on autophagy induced response to plant stress.

The study of autophagy in plants currently focuses on model crops such as Arabidopsis and tobacco. However, to be able to effectively use benefit from the knowledge of autophagy in plants more exhaustive studies will have to be carried out on crops as well. These studies will help to fast track the rate of development in crop improvement programs. In addition, although the involvement of autophagy has been identified in many life processes, its role in the various signaling pathways that regulate plant growth and stress tolerance still needs to be properly examined in future research. Furthermore, applications that induce autophagy in plants need to be well improved to ensure economical and efficient application in large scale agricultural production systems.

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8

Caffeine, Human Health and Sustainability

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Abstract

The coffee plant, belonging to the Rubiaceae family and Coffea genus, includes around 70 species, with Coffea Arabica L. (Arabica coffee) and Coffea canephora (Robusta coffee) being the most significant commercially. Arabica and Robusta differ in taste, appearance, and caffeine content. Arabica, favored for its superior flavor, accounts for 75–80% of global production, while Robusta, known for its higher caffeine content, holds the remaining market share. This review explores the sources of caffeine, including coffee beans, tea leaves, cacao beans, and certain nuts, emphasizing its widespread presence in foods, beverages, and medications. Caffeine, a widely studied stimulant, has significant psychological and physiological impacts. Its effects range from improving alertness and cognitive performance to causing sleep disturbances, anxiety, and gastrointestinal discomfort. The review also delves into the potential risks and benefits of caffeine consumption, focusing on cardiovascular health, bone health, mental health, and reproductive issues. Special attention is given to individual variations in caffeine sensitivity, which are influenced by genetics, metabolism, and overall health. In addition to its health impacts, the review addresses coffee production's role in sustainability. Coffee is produced mainly in countries such as Brazil, Vietnam, and Colombia, with Brazil leading global production. Sustainable practices in coffee farming are explored, including their environmental, economic, and social implications. The review highlights the importance of integrating sustainable methods to mitigate negative effects such as deforestation, soil erosion, and water contamination. Overall, this review aims to provide a comprehensive understanding of caffeine and coffee's multifaceted effects on human health and sustainability, equipping consumers, healthcare providers, and policymakers with knowledge for informed decision-making.

Keywords: Coffee, health, physiological effects, psychological impacts, sleep, sustainability

1. Introduction

The coffee plant, belonging to the *Rubiaceae* family and *Coffea* genus, typically grows as a woody perennial tree in higher altitude regions. There are over 100 species of *Coffea*, but only a few are widely known and cultivated. These species vary in taste, appearance, and caffeine content. The most prominent among them are *Coffea arabica* (Arabica coffee) and *Coffea canephora* (Robusta coffee). *Arabica* is preferred by consumers and accounts for 75–80% of global production, while *Robusta* captures the remaining 20% market share. *Robusta* coffee produces a less desirable taste with higher caffeine content compared to *Arabica* (Rahman, et al., 2024). In addition to Arabica and Robusta, several other *Coffea*

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species contribute to the diversity of coffee. *Coffea liberica* is recognized for its large beans and distinctive, fruity flavor. *Coffea excelsa*, often considered a variant of Liberica, is known for its tart, fruity taste. *Coffea stenophylla* can thrive in warmer climates and has a flavor profile similar to Arabica. *Coffea benghalensis* is a lesser-known species with limited cultivation, while *Coffea racemosa*, native to Mozambique, produces a milder coffee with low caffeine content. *Coffea mauritiana*, grown in the Mascarene Islands, is rare in commercial production. *Coffea eugenioides*, one of Arabica's parent species, is noted for its delicate flavor and very low caffeine levels. Lastly, *Coffea charrieriana*, native to Central Africa, is a unique caffeine-free coffee species.

Natural sources of caffeine include the Coffea plant, tea leaves, cacao beans, and certain nuts. Caffeine is a commonly used drug (Roberts, 2021). Specifically, coffee beans are known for having a high caffeine content and are used to manufacture the widely consumed beverage (Clifford, 2012). Caffeine is produced and added to a variety of foods, beverages, and medications in addition to its natural sources. It's easily accessible to customers as it may be found in a variety of items, including chocolate bars and energy drinks. Caffeine is a topic of interest in the domains of medicine, nutrition, and psychology because of its constant effects on the body and mind (McCook, 2024; Antonio et al., 2024).

Brazil, Vietnam, Indonesia, Colombia, Ethiopia, Uganda, India, Honduras, Mexico, and Peru rank as the top ten coffee-producing countries. At the forefront is Brazil, which produces an astonishing 4,131,600 tons of coffee each year (Figure 1). With an annual production of 1,963,500 tons of coffee, Vietnam comes in second. Indonesia is at third place with 782,100 tons annually, followed by Colombia, which produces 745,800 tons per annum. Ethiopia is the fifth-largest coffee-producing country producing 545,820 tons. Uganda and India also demonstrate significant coffee production output with 433,290 tons and 430,320 tons annually, respectively. Rounding off the top ten are Hondura, Mexico, and Peru, contributing 356,400 tons, 269,874 tons, and 239,250 tons to global coffee production each year, respectively (Maletic, 2023).

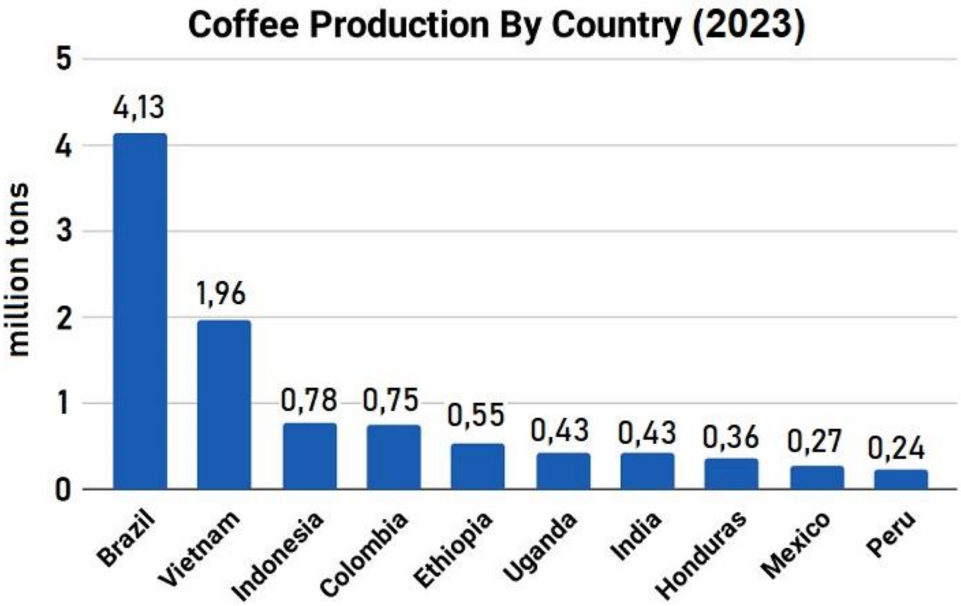

Figure 1. Countries with highest coffee production (Maletic, 2023)

Roasted coffee beans are used to make the famous beverage coffee. Caffeine is one of its selling points. Studies on coffee's health impacts mostly focus on observations since it contains a wide variety of compounds. Concerns over coffee's potential health effects were previously inspired by smoking and sedentary lifestyles. However, recent research indicates coffee may reduce the chance of developing various illnesses. However, specialists and the general public find it difficult to comprehend its health impacts due to contradictory data (Herawati et al., 2024).

Anxiety, sleeplessness, jitters, and hypertension can all be brought on by caffeine. As a diuretic, caffeine causes more urine. Since caffeine can aid with headaches, it is often used as a component in both prescription and over-the-counter pain medicines, generally together with aspirin or another analgesic (Cho et al., 2024). These days, energy drinks are a growing problem significance of caffeine and mental performance, coronary heart disease, cardiovascular effects of antidepressants in children and adolescents, and bone gain in children and adolescents (Mihaiescu et al., 2024). Thus, the World Health Organization, and some health care professionals recognize caffeine dependence as a clinical disorder.

