Edyta Kądzielawa
Politechnika Częstochowska
ul. J.H. Dąbrowskiego 69, 42-201 Częstochowa
email: edyta.kadzielawa@pcz.pl

MICROBIOLOGICAL ASPECTS OF CHEWING GUM WASTE DEGRADATION

MIKROBIOLOGICZNE ASPEKTY DEGRADACJI ODPADÓW Z GUMY DO ŻUCIA

ABSTRACT

The aim of this article is to analyze the current state of knowledge regarding the role of microorganisms in the biodegradation of chewing gum waste, with particular emphasis on the potential of selected bacterial and fungal strains to decompose its synthetic and natural components. The study addresses the growing presence of discarded gum in the environment, its resistance to biodegradation, and the potential use of microbiological and other methods to tackle this problem. The scope of the work includes a characterization of the chemical composition of chewing gum and its impact on microbial flora, an analysis of the succession dynamics of microorganisms colonizing gum after disposal, a review of known strains capable of degrading gum components (both natural and synthetic rubber), and a discussion of biotechnological strategies supporting biodegradation. The study includes analyses of strains such as *Streptomyces lividans, Rhodococcus rhodochrous, Pseudomonas citronellolis, Fusarium solani,* and *Penicillium variabile*, which have demonstrated the ability to degrade elastomers and aromatic compounds found in gum. The review results indicate that certain microorganisms exhibit enzymatic activity toward the polymeric components of gum (e.g., polyvinyl acetate, butadiene rubber) and are capable of decomposing some chemical additives. However, the efficiency of this process depends on prior substrate modification (e.g., through devulcanization or pre-oxidation), environmental conditions (humidity, temperature, presence of co-substrates), and the degree of toxicity of the gum to colonizing microorganisms. The conclusions highlight the need for further research into optimizing biodegradation conditions and selecting strains with high degradative activity. An important aspect is also the potential recycling of chewing gum, which could offer a sustainable alternative to conventional disposal methods in the future.

KEYWORDS: biodegradation, microorganisms, chewing gum, polymers

STRESZCZENIE

Celem niniejszego artykułu jest analiza aktualnego stanu wiedzy na temat roli mikroorganizmów w biodegradacji odpadów po gumie do żucia, ze szczególnym uwzględnieniem potencjału wybranych szczepów bakterii i grzybów do rozkładu jej syntetycznych i naturalnych składników. W pracy omówiono problem rosnącej ilości wyrzuconej gumy w środowisku, zwrócono uwagę na jej odporność na biodegradację oraz możliwości wykorzystania metod mikrobiologicznych i innych do rozwiązania tego problemu. Zakres pracy obejmuje charakterystykę składu chemicznego gumy do żucia i jego wpływu na florę mikrobiologiczną, analizę dynamiki sukcesji mikroorganizmów kolonizujących gumę po jej wyrzuceniu, przegląd znanych szczepów zdolnych do degradacji składników gumy (zarówno naturalnego, jak i syntetycznego kauczuku), a także omówienie strategii biotechnologicznych wspomagających biodegradację. W pracy przeanalizowano szczepy takie jak *Streptomyces lividans*, *Rhodococcus rhodochrous*, *Pseudomonas citronellolis*, *Fusarium solani* i *Penicillium variabile*, które wykazały zdolność do rozkładu elastomerów i związków aromatycznych występujących w gumie. Na podstawie przeprowadzonego przeglądu stwierdzono, że niektóre mikroorganizmy wykazują aktywność enzymatyczną wobec polimerowych składników gumy (np. octanu winylu i kauczuku butadienowego) oraz są zdolne do rozkładu niektórych dodatków chemicznych występujących w gumie. Jednak skuteczność tego procesu zależy od wcześniejszej modyfikacji substratu (np. poprzez wulkanizację lub utlenienie wstępne), warunków środowiskowych (wilgotność, temperatura, obecność współsubstratów) oraz stopnia toksyczności gumy dla kolonizujących ją mikroorganizmów. Wnioski podkreślają potrzebę dalszych badań nad optymalizacją warunków biodegradacji i selekcją szczepów o wysokiej aktywności degradacyjnej. Istotnym aspektem jest również potencjalny recykling gumy do żucia, który w przyszłości mógłby stanowić zrównoważoną alternatywę dla konwencjonalnych metod utylizacji.