This review will also explore the association between caffeine and common health issues such as cardiovascular problems, bone health concerns, and mental disorders. In addition to outlining these risks, we will offer practical guidelines for safe caffeine consumption, emphasizing the importance of moderation and self-awareness. Our goal is to equip consumers, healthcare providers, and policymakers with the knowledge necessary to make informed decisions about caffeine use, thereby enhancing overall well-being. We will also discuss the relationship between coffee production, consumption, and sustainability, as this is crucial given the significant global scale of coffee production.

Common risks and side effects of caffeine consumption include elevated heart rate and palpitations, anxiety and restlessness, insomnia and sleep disturbances, gastrointestinal discomfort, headaches, dependency and withdrawal, heightened blood pressure, interaction with medications, potential pregnancy complications, and effects on bone health.

The common coffee varieties, along with their key characteristics, are summarized (Barreto Peixoto et al., 2023; Butt & Sultan, 2011; Cano-Marquina et al., 2013; Farah, 2012; Freitas et al., 2024; Kolb et al., 2020; Ranheim & Halvorsen, 2005) below:

Arabica coffee, originating from Ethiopia, is widely known for its smooth and mild flavor, which is often accompanied by lower caffeine content and higher acidity. Common varieties of Arabica include Typica, Bourbon, and Caturra. While Arabica offers a rich and nuanced flavor profile, it may cause acidity and stomach discomfort in some individuals due to its higher acidity. However, its lower caffeine content makes it a preferred choice for those seeking a less intense caffeine intake. The recommended daily intake of Arabica coffee is 1-3 cups, which typically contains 150-300 mg of caffeine. Common side effects of excessive consumption include insomnia, jitteriness, and an increased heart rate.

Robusta coffee, which hails from Central and West Africa, is known for its strong, bold flavor, characterized by a higher caffeine content and lower acidity compared to Arabica. Robusta is commonly cultivated for its robustness and cost-effectiveness. However, its harsher taste and bitter aftertaste make it less popular among some coffee drinkers. Despite this, the higher caffeine content is an advantage for those looking for a stronger stimulant effect, and it is often more affordable. The recommended daily intake for Robusta coffee is 1-2 cups, providing 200-400 mg of caffeine. Side effects may include increased blood pressure and digestive issues.

Liberica coffee, originating from West Africa, is recognized for its unique fruity and floral notes, as well as its larger bean size compared to other coffee types. Despite its distinctive flavor, Liberica is less widely cultivated and harder to find on the global market, which limits its availability. The larger beans and distinctive taste profile make it a favorite among coffee enthusiasts who seek something different from the usual options. The recommended daily intake is 1-2 cups, typically containing 150-300 mg of caffeine. Some side effects associated with Liberica coffee include gastrointestinal discomfort and potential allergic reactions.

Excelsa coffee, cultivated in West Africa and Southeast Asia, is prized for its distinctive fruity and tart flavor, coupled with large beans. Though less common than both Arabica and Robusta, Excelsa offers a unique taste experience, making it an appealing option for coffee aficionados who want to explore beyond mainstream varieties. However, its rarity limits its market presence. The recommended daily intake is 1-3 cups, providing 150-300 mg of caffeine. Side effects from Excelsa coffee may include heartburn, acid reflux, and potential sleep disturbances due to its stimulating properties.

Coffee can be prepared in various ways, including drip brewing, espresso brewing, French press, and cold brew methods. The taste, strength, and aroma of coffee can vary depending on factors such as the type of coffee beans, the roast level, and the brewing technique used (de Figueiredo Tavares & Mourad, 2020).

2. Caffeine's Physiological Impacts

Caffeine, a stimulant naturally present in coffee and other plants such as tea leaves, cacao beans, and kola nuts, exerts significant effects on the body by blocking adenosine, a neurotransmitter that promotes sleep and relaxation. This leads to increased alertness, improved focus, and heightened mood, primarily through the release of neurotransmitters like dopamine and norepinephrine (Weckerle et al., 2010; Czchowski et al., 2024). The stimulant effect of caffeine temporarily raises heart rate and blood pressure, and moderate intake is linked to enhanced cognitive performance and physical alertness. Coffee, as one of the primary sources of caffeine, is not only appreciated for its stimulating effects but also for other bioactive compounds like chlorogenic acids and antioxidants, which may contribute to various health benefits (Czchowski et al., 2024).

However, caffeine consumption is often confused with coffee's broader effects due to the multitude of other compounds present in coffee that may also affect health (Munyendo et al., 2024). For instance, while caffeine is known to suppress adenosine's influence on the brain even at low doses (Dranoff, 2024), coffee contains several micronutrients, including magnesium, potassium, niacin, and vitamin E, which might offer additional health advantages (Monib et al., 2023; Pérez et al., 2020). The combined effects of these compounds make it challenging to isolate caffeine's impact from coffee's overall influence.

Caffeine rapidly enters the bloodstream when consumed, affecting the central nervous system by increasing the turnover of neurotransmitters like monoamines and acetylcholine (Ribeiro & Sebastiao, 2010; Huang et al., 2024). This contributes to its ability to keep individuals awake and alert but can also interfere with the quality of sleep, especially when consumed later in the day. Mistimed caffeine consumption, such as having coffee or caffeine-containing drinks in the evening, can disrupt the circadian rhythm by delaying the sleep cycle, contributing to widespread sleep issues in society (Lorist & Snel, 2008).

Moreover, while moderate caffeine consumption is generally safe and even beneficial for most adults—typically between 200-400 milligrams per day or around 2-4 cups of coffee—excessive intake can lead to negative side effects. These include jitteriness, anxiety, increased heart rate, and gastrointestinal issues like acid reflux (Tearney, 2024; Gaspar et al., 2024). Caffeine's diuretic effects can also promote dehydration if fluids are not replenished, making it essential to stay hydrated throughout the day. Furthermore, those with specific health concerns, such as anxiety disorders, heart problems, insomnia, or gastroesophageal reflux disease (GERD), may need to limit or avoid caffeine entirely and should consult with healthcare providers to adjust their intake accordingly.

It is important to note that caffeine is only one of several bioactive compounds capable of affecting the body, similar to how capsaicin in hot peppers can cause a burning sensation (Tearney, 2024). Therefore, while caffeine in moderation can offer cognitive and physical performance benefits, overconsumption, particularly through energy drinks or caffeine supplements that often contain excessive amounts of caffeine and other additives, poses health risks. Additionally, caffeine's potential health benefits may be negated by the consumption of sugary or artificially sweetened caffeinated beverages, which can increase calorie intake and contribute to adverse health outcomes.

For optimal health and well-being, it is crucial to manage caffeine consumption carefully. Choosing healthier sources of caffeine, such as coffee or tea, and avoiding excessive intake of sugary energy drinks can help balance caffeine's stimulating effects with its potential risks. Additionally, being mindful of individual caffeine sensitivity and consuming it at appropriate times of the day can minimize sleep disruption and support overall health (Gaspar et al., 2024).

2.1. Impact on central nervous system

Caffeine has appeared to be associated with a higher overall arousal level, better processing of attended, and unattended information, and more rapid motor processes (Wang et al., 2024). Clinical studies show that caffeine boosts alertness and reduces drowsiness by stimulating the central nervous system, it does this by blocking adenosine, a chemical that makes us feel sleepy. Caffeine can increase the release of dopamine and norepinephrine, further enhancing alertness and cognitive function (Yu, 2024). These findings have important implications for productivity, cognitive abilities, and managing sleep-related issues, these studies confirm that caffeine is a popular and effective way to stay awake and alert, there is a growing body of evidence that caffeine has a significant effect on the sleep wake cycle and on circadian rhythm.

2.2. Impact on heart and lungs

Studies on the effects of coffee and caffeine on the heart and lungs have been conducted. Moderate coffee consumption, containing caffeine, might have heart benefits like better blood vessel function and lower heart disease risk, but too much caffeine, especially from energy drinks or supplements, can increase heart rate, blood pressure, and risk of irregular heartbeats. Caffeine can also briefly narrow blood vessels, affecting blood flow to the heart. For the lungs, caffeine acts as a bronchodilator, helping with asthma symptoms and improving breathing. But excessive caffeine intake can worsen breathing problems, especially for those with existing conditions, while some coffee and caffeine may be good for the heart and lungs in moderation, it's important not to overdo it to avoid possible problems (Lin et al., 2024).