SŁOWA KLUCZOWE: biodegradacja, mikroorganizmy, guma do żucia, polimery

INTRODUCTION

Although commonly categorized as a recreational product, chewing gum has also garnered significant interest in the biomedical field due to its efficacy as a delivery system for bioactive compounds (Yang *et al.*, 2004; Thivya *et al.*, 2021; Banakar *et al.*, 2022). Its unique physicochemical properties allow for the controlled and sustained release of active substances, making it a practical, cost-effective, and patient-friendly alternative for drug administration (Yang *et al.*, 2004; Konar *et al.*, 2016; Thivya *et al.*, 2021; Hosseini *et al.*, 2024). Moreover, the act of mastication itself has been associated with various potential health benefits, including reduction of psychological stress, enhancement of cognitive functions such as concentration and memory, and support in body weight regulation (Milov *et al.*, 1998; Smith, 2009; Palabiyik *et al.*, 2020). From an economic perspective, chewing gum represents a major global consumer product. In 2020, worldwide consumption was estimated at approximately 4.1 million metric tons, corresponding to a market valuation of around USD 20.3 billion (‘Chewing Gum - World’, 2025). In Poland, production figures for the same year reached 26,000 tons, with an estimated value of USD 230.8 million (‘Chewing Gum - World’, 2025). The market demonstrates a positive growth trajectory; however, reported valuations vary depending on the source. For instance, estimates of the global gum base market in 2023–2024 ranged from USD 1.1 billion to USD 3.5 billion annually, with projections indicating potential growth to USD 5.8 billion by 2033 (*Gum Base - Global Forecast*, 2024; ‘Gum Base Market Size, 2025; ‘Chewing Gum Base Market, 2025; More, 2025). Some analyses suggest the market had already reached USD 5.22 billion in 2023, while others cite figures between USD 13.8 billion and USD 33 billion per annum, with anticipated expansion to USD 45 billion by 2032(*Chewing Gum Market*, 2023; *Chewing Gum Market Report*, 2024; ‘Global Chewing Gum Market, 2024; ‘Chewing Gum - World’, 2025; *Chewing Gum Market*, 2025; *Chewing Gum Market Size, Share, Trends, Growth 2032*, 2025; ‘Chewing Gum Base Market Size, 2025; More, 2025). The most optimistic forecasts predict a market value of USD 111.2 billion in 2024 and USD 139.8 billion by 2032 (*Chewing Gum Market*, 2025). Despite the discrepancies among sources, the available data collectively underscore the substantial economic relevance of the chewing gum industry on a global scale.

The aim of this article is to present the current state of knowledge regarding the role of microorganisms in the biodegradation of chewing gum waste, to assess the potential of selected bacterial and fungal strains in the breakdown of its synthetic and natural components, as well as to verify existing recycling methods for chewing gum waste and reflect on possibilities for their effective and safe neutralization for environmental benefit. A narrative literature review was conducted to provide a comprehensive analysis of existing studies on the biodegradation of chewing gum by microorganisms and the available recycling methods for these wastes. Publications were selected based on searches in databases such as PubMed, Scopus, and Google Scholar, covering works published between 2000 and 2025. The search was performed using the following keywords: chewing gum waste, biodegradation, microorganisms, bacteria, fungi, rubber, synthetic polymers, environmental microbiology, sealants, recycling methods. The analysis included statistical studies, original research articles, and review papers, as well as publications identified through secondary literature reviews. The inclusion criterion was thematic relevance to the objectives of the article, whereas incomplete publications, those of low credibility, or those not meeting scientific standards were excluded. Older articles were included only if the state of knowledge presented in them remains current or if they were necessary to illustrate progress and achievements in this field. The selected publications were critically analyzed in terms of research methodologies, obtained results, and their significance for the development of biotechnological strategies for chewing gum recycling. The review was qualitative in nature, with particular emphasis on the identification of microbial strains with documented degradative potential, factors influencing the efficiency of biodegradation processes, and the evaluation of processing possibilities consistent with the principles of circular economy and microbiological safety of proposed solutions.