Caffeine induces various Cardiovascular, and respiratory effects. Arterial stiffness, and endothelium dependent vasodilatation also result, leading to increases in systolic and diastolic blood pressure. An increase in the respiration rate is the prime effect dependent on the plasma caffeine value (Cho et al., 2024). High doses of caffeine could potentially exacerbate cardiac conditions for which stimulants are contraindicated, including ion channelopathies and hypertrophic cardiomyopathy in children, and young adults, due to the risk of hypertension, syncope, arrhythmias, and sudden death (Reddy et al., 2024).

2.3. Cancer risk

Research on coffee's effects on cancer is mixed. Some studies suggest that moderate coffee drinking might lower the risk of certain cancers like liver and colorectal cancer, possibly due to antioxidants in coffee, high coffee intake could potentially raise the risk of some cancers, such as bladder cancer (Thabit et al., 2024). Many epidemiological studies have explored the link between coffee or caffeine intake and cancer risk, there's scant evidence to suggest that drinking coffee increases cancer risk, particularly when accounting for smoking habits (Nkondjock et al., 2006). While early studies hinted at connections between caffeine intake and cancers like pancreatic, bladder, and ovarian, newer and more robust research hasn't backed up these claims, drinking a hot coffee might increase the risk of esophageal cancer, while moderate coffee drinking may have some benefits for certain cancers, more research is needed, and other factors like genetics and lifestyle also play a role, it's important to maintain a balanced diet and lifestyle to lower overall cancer risk (Taborska et al., 2024).

Most of the research on possible links between cancer and caffeine has been conducted on coffee, and tea. Consequently, research on caffeine and its effects on cancer, if any, is sparse (Shan et al., 2024). There are however, references in coffee, and tea research relating to caffeine that are generally positive. Caffeine has not been shown in animal or human studies to be carcinogenic (Tamura et al., 2018). WHO IARC (1991) concluded in his review of the research that caffeine is unlikely to be a human carcinogen at levels below cups of coffee per day, or less than 500 mg caffeine per day, the evidence indicates that caffeine, as present in coffee does not cause breast or bowel cancer, although early case control studies appeared to link caffeine intake to pancreatic, bladder, and ovarian cancers, more recent, better designed studies have not supported these conclusions, a number of case control studies have demonstrated reduced risk of colorectal cancer with coffee consumption.

Studies have shown mixed results regarding the relationship between coffee consumption and the risk of colon cancer (Oyelere et al., 2024). Case-control studies suggest a lower risk of colon cancer with higher coffee intake, while prospective cohort studies don't show the same association, this could be due to biases in case-control studies regarding recalling coffee consumption and selecting control groups (Li et al., 2013). Recent reviews found similar patterns, with case-control studies suggesting a link between coffee and lower colon cancer risk, but prospective cohort studies not showing the same association. Interestingly, large cohort studies found a lower risk of rectal cancer among those who drank decaffeinated coffee regularly, but no association was found with caffeinated coffee, tea, or caffeine intake (Taborska et al., 2024), coffee consumption didn't show a consistent association with the risk of colorectal adenoma or recurrent adenomas over time in case-control studies (Dominianni, 2016).

2.4. Caffeine's Impact on the Reproductive System

Research on caffeine and coffee's impact on the reproductive system has varied results. Moderate caffeine intake, like that from coffee, may not harm fertility or reproductive health in most individuals (Adelakun et al., 2024). However, excessive caffeine especially in women could increase the risk of miscarriage and affect fertility, some studies indicate high caffeine intake might lower sperm quality and male fertility, caffeine could influence hormone levels, which might affect reproductive health (Raoofi et al., 2024). While moderate caffeine and coffee consumption may not greatly affect most people's reproductive function, it is crucial to watch intake, especially for those trying to conceive or with fertility concerns (Pollard & Claassens, 1992).

Conducted a very systematic review on the relationship between caffeine consumption by both pregnant women, and women of child-bearing age, and the occurrence of congenital malformations, fetal growth retardation, small- for-date babies, miscarriages, behavioral effects, maternal infertility and genetic effects (Alquaiz et al., 2013). The only statistically significant results were teratogenic (birth defect) effects in rats administered extremely high levels of caffeine intravenously, which do not necessarily translate to humans, and also could never be attained merely by drinking beverages containing caffeine (Raoofi et al., 2024). Consulting a healthcare provider for personalized advice is recommended.

2.5. Caffeine's Effects on the Gastrointestinal and Urinary Systems

Coffee and caffeine affect the stomach and bladder. Coffee, containing caffeine, can increase stomach acid, causing heartburn in some people. It can also make some people need to use the bathroom more often due to increased bowel movements (Searle, 2024). However, drinking coffee has been linked to a lower risk of certain stomach and liver issues, caffeine's diuretic effect can lead to more frequent urination, but regular coffee drinkers often become tolerant to this, while coffee and caffeine can have both good and bad effects on the stomach and bladder, it's important to use them in moderation to avoid problems (Bird et al., 2005). Caffeine excites the small intestine, causing secretion of water, and sodium. Caffeine has been seen to promote apoptosis in, and even serves as a psychoactive drug in the treatment of Parkinson's disease, with its potential utilization in medicine, the safety, and effects of caffeine are important issues (Mohamed, 2024).

2.6. Caffeine's Impact on Physical Performance

The influence of caffeine on physical performance is well-documented with numerous studies showing its potential benefits for athletes and active individuals (Szerej et al., 2024). Caffeine acts as a stimulant affecting both the central nervous system and the muscular system (Pakosz et al., 2024). By blocking adenosine receptors in the brain, caffeine can reduce perceived effort and fatigue allowing individuals to exercise for longer periods with increased intensity. Caffeine has been shown to enhance muscle contraction and strength leading to improved performance in activities such as weightlifting and sprinting (Davis & Green, 2009). Caffeine can increase the mobilization and utilization of fat stores, thereby sparing glycogen and delaying the onset of fatigue during endurance exercise (Graham, 2001). The ergogenic effects of caffeine are dose-dependent, with optimal doses typically ranging from 3 to 6 milligrams per kilogram of body weight (Searle, 2024). However, individual responses to caffeine can vary, and some individuals may experience side effects such as jitteriness, increased heart rate, or gastrointestinal discomfort, caffeine is widely recognized as a safe and effective ergogenic aid for improving physical performance in a variety of athletic endeavors (Brice & Smith, 2002).

3. Caffeine's Psychological Impacts

The psychological effects of caffeine encompass a range of influences on mood, cognition, and behavior (Reich et al., 2024), caffeine as a central nervous system stimulant, can enhance alertness, concentration, and cognitive function, making individuals feel more awake and focused. Many people rely on caffeine to combat feelings of fatigue and improve productivity, caffeine consumption has been associated with mood enhancement, leading to feelings of well-being and reduced perception of effort (Domínguez et al., 2021). However, excessive caffeine intake can also induce feelings of jitteriness, anxiety, and restlessness, particularly in sensitive individuals, caffeine can disrupt sleep patterns, leading to difficulties in falling asleep or staying asleep, which can further impact mood and cognitive function, while moderate caffeine consumption can have positive psychological effects, it's important to be mindful of individual tolerance levels and potential negative outcomes associated with excessive intake (Valero et al., 2024).

4. Variations in Caffeine Sensitivity: Influences and Implications

Individual differences in caffeine sensitivity refer to variations in how people respond to caffeine based on factors such as genetics, age, weight, metabolism, and overall health (Penolazzi et al., 2012). Some individuals may be more sensitive to caffeine and experience stronger effects even with small amounts, while others may require higher doses to feel its effects. Some are more sensitive and feel its effects strongly, while others need more to feel anything. Pregnant women, people with health issues, and those on medications need to be extra careful with caffeine. It's essential to know your limits and how caffeine affects you personally to stay safe and get the benefits without the drawbacks (Caplan, 2024). Genetic factors play a significant role in determining caffeine sensitivity, with certain genetic variations influencing how caffeine is metabolized in the body (Yokomukai et al., 1993). Age can also affect caffeine sensitivity, with younger individuals typically being more sensitive than older adults due to differences in metabolism and liver function (Clark & Landolt, 2017). Body weight and metabolism can also influence caffeine sensitivity, as caffeine is distributed differently in the body based on these factors, overall health and medical conditions can impact caffeine sensitivity, with certain conditions such as anxiety disorders or gastroesophageal reflux disease (GERD) making individuals more susceptible to the negative effects of caffeine (Özenoğlu et al., 2023), caffeine metabolism is slower among infants, pregnant women, and individuals with liver disease (dePaula & Farah, 2019).

Understanding individual differences in caffeine sensitivity is important for optimizing caffeine consumption and minimizing potential adverse effects.

5. Benefits and Drawbacks of Caffeine for the Human Body

5.1. Benefits

Caffeine and coffee provide numerous potential benefits to the human body (Kumar et al., 2018). Caffeine's stimulating effect on the central nervous system increases alertness and improves cognitive function, enhancing concentration and mental clarity (Glade, 2010), caffeine can boost physical performance by increasing adrenaline levels, making it a popular choice for athletes and those engaging in strenuous activities (Nehlig & Debry, 1994). Coffee rich in antioxidants, offers protection against oxidative stress, reducing the risk of chronic diseases such as heart disease and certain cancers (Ribeiro et al., 2024). Furthermore regular coffee consumption has been associated with a lower risk of neurodegenerative diseases like Parkinson's and Alzheimer's (Ng et al., 2024). Caffeine's ability to boost metabolism and increase fat burning makes it a potential aid in weight loss efforts (Gravely, 2024). Moderate coffee intake has also been linked to improved liver health and mood enhancement, while some research suggests it may reduce the risk of stroke (Wachamo, 2017; Nehlig, 2016).

Besides the mental and physical performance benefits of caffeine several areas are emerging in which consumption of caffeine could be beneficial to health, some studies investigate pure caffeine, while the others not pointing out the other components in coffee and their potential confounding effects (Reddy et al., 2024). Caffeine levels observed to have beneficial effects for some conditions could have adverse effects for other health conditions, and individuals should consult a physician about safe caffeine intake levels when faced with multiple health concerns, despite these limitations, extensive explorations of caffeine have been carried out, and have provided a great deal of information regarding the effects of caffeine (Mihaiescu et al., 2024). Caffeine consumption has also been associated with positive effects on the brain. Last three years a study from the Harvard School of Public Health suggested that drinking between two, and four cups of coffee a day may reduce suicide risk in adults, while more recent research found that ingesting 200 mg of caffeine each day may boost long term memory (Lucas et al., 2014)

5.2. Drawbacks

Coffee and caffeine can have downsides too despite their benefits. Having too much caffeine whether from coffee or other sources can cause problems like feeling jittery, anxious, getting headaches, or having trouble sleeping (Mushtaq, 2024), It can also make heart issues worse, raise blood pressure, and cause irregular heartbeats especially in people with heart conditions. Pregnant women should be careful too, as too much caffeine can raise the risk of miscarriage and affect the baby's development (Ramalakshmi & Raghavan, 1999). Drinking lots of caffeine regularly can make your body used to it needing more for the same effects, and you might feel tired and irritable if you suddenly cut back (Thayer, 1996). Some people like those with anxiety, trouble sleeping, or stomach issues, might be more sensitive to caffeine's negative effects.

Caffeine could have detrimental effects on a hypertensive that is stressed, and consumes caffeine as ultimately caffeine is a stimulant, and as with as all stimulants and substance's abuse or overuse has negative effects (Cappelletti et al., 2015), heavy daily caffeine use more than 500 to 600 mg a day may cause side effects such as; insomnia, nervousness, restlessness, irritability, stomach upset, fast heartbeat, muscle tremors (Atemni et al., 2022). Adverse health effects of caffeine intake in specific population group's relevant population groups are: breast-fed infants consuming caffeine via mother's milk, children possibly divided by age group, pregnant women, Lactating women, adults, and adolescents, adults, and adolescents performing endurance exercise (Nawrot et al., 2003), while moderate coffee and caffeine intake can be healthy for most people, it's crucial to watch how much you have and be aware of potential problems (Caton et al., 2012).

5.3. Caffeine's Impact on Sleep

The effects of caffeine on sleep can be significant (Clark & Landolt, 2017). As a stimulant, caffeine can interfere with the body's natural sleep-wake cycle (Weinberg, 2024). Consuming caffeine especially in large amounts or later in the day can make it difficult to fall asleep and may reduce sleep quality (Snel & Lorist, 2011). Caffeine blocks the action of adenosine (Trujillo-Colmena et al., 2024), a neurotransmitter that promotes sleepiness, leading to increased alertness and wakefulness (Huang et al., 2024), caffeine can delay the onset of sleep and reduce total sleep time, leading to feelings of restlessness and sleep fragmentation (Reddy et al., 2024). Even moderate caffeine intake particularly within several hours of bedtime can disrupt sleep patterns and contribute to insomnia (Lewis, 2024). Individuals vary in their sensitivity to caffeine's sleep-disrupting effects with some people being more affected than others (Curtis et al., 2024), it's advisable to limit caffeine consumption especially in the afternoon and evening to promote better sleep quality and overall well-being.

The effects of energy drink use among adolescents and children have raised concerns in recent years (Ajibo et al., 2024), these beverages typically contain high levels of caffeine, along with other stimulants and sugar. Excessive consumption of energy drinks by adolescents and children has been linked to various adverse effects; including increased heart rate and blood pressure, disrupted sleep patterns, anxiety, and dehydration, the high caffeine content in these drinks can negatively impact developing brains and bodies, leading to impaired cognitive function and behavior problems, the combination of caffeine and other ingredients in energy drinks may pose risks for cardiovascular health, particularly in individuals with underlying heart conditions (Żuber et al., 2024; Al-Shaar et al., 2017; Ali et al., 2015; Oddy & O'Sullivan, 2009). Furthermore, frequent consumption of energy drinks has been associated with a higher likelihood of engaging in risky behaviors such as alcohol and substance abuse, the potential risks, it's important for parents, caregivers, and healthcare professionals to educate adolescents and children about the potential dangers of energy drink consumption and to encourage healthier beverage choices.

Children and adolescents with eating disorders, especially anorexia nervosa, may regularly consume high amounts of caffeine to counter caloric restriction–associated fatigue, suppress appetite, and produce looser stools and some diuresis. Given that children and adolescents with eating disorders have a propensity for cardiac morbidity/mortality and electrolyte disorders, consumption of high-caffeine energy drinks may put them at further risk for cardiac dysrhythmias and intracardiac conduction abnormalities. (Seifert et al., 2011).

6. Relation with Sustainability

The relationship between coffee production and sustainable development is intricate and involves several key dimensions: environmental, economic, social, and quality-related impacts. Here's a detailed exploration:

6.1. Environmental Impact

Deforestation and Habitat Loss: Traditional coffee farming practices, especially in tropical regions, often involve clearing forests to create coffee plantations. This deforestation leads to habitat loss for numerous species and contributes to biodiversity decline. Sustainable coffee practices, such as shade-grown coffee, aim to preserve existing forest cover by growing coffee under the canopy of trees. This approach helps maintain habitat diversity and contributes to ecosystem stability.

Soil Erosion and Water Use: Coffee cultivation can lead to significant soil erosion, especially on steep slopes, which depletes the soil of vital nutrients. Sustainable practices like agroforestry and contour planting help reduce soil erosion and maintain soil health. Additionally, coffee farming can be water-intensive, affecting local water resources. Sustainable irrigation techniques, such as drip irrigation and rainwater harvesting, aim to reduce water consumption and improve water efficiency in coffee production.

Pesticide and Fertilizer Use: The use of synthetic pesticides and fertilizers in conventional coffee farming can lead to soil and water contamination. Sustainable practices often involve organic farming methods that avoid synthetic chemicals and use natural alternatives. This approach helps protect water quality and soil health while reducing the environmental footprint of coffee production.