ON CHEWING GUM COMPOSITION

Chewing gums are typically classified into four main categories: medicinal gums, sugar-containing gums, sugar-free gums, and coated gums (Hosseini *et al.*, 2024). From a compositional perspective, chewing gum consists of two primary phases (Table 1): an insoluble gum base and a soluble phase comprising various additives, including sweeteners, flavorings, colorants, and auxiliary compounds (Yang *et al.*, 2004). In the case of coated gums, a third phase—the coating layer—is sometimes distinguished (Yang *et al.*, 2004; Thivya *et al.*, 2021). The gum base generally constitutes 20–30% of the total mass and represents the most environmentally problematic component. It is non-edible, indigestible, and non-absorbable, yet it plays a crucial role in providing the gum with its characteristic chewable texture (Yang *et al.*, 2004; Konar *et al.*, 2016). Depending on its origin and chemical composition, gum base can be divided into two primary categories: conventional (non-biodegradable) and natural (biodegradable) (Kaveh *et al.*, 2023). Conventional gum base, devoid of nutritional value, is an inert and insoluble substance that serves as a carrier for active and flavoring agents. It is typically produced from synthetic polymers and includes substances such as petroleum derivatives, lanolin, glycerol, polyethylene, poly(vinyl acetate), paraffin wax, and other hydrophobic compounds (Kaveh *et al.*, 2023). The exact formulation of gum base is usually proprietary and protected as a trade secret. Common ingredients in conventional gum bases include polyisobutylene and styrene-butadiene rubber. An alternative to these synthetic materials is natural, biodegradable gum base, derived from sources such as *chicle*, the latex from the *Chicozapote* tree (Roy, 2021). Ongoing research explores the use of additional plant-based raw materials, including corn protein zein, in the development of environmentally friendly gum bases. Although the market share of biodegradable gums remains limited, increasing environmental regulations and rising consumer awareness are driving the demand for more sustainable alternatives. It is estimated that the global market value for natural gum bases will reach approximately USD 62.1 million by 2031 (*Global Natural Gum Base*, 2025).

Table 1. Chemical composition of chewing gum and biodegradability of its components (Yang *et al.*, 2004; Konar *et al.*, 2016; Kaveh *et al.*, 2023; Roy, 2021).

Component	Type	Examples	Biodegradation Potential
Gum base	Synthetic	PVAc, PVA, styrene-butadiene	Low
Gum base	Natural	Chicle, zein	High
Sweeteners	Soluble	Aspartame, mannitol	Moderate
Aromatic polymers	Synthetic	Polyisobutylene	Very low

CHALLENGES IN BIODEGRADATION: THE ENVIRONMENTAL IMPACT OF CHEWING GUM

The practice of chewing natural substances by humans dates back thousands of years; however, the development of modern chewing gum began in the 19th century, when John B. Curtis introduced the first commercial product—*The State of Maine Pure Spruce Gum*—in 1848 (Hartel *et al.* 2018). Despite its long history of use, it was not until the 1990s that the issue of urban pollution caused by discarded chewing gum began to receive broader attention, reflected in public awareness campaigns as well as in urban planning and environmental literature.