6.2. Economic Development

Fair Trade and Livelihoods: Fair Trade certification and other sustainable practices ensure that coffee farmers receive fair prices for their products. This can improve their livelihoods by providing a stable income and better working conditions. Fair Trade initiatives also often support community development projects, such as building schools and healthcare facilities, which contribute to overall economic development in coffee-growing regions.

Market Access and Stability: Sustainable coffee production often involves certification programs that help farmers access global markets. Certifications like Rainforest Alliance, Organic, and Fair Trade provide consumers with assurance of sustainable practices and open new market opportunities for farmers. This market access can help stabilize incomes and reduce economic vulnerability for smallholder farmers.

6.3. Social Impact

Worker Rights and Community Well-being: Sustainable coffee practices place a strong emphasis on improving working conditions and ensuring fair labor practices. This includes fair wages, safe working environments, and access to basic services such as healthcare and education. These improvements contribute to the overall well-being of coffee-growing communities and foster social equity.

Empowerment and Inclusivity: Sustainable coffee programs often focus on empowering women and marginalized groups within coffee-growing communities. Initiatives aimed at supporting women farmers, for example, can lead to greater gender equality and enhance the social fabric of communities. This inclusivity helps build stronger and more resilient communities.

6.4. Quality and Innovation

Improved Quality: Sustainable coffee production methods often lead to improved coffee quality. Practices such as selective harvesting, proper processing, and organic farming can enhance the flavor and quality of coffee beans. Consumers are increasingly seeking high-quality, sustainably produced coffee, which drives demand for better farming practices.

Innovation in Production: Sustainable development encourages innovation in coffee cultivation and processing methods. This includes developing new coffee varieties that are more resilient to pests and climate change, as well as adopting more efficient processing techniques that reduce waste and energy use. Innovation in these areas can lead to more sustainable and efficient coffee production.

6.5. Climate Change

Mitigation and Adaptation: Coffee production is highly sensitive to climate change, with shifts in temperature and rainfall affecting coffee yields and quality. Sustainable practices aim to mitigate these impacts through climate-smart agriculture. This includes planting climate-resilient coffee varieties, improving soil carbon storage through agroforestry, and adopting water-conservation techniques. By adapting to climate change, coffee farmers can maintain productivity and sustainability in the face of environmental challenges.

In conclusion, integrating sustainable practices into coffee production supports environmental protection, economic stability, social equity, and product quality. These efforts align with the broader goals of sustainable development by fostering a more resilient and equitable coffee industry while minimizing negative impacts on the environment and local communities.

7. Conclusion

Coffee has a significant impact on both the body and mind by enhancing alertness and cognitive function through its effects on the central nervous and cardiovascular systems. In moderate amounts, it can also elevate mood and alleviate mild depression. However, careful management of caffeine intake is important to prevent disruptions in sleep patterns. Understanding individual tolerance and the optimal dosage is key to maximizing its benefits while minimizing risks.

Research suggests that caffeine may lower the risk of several chronic diseases and does not significantly increase the likelihood of coronary heart disease, stroke, cancer, or many women's health issues. In contrast, energy drinks, despite being marketed as nutritional supplements, offer minimal therapeutic benefits and can pose serious health risks, particularly to children, due to high levels of caffeine and taurine.

While moderate caffeine consumption can improve alertness, cognition, and physical performance, excessive intake can lead to anxiety, sleep disturbances, and heart problems. It is essential to use caffeine in moderation and be mindful of individual tolerance levels. Our recommendations are designed to help individuals make informed decisions about caffeine intake to promote overall well-being and avoid potential health risks. Further research is needed to fully understand caffeine's broad effects and potential health benefits.

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9

Kemik Doku Üretimi İçin Biyoyazıcılarda Kullanılan Malzemeler

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Özet

Geleneksel 3B yazıcılardan farklı olarak, hastaların yaşam beklentilerini iyileştirmek amacıyla kullanılan biyoyazıcılar ile hastaya göre kişiselleştirilmiş doku ve organ üretme fikri, son yıllarda giderek artan bir eğilim göstermiştir. Az miktarda bir hasar gördüğünde kendisini yenileyip onarabilme yeteneğine sahip olan kemik dokusunun, büyük kemik defektlerini onarmak için yetersiz kalması ve tedavide kullanılan geleneksel metal implantların birçok dezavantajının bulunması, 3B biyobaskı ile birlikte doğal kemik dokusu üretme fikrini ortaya çıkarmıştır. Biyoyazıcıları diğer yazıcılardan farklı kılan en büyük özellik baskı maddesi olarak biyomürekkep kullanmasıdır. Mürekkep tüplerinin içine doldurulan biyomürekkebin içeriğini canlı insan hücreleri ve çeşitli biyomalzemeler oluşturmaktadır. 3B biyobaskı teknolojisi, hücre yüklü biyomürekkep ile birlikte hücrelerin eşit şekilde dağılımına, sinyal faktörlerinin düzenli salınımına ve karmaşık ve çeşitli geometrilere sahip gözenekli kemik iskelesinin üretilmesine imkân sağlamaktadır. Biyomürekkep ile üretilmiş kemik dokusunun, doğal kemik yapısına benzer, hücre dışı matrisin özelliklerini taklit eden ve hücresel aktiviteyi destekleyen, yeterli mekanik dayanıklılığa sahip, iyi derecede biyouyumlu, biyolojik bozunmaya ve artan yeni doku oluşum hızına sahip bir yapıda olması gerekmektedir. Bununla birlikte, ideal bir biyomürekkebin biyolojik, fiziksel ve mekanik özellikleri, üretilen kemik dokusunun morfolojik yapısını ve dayanıklılığını, yüzey alanı ve yüzey özelliğini, basılabilirliğini, doku canlılığını, doku iyileşmesini, bozunma süresini, hücre büyümesi veya farklılaşması gibi durumlarını etkilemektedir. 3B biyobaskı teknolojisinde kullanılmak üzere seramiklerin, doğal ve sentetik polimerlerin, hidrojellerin ve bunların kompozitleri de dâhil olmak üzere çeşitli biyomalzeme türlerinin biyomürekkep içeriğine dâhil edilmesi, iskele mimarisi ve rejeneratif tıp yaklaşımı açısından kemik doku mühendisliği araştırmalarında umut vaat etmektedir. Tüm bu gereksinimler ışığında, bu çalışma ile birlikte, 3B biyobaskı teknolojisiyle birlikte kemik doku mühendisliğinde kullanılma potansiyeli olan biyomalzemeler ve biyomürekkepler hakkında okuyucuya bilgi verilmesi amaçlanmıştır.

Anahtar Kelimeler: Biyoyazıcı, biyomürekkep, kemik doku mühendisliği, kemik dokusu rejenerasyonu.

Abstract

Unlike traditional 3D printers, the idea of producing personalized tissues and organs with bioprinters used to improve the life expectancy of patients has shown an increasing trend in recent years. The fact

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that bone tissue, which has the ability to regenerate and repair itself when it is slightly damaged, is insufficient to repair large bone defects and that traditional metal implants used in treatment have many disadvantages has led to the idea of producing natural bone tissue with 3D bioprinting. The biggest feature that makes bioprinters different from other printers is the use of bioink as a printing medium. The content of the bioink, which is filled into the ink tubes, consists of living human cells and various biomaterials. 3D bioprinting technology, together with the cell-laden bioink, allows for the even distribution of cells, the regular release of signaling factors and the production of porous bone scaffolds with complex and varied geometries. Bone tissue produced with bioink should be similar to natural bone structure, mimic the properties of the extracellular matrix and support cellular activity, have sufficient mechanical strength, good biocompatibility, biodegradability and increased rate of new tissue formation. However, the biological, physical and mechanical properties of an ideal bioink affect the morphological structure and durability, surface area and surface property, printability, tissue viability, tissue healing, degradation time, cell growth or differentiation of the produced bone tissue. Incorporation of various types of biomaterials including ceramics, natural and synthetic polymers, hydrogels and their composites into bioink content for use in 3D bioprinting technology holds promise in bone tissue engineering research in terms of scaffold architecture and regenerative medicine approach. In the light of all these requirements, this study aims to inform the reader about biomaterials and bioinks that have the potential to be used in bone tissue engineering with 3D bioprinting technology.