Used chewing gum, along with often-overlooked manufacturing waste, poses a significant global environmental challenge. Chewing gum is an amphiphilic material—containing both hydrophobic and hydrophilic components—which contributes to its strong adhesion to various surfaces and impedes its degradation (Konar *et al.*, 2016; Palabiyik *et al.*, 2020). The gum base, representing the water-insoluble phase of the product, is particularly persistent; it is estimated that its complete degradation may require several hundred years (Basik *et al.*, 2021). This persistence is primarily due to the composition of conventional gum bases, which are formulated from synthetic polymers that are chemically inert, insoluble, and highly resistant to biodegradation. Although both natural and synthetic rubbers used in gum bases have demonstrated some biodegradation potential through microbial activity, the process is significantly hindered by the presence of cross-linked polymer structures, including sulfur bonds (Bin Samsuri, (n.d); Basik *et al.*, 2021). Such cross-linking reduces the substrate's accessibility to microbial enzymes, rendering the environmental degradation of gum base a prolonged and inefficient process under natural conditions.

Microorganisms Capable of Chewing Gum Degradation

The structure of chewing gum facilitates the adsorption and retention of bacteria, thereby creating potential microbiological hazards related to its safety and, in extreme cases, posing a population-scale risk of pathogen transmission (Satari *et al.*, 2020; Roy, 2021). During mastication, microorganisms present in saliva—including *Streptococcus*, *Rothia*, *Haemophilus*, *Granulicatella*, *Corynebacterium*, *Veillonella*, *Actinomyces*, and *Gemella*—are introduced into the gum matrix (Satari *et al.*, 2020). Research has shown that the microbiota associated with chewing gum undergoes dynamic changes over time (Figure 1). Initially, microbial populations are dominated by species from the human oral cavity; however, their abundance and diversity decline following several weeks of environmental exposure. Over time, microbial succession leads to the colonization of the gum by environmental bacteria commonly found in soil, flowers, or urban surfaces (Satari *et al.*, 2020).

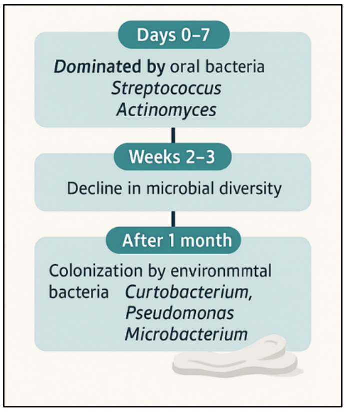

Figure 1. Diagram of microbial succession on discarded chewing gum (Satari *et al.*, 2020).

The presence of additives in chewing gum, such as aspartame, mannitol, and glycerol, may serve as nutrient sources for specific microbial taxa. Several bacterial strains capable of degrading these compounds have been identified, including *Pantoea vagans*, *Paenibacillus illinoisensis*, *Curtobacterium herbarum*, *Pseudomonas oryzihabitans*, *Microbacterium arborescens*, *Arthrobacter agilis*, and other *Curtobacterium* species (Gatidou *et al.*, 2020; Satari *et al.*, 2020). The biodegradation of gum materials, including chewing gum, presents a significant environmental challenge due to the structural durability of these materials—even when derived from natural sources (Shah *et al.*, 2013; Satari *et al.*, 2020). This process is further complicated by the presence of various chemical additives employed in the gum industry, such as antioxidants, stabilizers, and plasticizers, which not only enhance resistance to environmental factors but also often exhibit toxicity toward microorganisms potentially capable of accelerating degradation (Shah *et* *al.*, 2013). Previous studies have confirmed the capability of certain microorganisms to degrade natural rubber, with the most active taxa belonging to the order *Actinobacteria* and fungal genera such as *Aspergillus* and *Penicillium* (Kwiatkowska *et al.,* 1980; Rose and Steinbüchel, 2005; Imai *et al.*, 2011). Particularly promising results (Table 2) were obtained in soil-based studies: for instance, the fungus *Fusarium solani* was shown to reduce rubber mass by 40% over a three-month period, while *Penicillium variabile* achieved a 13% mass reduction over two months (Kalinenko, 1938; Williams, 1982; Rose and Steinbüchel, 2005).

In contrast, the degradation of synthetic rubbers is considerably more complex due to the vulcanization process. Cross-linking of polyisoprene chains via covalent sulfur bridges (mono-, di-, and polysulfidic bonds) imparts substantial chemical resistance. A critical step in improving degradability is devulcanization, which involves the cleavage of sulfur bonds (Aprem *et al.*, 2003; Rose and Steinbüchel, 2005). Microbiological research has predominantly focused on bacterial rather than fungal mechanisms. Identified strains (Table 2) with degradative or devulcanization-supporting capabilities include *Streptomyces lividans* (strain 1326), *Rhodococcus rhodochrous*, *Sulfolobus acidocaldarius*, and *Pyrococcus furiosus* (Torma and Raghavan, 1990; Chritiansson *et al.*, 1998; Bode *et al.*, 2000; Rose and Steinbüchel, 2005). Among fungi, *Paecilomyces variotii* SFA-25, isolated from a hot spring in Balakot, Pakistan, demonstrated effective degradation of synthetic rubber (Zeb, 2009; Rose and Steinbüchel, 2005).

Table 2. Microorganisms capable of degrading chewing gum (Torma and Raghavan, 1990; Chritiansson *et al.*, 1998; Bode *et al.*, 2000; Rose and Steinbüchel, 2005; Kalinenko, 1938; Williams, 1982; Rose and Steinbüchel, 2005).

Microorganism	**Type**	**Degradative Ability**	**Notes**
Streptomyces lividans	Bacterium	Polyisoprene degradation	Produces Lcp enzyme
Rhodococcus rhodochrous	Bacterium	Devulcanization	Degrades synthetic rubber
Fusarium solani	Fungus	40% mass reduction	Soil-based studies
Penicillium variabile	Fungus	13% mass reduction	Shorter degradation time

These studies primarily highlight the ability of environmental bacteria to degrade soluble components of chewing gum rather than the highly resistant synthetic polymer base. Nonetheless, the findings suggest that environmental microbiota possesses a broad metabolic versatility that could potentially be harnessed for the degradation of complex polymeric substrates under optimized conditions.

MECHANISMS OF BIODEGRADATION

An insightful overview of research on the biodegradation of synthetic polymers was presented by Amman and Minge (2011), with particular focus on polyvinyl alcohol (PVA), a polymer frequently used in chewing gum production (Rieger *et al.*, 2012). Homopolymers such as poly(vinyl acetate) (PVAc), polyvinyl alcohol (PVA), and poly(vinyl butyral) (PVB) share a common structural motif—a carbon–carbon backbone (Rieger *et al.*, 2012). This feature poses a substantial barrier to biodegradation, as the cleavage of such bonds is energetically demanding and inefficient from a biological perspective. Structurally, vinyl-based polyesters resemble polymers considered non-biodegradable, such as polyolefins, polystyrene, and polyacrylates (Rieger *et al.*, 2012). Rather than undergoing true biodegradation, these materials are subject to slow breakdown via ultraviolet radiation, oxidation, and hydrolysis—processes that are not classified as biologically mediated degradation. The biodegradation of polymers is predominantly governed by enzymatic activity, which typically targets only accessible surface regions of the material (Figure 2). Enzymes cleave polymers into oligomers and monomers, which can then be further metabolized by microorganisms, since high molecular weight polymer chains cannot cross cell membranes. In some cases, degradation occurs indirectly through enzymatically generated reactive intermediates. PVA is regarded as a biodegradable synthetic polymer, although its actual biodegradability is highly dependent on several variables. In commercial applications, pure PVA is rarely encountered; residual acetyl groups from incomplete hydrolysis of PVAc are commonly present (Rieger *et al.*, 2012). These residues influence crystallinity and water uptake—both critical factors in biodegradation. Additionally, PVA is often incorporated into polymer blends, which may either enhance or hinder its susceptibility to microbial degradation. Consequently, comparing its degradation rate with other biodegradable polymers is complex and often inconclusive. A similar phenomenon is observed with other polymers employed in chewing gum base formulations: although individual components may be biodegradable in isolation, their degradability decreases markedly when incorporated into complex, multi-component systems (Rieger *et al.*, 2012).