Keywords: Bioprinter, bioink, bone tissue engineering, bone tissue regeneration

1. Giriş

Kemik**,** iç organları koruma, kırmızı ve beyaz kan hücrelerini üretme, mineralleri depolama ve hareket yeteneği sağlama gibi özelliklerinin yanı sıra vücuda yapısal destek veren doğal, karmaşık ve canlı bir bağ dokusudur (Alavi vd., 2023; Sheikh vd., 2015) . Kemiği oluşturan ve osteoblast olarak bilinen kemik hücreleri, temel olarak hidroksiapatit (HA) içeren bir inorganik faz ve tip I kolajen içeren organik bir faz olan hücre dışı matris (Extracellular matrix-ECM) ile çevrilidir. ECM'nin temel görevi ise mekanik destek, mineralizasyon, kemik oluşumu, kemik onarımı ve homeostaziyi sağlamaktır (Alavi vd., 2023).

Kemik dokusu, az miktarda bir hasar gördüğünde kendisini yenileyip onarabilme yeteneğine sahip olmasına rağmen, travma, osteoporoz, kanser, doğumsal bozukluklar gibi kişinin yaşam kalitesini önemli ölçüde etkileyen büyük kusurları onarmakta yetersiz kalmaktadır ve bu gibi durumlarda klinik müdahale gerekmektedir (Alavi vd., 2023; Büyük vd., 2023). Bu tür büyük ölçekte oluşan kemik defektlerini onarmak için günümüzde otogreft, allogreft ve ksenogreft uygulamaları gerçekleştirilse de donör eksikliği, genetik farklılık, enfeksiyon, doku reddi vb. riskler nedeniyle sınırlamalar mevcuttur (Salehi vd., 2022). Tam bu noktada, doku mühendisliği ve rejeneratif tıp ve onun bir alt çalışma alanı olan kemik doku mühendisliği ve 3B (3 boyutlu) biyoyazdırma, kemik defektlerinin tedavisindeki bu kısıtlamaları gidermek için gelecek vaat eden yeni bilimlerden biri olarak ortaya çıkmıştır (Haleem vd., 2020).

Kemik dokusunun 3B biyoyazıcı ile başarılı bir şekilde taklit edilebilmesi için öncelikle kemik dokusunun anatomisini ve fizyolojisini iyi anlamak gerekmektedir. İnorganik bir yapı olan HA ile organik yapıların %90'ını oluşturan, hücrelerin yapışmasını destekleyen, dokuya sertlik ve esneklik veren kolajen gibi yapılar kemiğe mekanik sertlik ve yük dayanımı sağlamaktadır (İbrahim, 2018). Kemik dokusunun mekanik kuvveti vücudun çeşitli yüklere dayanabilmesi için önemli bir özelliktir, bu nedenle kemik dokusu biyomalzemelerin kusurlu bölgede fizyolojik rolünü üstelenmesini ister. Doku mühendisliği ile kemik iskelesi oluşumu için, biyomalzemenin bozunma süresini kontrol etmek, hücreler için biyouyumlu özellik sağlamak ve matris birikimini mümkün kılmak temel konulardır. Bu nedenle, kemik doku iskelesi üretiminde kullanılacak malzemelerin, biyolojik olarak uyumlu, mekaniksel olarak kemik dokusuna benzer özelliklere sahip olması ve hücre adezyonunu ve çoğalmasını kolaylaştırmak için birbirine bağlı gözeneklerle yapılanması gerekmektedir (İbrahim, 2018; Akguner, 2021). Ayrıca, hasarlı kemik dokusunun yerini alması istenen, rejenerasyon sürecini başlatan ve hızlandıran kemik doku iskeleleri, mühendisler tarafından özel olarak tasarlanmakta ve uygun biyomalzemelerle üretimi gerçekleştirilmektedir (Özel vd.,2021).

2. 3B Biyoyazıcı ve Biyomürekkep

2.1. İskele Yapısı

Doku mühendisliğinin 3B biyobasıma geçiş sürecinde kemik iskelesi üretimi için hücreler, hidrojel ve biyoyazıcılar kullanılmaktadır. Biyomürekkep olarak bilinen bu yazdırılabilir biyomalzemeler, hücre yapışmasını, farklılaşmasını ve çoğalmasını desteklemek için ECM ortamını taklit edebilmektedir ve içeriğinde canlı hücreler bulunduğu için geleneksel eklemeli imalat yöntemlerinde kullanılan biyomalzemelerden farklıdır. Bu nedenle, çok daha düşük sıcaklıklarda baskı işlemi gerçekleşir ve doğal veya sentetik olarak elde edilebilirler. Üretimi gerçekleştirilen 3B şeklin kararlı ve uygulanabilir bir yapısını oluşturmak için bu biyomalzemeler baskıdan sonra çapraz bağlanırlar (Malda vd., 2013; Dey ve Özbolat, 2020).

Genel olarak, kemik doku iskelesinin, hücre beslenmesi, çoğalması, atıkların uzaklaştırılması vb. işlevleri yerine getirmesi için gözenek ağları ile birbirine bağlı yapıda olması esastır (Loh ve Choong, 2013). Bu gözenekli ve birbirine bağlı ağlar, doku vaskülarizasyonu ve yeni dokuların oluşumu için gereklidir (Salerno vd., 2012; Hollister, 2005; Causa vd., 2007). Ayrıca, hücre göçü ve büyüme faktörlerinin dâhil edilmesine uygun bir mikro ortam sağlamak için tutarlı ve yeterli gözenek büyüklüğüne sahip olmalıdır. Gözenekli bir yüzey aynı zamanda iskeleler ile çevre doku arasında mekanik kenetlenmeyi kolaylaştırmaya yardımcı olur ve iskelenin mekanik stabilitesini iyileştirir (Story vd., 1998).

3B biyoyazıcı ile oluşturulan kemik iskelesi, yerine geçeceği defekt dokuya benzer mekanik özelliklere sahip, hücre yapışmasını ve büyümesini teşvik eden, biyouyumlu ve biyobozunur bir yapıda olmalıdır. Biyobozunur yapıda olan iskele, zamanla konakçı hücrelerin, kendi hücre dışı matrisini oluşturması için kolaylaştırıcı bir yapıda olmalıdır (Tan ve Marra, 2010; O'brien, 2011). Şekil 1'de bir iskele tasarımı için gerekli parametreler gösterilmiştir.

Şekil 1. İskele tasarımı için gereksinimlerin şematik gösterimi (Giannitelli vd., 2014)

2.2. Biyomürekkep

Kemik doku iskelelerinde başarılı sonuç elde edebilmek için gerekli olan en büyük etkenlerden biri, hedeflenen dokunun 3B baskısını yerine getirebilmek için uygun biyomürekkebin seçilmesidir. Bu amaçla, farklı biyofonksiyonel mürekkep çeşitleri arasından ideal bir seçim yapabilmek için farklı yöntem ve özellik kriterleri göz önünde bulundurulmalıdır (Gopinathan ve Noh, 2018). Biyofonksiyonel mürekkeplerin seçim kriterleri iskelenin baskı süresini, morfolojik yapısını ve dayanıklılığını, yüzey alanını ve yüzey özelliğini, hücrelerin iskele üzerinde büyüme veya farklılaşma yeteneğini, doku canlılığını, doku iyileşmesini, iskelenin bozunma süresini ve biyouyumluluğunu etkiler (Camacho vd., 2019). Şekil 2'de biyomürekkepler için seçim kriterleri şematize edilmiştir.

Kemik doku mühendisliği uygulamalarında doku iskelesi üretiminde kullanılan biyomalzemeler; polimerik biyomalzemeler, seramik biyomalzemeler ve bunların birleşiminden oluşan kompozit biyomalzemeler olarak sınıflandırılabilir. Polimerik ve seramik biyomalzemelerin bir arada kullanılmasıyla doğal kemik yapısına benzer özellikler gösteren kompozit bir matris elde edilebilir. Biyobozunur özelliğe sahip olan polimerler kemiğin üç boyutlu yapısının elde edilmesini sağlarken, biyoaktif özelliğe sahip olan seramikler kemik yenilenmesini hızlandırır (Akguner, 2021; Mobaraki vd., 2020).