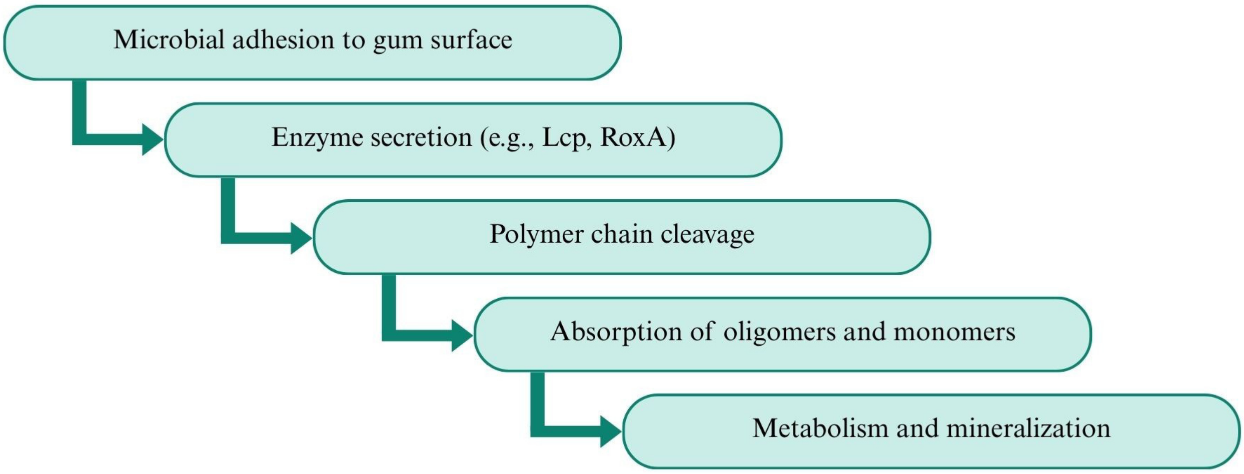

Figure 2. Microbial degradation mechanism of chewing gum polymers (Rieger *et al.*, 2012; Shah *et al.*, 2013).

Key enzymes involved in the degradation of natural rubber, such as poly(cis-1,4-isoprene), have been identified. One such enzyme is the latex clearing protein (Lcp), an extracellular oxygenase produced by the Gram-positive bacterium *Streptomyces* sp. strain K30 (Shah *et al.*, 2013). Lcp catalyzes the cleavage of polyisoprene chains into isoprenoid aldehydes . Disruption of the *lcp* gene results in the loss of rubber-mineralizing ability and the absence of characteristic clearing zones on latex-containing media. Another significant enzyme is Rubber Oxygenase A (RoxA), a heme-dependent dioxygenase isolated from the Gram-negative bacterium *Xanthomonas* sp. strain 35Y (Shah *et al.*, 2013). RoxA catalyzes the oxidative cleavage of double bonds within poly(cis-1,4-isoprene), producing 12-oxo-4,8-dimethyltrideca-4,8-diene-1-al as the primary product. The incorporation of molecular oxygen into degradation products has confirmed its dioxygenase mechanism. Degradation of polyisoprene has also been documented in other microbial genera, including *Gordonia*, *Mycobacterium*, and *Nocardia* (Shah *et al.*, 2013). These microorganisms require direct physical contact with the polymer for effective degradation. The hydrophobic nature of their cell surfaces, often attributed to mycolic acids and the production of biosurfactants, plays a critical role in facilitating polymer interaction and breakdown. Furthermore, enzymatic systems containing lipoxygenases, peroxidases, and laccases—operating in the presence of radical mediators such as linoleic acid or 1-hydroxybenzotriazole—have demonstrated the ability to reduce the molecular mass of polyisoprene under in vitro conditions (Shah *et al.*, 2013). These findings suggest that reactive oxygen species and free radicals may play a significant role in the enzymatic degradation pathways of isoprenoid polymers.