Kemik doku mühendisliği için biyomalzemeler, progenitör hücrelerin osteoblastlara farklılaşmasını (osteoindüktif) ve kemikleşmeyi (osteogenezi) teşvik edebilmeli, çevreleyen kemiğin içe doğru büyümesini (osteokondüktif) desteklemeli ve mevcut kemiğe entegre (osseointegrasyon) olabilmelidir (Stevens vd., 2004). Ayrıca bu biyomalzemeler biyolojik olarak emilebilir olmalı ve vücutta yeni rejenerasyona uğramış biyolojik doku ile değiştirilmelidir (Vacanti ve Langer, 1999). Bu aşamada, biyomalzemenin vaskülarizasyonu destekleme yeteneği de kritiktir (Ibrahim, 2018).

Şekil 2. Biyomürekkep seçim kriterleri (Hospodiuk vd., 2017)

2.2.1. Polimerik Biyofonksiyonel Biyomürekkepler

Doğal ve sentetik olarak iki grupta incelenebilen polimerler, biyouyumlu, düşük maliyetli ve güvenli yazdırılabilir olması sebebiyle kemik doku iskelesi üretiminde sıklıkla kullanılmaktadır ve ECM'in doğal yapısını taklit ederek hücrelere bir ortam sağlayan, büyük miktarda su tutabilen, çapraz bağlı hidrofilik polimerler hidrojeller olarak bilinir. Hidrojellerin su tutabilme yeteneği polimerik ana zincire bağlı hidrofilik fonksiyonel gruplardan kaynaklanırken, çözünmeye karşı dirençleri ise ağ zincirleri arasındaki çapraz bağlardan kaynaklanmaktadır (Hölzl vd., 2016; Jessop vd., 2016). 3B biyoyazıcıda kullanılan doğal polimerler; aljinat, kitin/kitosan ve hyaluronik asit, kolajen, fibrin ve ipek gibi proteinleri içerirken, sentetik polimerler arasında ise poli(glikolik asit) (PGA), poli(laktik asit) (PLA) ve polikaprolakton (PCL) sayılabilmektedir (Akgüner, 2021; Akkuş vd., 2020).

2.2.1.1. Doğal Polimerler

Sentetik polimer bazlı doku iskelelerine göre biyolojik olarak aktif olan ve mükemmel hücre yapışmasını ve büyümesini destekleyen doğal polimerler, biyolojik olarak bozunabilirler. Bu nedenle zaman içinde konak hücrelerinin kendi hücre dışı matrislerini üretmesini ve bozulan iskeleyi değiştirmesini sağlarlar. Bununla birlikte, doğal polimerlerden elde edilen hidrojeller genellikle vücut sıvılarıyla temas ettiklerinde hızlı bir şekilde bozunmaktadır (Tan ve Marra, 2010; O'brien, 2011).

Kolajen

ECM'nin ana bileşeni olan ve memeli canlılarda en bulunan en bol protein olan kolajen, dokularda yapısal bir iskele görevi görür (Brett, 2015). Jelatin ise, kolajenin doğal üçlü sarmal yapısının hidrolize edilmesi ile oluşan bir kolajen türevidir (Tan vd., 2009). Yapısında arjinin-glisin-aspartik asit bulunan jelatin, hücre yapışmasını, göçünü, farklılaşmasını ve çoğalmasını teşvik etmekte ve çeşitli kimyasal çapraz bağlayıcılar varlığında hidrojelleri oluşturarak iskelenin mekaniksel özelliklerini arttırılabilmektedir (Huang vd., 2005; Pina vd., 2015).

JelMA ise jelatinin metakrilat gruplarıyla modifiye edilmesiyle elde edilen ve UV ışık altında çapraz bağlanma özelliğine sahip sitotoksik olmayan ve biyobozunur bir hidrojeldir. JelMA bazlı hidrojeler yüksek oranda biyouyumludurlar ve ışık altında çapraz bağlanabildikleri için ayarlanabilir fizikokimyasal özellikleri sebebiyle doku mühendisliği uygulamalarında çokça tercih edilmektedirler (Ying vd., 2018).

Rodrigues ve ark. (2003), yürüttüğü bir çalışmada, kemik doku mühendisliğinde kullanılmak üzere HA ve kolajenden oluşan hibrit doku iskeleleri geliştirmiş ve tasarlanan doku iskelelerinde hücrelerin kolajen liflere yapışarak yayıldığını ve iskelenin ostekondüktif ve osteoindüktif bir iskele olarak kullanılabileceğini göstermişlerdir.

Aljinat

Kahverengi su yosunlarından elde edilen aljinat, biyouyumlu, düşük maliyetli ve farklı basım tekniklerine uygun olması önemli özelliklerinden dolayı hücre kapsüllenmesi için üzerinde çokça çalışılan malzemelerden biridir (Akgüner, 2021; Akkuş vd., 2020). Aljinatın bir diğer özelliği de kılcal kuvvetler ile sıvıların hareketine izin verebilme yeteneğidir. Tüm bu özellikler aljinatı, kıkırdak, kemik ve vasküler doku mühendisliği uygulamalarında en çok tercih edilen polimerlerden biri yapmıştır (Tezcan, 2008). Kemik doku mühendisliği uygulamalarında düşük mekanik özelliklerin iyileştirilmesi için aljinatın kolajen, hyaluronik asit, HA ve sentetik polimerlerden polietilen glikol (PEG) ve PCL ile birlikte kullanıldığı çalışmalar yapılmıştır (Axpe ve Oven, 2016).

Kitosan

Kitinin deasetilasyonu ile oluşan kitosan, düşük immünojenite, hücre yapışması ve antimikrobiyal özelliklere sahip, biyouyumlu, biyolojik olarak parçalanabilir ve toksik olmayan bir biyopolimerdir (Aranaz vd., 2009; Di Martino vd., 2005). Çalışmalar iskelede osteoblast büyümesini hızlandırma ve osteoblastların yapışmasını destekleme yeteneği olduğunu göstermiştir (Di Martino vd., 2005; Fakhry vd., 2004; Uslu ve Arbak, 2010)]. Demirtaş ve ark. (2017), MC3T3-E1 pre-osteoblast hücresini kitosan, kitosan-HA ve aljinat, aljinat-HA hidrojellerine yükleyerek karşılaştırmalar yapmıştır. Tüm grupların viskoelastik özelliğe sahip olduğu ve çözeltilerin viskozite değerlerinin 3B yazıcıda kullanılabilecek aralıkta olduğu görülmüştür. Basıldıktan sonra tüm gruplarda hücre canlılığı devam etmiştir. Sonuçlar, kitosan hidrojellerin en yaygın çözüm olarak görülen aljinattan daha üstün olduğunu ve hücre çoğalması, proliferasyon ve osteojenik farklılaşmayı geliştirmesi yönünden kemik doku mühendisliği uygulamalarında tercih edilebileceğini göstermiştir.

İpek Fibroin

Çoğunluğu fibroinden oluşan ipek, yüzyıllar boyunca dikiş malzemesi olarak kullanılmış ve son zamanlarda hem in vitro hem de in vivo olarak mükemmel biyolojik uyumluluğu, in vivo yavaş bozunma hızı ve immün yanıt oluşturmaması gibi özelliklerden dolayı rejeneratif tıpta ve doku mühendisliğinde kullanılan protein yapılı bir malzeme olarak dikkat çekmeye başlamıştır. Genellikle böceklerin (ipek böcekleri veya örümcekler) larvalarının içinde büyüdüğü kozalardan elde edilir (Pina vd., 2015).

Nadiren tek başına kullanılan ipek, mekanik özelliklerinin iyileştirilmesi için aljinat, jelatin veya PEG ile karıştırılarak kullanılmaktadır (Camacho vd., 2019). Kalsiyum fosfat tozlarının ipek bazlı doku iskelelere ilavesi ile, gelişmiş gözenekli bir yapı, osteojenik farklılaşma ve in vivo kemik oluşumu gözlenmiştir (Zhang vd., 2009; Yan vd., 2013).

Fibrin

İnsan vücudunda kanda bulunan, trombin ve fibrinojenlerin enzimatik reaksiyonu sonucu meydana gelen fibrin hidrojeller protein yapıda olan malzemelerdir (Camacho vd., 2019). Biyouyumluluk, biyodegradasyon ve jelleşme yönünden avantaj göstermesine rağmen, zayıf mekanik özellikleri nedeniyle dezavantaj oluştururlar. Bu dezavantajı ortadan kaldırmak amacıyla genelde hyaluronik asit gibi diğer polimerlerle karıştırılarak kullanılırlar (Shirwaiker vd., 2014). Hyaluronik asit miktarı arttıkça viskozitesi artan fibrin, genelde vasküler uygulamalarda kullanılırlar (Camacho vd., 2019).

Hyaluronik Asit

Hyaluronik asit, kıkırdak ve bağ dokularda ECM içerisinde bulunan bir polisakkarit polimerdir. Hücre adezyonu özelliği 3B biyobaskı için avantaj sağlamasına rağmen, bu polimer de tek başına kullanıldığında zayıf mekanik özellik göstermektedir (Camacho vd., 2019; Güngör-Özkerim vd., 2018). HA, PEG ile karıştırılarak menisküs yapısının basımında kullanılabilmektedir (Hospodiuk vd., 2017).

2.2.1.2. Sentetik Polimerler

Doğal polimerlerin bazı sınırlamalarını aşan özelliklere sahip PGA, PLA, ve PCL, PEG ve pluronik gibi sentetik polimerler, kemik doku mühendisliği alanında yaygın olarak kullanılmaktadır. Biyobozunurluk oranının, mekanik mukavemetinin ve yapısal özelliklerinin kontrol edilebilmesi, istenilen desen ve yapıda iskele üretilebilmesi avantaj sağlamaktadır. Bu polimerlerin hücrelerin in vitro ve in vivo osteoindüksiyonunu desteklediği görülmüştür (Chen vd., 2016; Wang vd., 2010; Lee vd., 2008; Hao vd., 2010; Temple vd., 2014)

Poli(glikolik asit)

PLA ile karşılaştırıldığında daha az bazik ve hidrofobik bir polimer olan PGA, yüksek mukavemeti ve biyouyumluluğu nedeniyle cerrahide kullanılmaktadır. Ayrıca doku mühendisliği uygulamalarında sıklıkla kullanılan PGA, vücut içerisinde biyolojik olarak bozunmaya uğradığından, etrafındaki dokularda asit birikimine neden olarak doku hasarına yol açabilmektedir (Mayilswamy vd., 2023).

Poli(laktik asit)

PLA, 21–60 MPa gerilme mukavemeti ve 0,35–3,50 GPa'lık elastisite modülü ile esas olarak doku mühendisliği uygulamaları için 3B biyoyazdırmada kullanılmaktadır (Farah vd., 2016). Biyolojik bozunurluk üzerinde önemli bir etkiye sahip olan yüksek moleküler ağırlığının, in vivo enfeksiyon ve iltihaplanmaya sebebiyet vermesi olasıdır (Andreopoulos vd., 2000). Ayrıca, kemik rejenerasyonu uygulamaları için doğal kemik dokusu ile mekanik olarak kıyaslanan PLA'da, bozulmanın kontrollü ve kademeli olması beklenir ve böylece stres kalkanı etkisinin ortadan kaldırılarak yükün kemik dokusuna ve yumuşak dokuya aktarılması sağlanır (Hutmacher ve Hürzeler, 2024; Chanlalit vd., 2012).

Polikaprolakton

3B biyoyazdırmada sıklıkla kullanılan PCL, düşük erime ve camsı geçiş sıcaklığına sahip olması nedeniyle biyoyazdırmada önemli bir avantaj sağlayan alifatik bir polimerdir (Li ve Tan, 2014). Hedef doku oluşturulmadan önce biyomalzemeler için bozunma oranına dikkat edilmesi ve PCL'nin kopolimerlerin ve polimerin çeşitli oranlarını karıştırarak bozunma oranını yönetebilmesi de başka bir olumlu özelliğidir (Woodruff ve Hutmacher, 2010; Guo ve Ma, 2014).

Polietilen glikol

PEG, tek başına hidrojel olmadığı için polietilen glikol diakrilat (PEG-DA) hidrojel ve polietilen glikol monometakrilat (PEG-MA) hidrojeli şeklinde kullanılır (Camacho vd., 2019). Biyoinert bir malzeme olması nedeniyle, tek başına bir hücreye bağlanması zordur (Hacıoğlu vd, 2018). Bu nedenle hücresel etkileşimleri artırmak için fibronektin, kolajen, elastin gibi biyopolimerlerle karıştırılarak kullanılmaktadır. Yapılan çalışmalarda ipek/PEG biyomürekkep hidrojellerinin uygun iskele ortamı sağlayabileceği görülmüştür (Zheng vd., 2018).

Pluronik

Yüksek biyouyumlu ve düşük miyotoksisiteye sebep olması sebebiyle tercih edilen bir malzemedir. Çok stabil olmaması sebebiyle genellikle 3B biyoyazdırma için destekleyici olarak kullanılmaktadır (Shirwaiker vd., 2014).

2.2.2. Biyoseramikler

Biyoseramik gibi inorganik biyomalzemeler, kemiğin mineral fazının bileşimine benzer olması, mekanik mukavemetleri, osteoindüktif potansiyelleri sebebiyle kemik doku mühendisliği için çekici bir iskele sağlamaktadır. Biyoseramiklerde emilebilir gözenekli iskeleler ve biyolojik olarak aktif yüzeyler oluşturmak için yaygın olarak, trikalsiyum fosfat (TCP), HA, biyoaktif camlar ve bunların kombinasyonları şeklinde kullanılmaktadır (Baino vd., 2015). İnsan osteoblastlarının proliferasyonunu ve osteojenik farklılaşmasını teşvik ettiği, kemik mikro ortamını taklit etme potansiyeli sağladığı ve porozlu yapılar oluşturarak vaskülarizasyon, besin iletimi ve kemik büyümesini teşvik ettiği görülmüştür (Stevens, 2008; Cheng vd., 2019; Roohani-Esfahani vd., 2016. Bununla birlikte, çok yönlülüğüne ve kemik doku mühendisliğindeki umut verici sonuçlarına rağmen biyoseramik bazlı yapı iskelelerinin klinik uygulamaları düşük yük taşıma performansları sebebiyle sınırlıdır (Stevens, 2008; Cheng vd., 2019).

3. Sonuç

Kemik doku mühendisliği hızla gelişen bir alandır ve araştırmacılar, kişiye özel ve hastadan hastaya değişmekte olan doku hasarlarını daha kısa sürede kolayca biyoyazıcı ile basabilecek, vücudun biyolojik ortamını olabildiğince özgün bir şekilde taklit edebilecek yeni malzemeler ve yöntemler geliştirmeye odaklanmışlardır. 3B biyobasım kısa tarihine rağmen yenilikçi ve etkili tedavi yöntemlerinin geliştirilmesine olanak tanımakta ve etkileyici vaatleri ilgi çekmektedir. Ancak, doku mühendisliği çalışmalarının dokudaki uzun vadeli biyolojik etkisini gözlemlemek adına daha fazla araştırma ve çalışma gereklidir. Biyofonksiyonel mürekkepler için biyomalzeme seçimi, istenilen doku/organın başarılı bir şekilde basılması için oldukça önemlidir. Bu sebeple, kemik doku mühendisliği için uygun biyofonksiyonel mürekkeplerin seçiminde, basılan malzemenin morfolojik yapısı, dayanıklılığı, yüzey alanı ve yüzey özelliği, basılabilirliği, hücre büyümesi veya farklılaşması için uygun bir ortam olup olmadığı, bozunma süresi ve biyouyumluluğu gibi çok çeşitli seçim kriterleri düşünülerek hareket edilmelidir.

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