MODERN SOLUTIONS

Only recently have efforts been undertaken to recycle post-consumer chewing gum waste into functional products such as footwear components, pencils, containers, and drinking cups (‘Great Central Plastics Ltd.’, n.d). The inherent durability and resistance of synthetic polymers—including chewing gum base polymers—to biological degradation render them potentially valuable raw materials for various industrial sectors, including construction, electronics, and automotive manufacturing, where both natural and synthetic rubbers are already widely utilized. The chemical composition of gum bases, particularly those used in chewing gums, closely resembles that of sealing compound formulations, indicating a possible niche application for these materials. However, gum waste containing food-grade additives (e.g., sweeteners, flavoring agents) and exhibiting amphiphilic properties that promote microbial adhesion and retention poses potential microbiological risks, particularly in humid environments (Roy, 2021). Such characteristics limit the suitability of this material for use in consumer products that demand long-term durability and microbiological stability, such as industrial sealants. Therefore, the development of technologies that can effectively inactivate microbial flora and stabilize the material is essential. Nevertheless, it must be recognized that aggressive sterilization or stabilization techniques aimed at eliminating microbial contaminants may adversely affect the material's recyclability or future utility. Moreover, such processes may generate by-products that are potentially toxic to specific ecological groups, such as pollinating insects. In this context, there is a pressing need to develop sustainable and ecologically safe methods for processing spent chewing gum into functional products. These approaches should integrate both environmental and public health considerations, ensuring that the benefits of recycling are not outweighed by unintended ecological or toxicological consequences.

There are few known biocidal agents that are not, at least to some extent, harmful to the environment. However, promising natural biocides do exist. Bio-inspired compounds—such as Zosteric acid, a secondary metabolite derived from seagrass that inhibits biofilm formation, and its analogues—have been incorporated into natural rubber networks to impart antifouling and antimicrobial properties without releasing toxic leachates (Tran, 2018). The efficacy of green biocides is largely determined by their mode of action on microbial cells. A key mechanism, particularly for polymers functionalized with guanidinium groups, involves a contact-killing process. Here, positively charged guanidinium moieties interact electrostatically with the negatively charged bacterial membranes. This interaction disrupts membrane integrity by displacing native counter-ions such as Ca^{2+} and Mg^{2+}, ultimately leading to bacterial cell lysis (Tran, 2018). Furthermore, by acting through a surface-bound mechanism rather than through the release of diffusible antimicrobial agents, such systems mitigate environmental risks associated with leaching and persistent toxicity—an essential feature for sustainable applications in sealants and roofing membranes. An alternative non-leaching strategy involves the use of natural antifouling agents such as Zosteric acid. Unlike conventional biocides, which exert toxicity via direct microbial killing, Zosteric acid modifies surface properties to inhibit microbial attachment and subsequent biofilm development. This mode of action not only prevents the emergence of resistant bacterial strains but also minimizes adverse effects on non-target organisms, making it particularly appealing for environmentally benign applications.

CONCLUSION

Addressing the issue of the microbiological degradation of chewing gum represents a significant step toward sustainable waste management and the protection of urban environments. Although certain microorganisms demonstrate the capacity to decompose components of chewing gum—particularly those of natural origin—the complex structural nature of the material, coupled with the presence of recalcitrant additives, substantially limits the overall efficiency of biodegradation processes. Future research should prioritize the development of microbial-based recycling technologies, the optimization of biodegradation conditions (e.g., through devulcanization), and the design of alternative, biodegradable gum bases derived from plant-based raw materials. The integration of microbiological, chemical, and materials science knowledge may ultimately enable the creation of effective strategies for the disposal and transformation of used chewing gum, thereby mitigating its adverse impact on ecosystems and public spaces. The widespread use of polymeric materials has become a defining feature of modern society, and reversing this trend appears increasingly unlikely. Despite their numerous benefits and broad applicability, these materials pose considerable environmental challenges, particularly due to their resistance to degradation. Given the difficulties associated with the removal of synthetic waste, such as chewing gum residues, it is imperative to adopt alternative approaches—namely, the repurposing of these materials through value-added reuse. The implementation of circular economy principles offers a promising avenue for reconciling the functional advantages of synthetic polymers with the need to reduce their long-term environmental burden. Such strategies not only contribute to ecological sustainability but may also yield economic benefits and enhance the public image of enterprises that adopt environmentally responsible innovations.

REFERENCES

Aprem, A.S., Joseph, K., Mathew, T., Altstaedt, V., and Thomas, S. (2003) 'Studies on accelerated sulphur vulcanization of natural rubber using 1-phenyl-2,4-dithiobiuret/tertiary butyl benzothiazole sulphenamide', *European Polymer Journal*, 39(7), pp. 1451–1460. doi: 10.1016/S0014-3057(02)00382-8.

Banakar, M., Moayedi, S., Shamsoddin, E., Vahedi, Z., Banakar, M. H., Mousavi, S. M., Rokaya, D. and Bagheri Lankarani, K. (2022) 'Chewing Gums as a Drug Delivery Approach for Oral Health', *International Journal of Dentistry*, 2022(1), pp. 1-10. doi: 10.1155/2022/9430988.

Basik, A.A., Sanglier, J.J., Yeo, C.T., and Sudesh, K. (2021) 'Microbial degradation of rubber: Actinobacteria', *Polymers*, 13(12), 1989, pp. 1-27. doi: 10.3390/polym13121989.

Bin Samsuri, A. (2010) Degradation of Natural Rubber and Synthetic Elastomers, in Cottis, B., Graham, M., Lindsay, R., Lyon, S., Richardson, T., Scantlebury, D., Stott, H. (eds.) *Shreir's Corrosion*, pp. 2407-2438, Amsterdam: Elsevier.

Bode, H.B., Zeeck, A., Plückhahn, K., and Jendrossek, D. (2000) 'Physiological and chemical investigations into microbial degradation of synthetic poly(cis-1,4-isoprene)', *Applied and Environmental Microbiology*, 66(9), pp. 3680–3685. doi: 10.1128/AEM.66.9.3680-3685.2000.

Chewing Gum – World (2025). Available at: https://app.indexbox.io/table/170410/0/ (Accessed: 5 February 2025).

Chewing Gum Base Market Size, Future Growth and Forecast 2033 (2025). Available at: https://www.strategicrevenueinsights.com/industry/chewing-gum-base-market (Accessed: 2 May 2025).

Chewing Gum Market (2023). Available at: https://marketresearch.biz/report/chewing-gum-market/ (Accessed: 5 February 2025).

Chewing Gum Market (2025). Available at: https://www.businessresearchinsights.com/market-reports/chewing-gum-market-118651 (Accessed: 5 February 2025).

Chewing Gum Market Report (2024). Available at: https://www.researchandmarkets.com/report/chewing-gum (Accessed: 2 May 2025).

Chewing Gum Market Size, Share, Trends, Growth 2032 (2025). Available at: https://www.zionmarketresearch.com/report/chewing-gum-market (Accessed: 5 February 2025).

Chritiansson, M., Stenberg, B., Wallenberg, L. R., and Holst, O. (1998) 'Reduction of surface sulphur upon microbial devulcanization of rubber materials', *Biotechnology Letters*, 20(7), pp. 637–642. doi: 10.1023/A:1005306220566.

Gatidou, G., Vazaiou, N., Thomaidis, N.S., and Stasinakis, A.S. (2020) 'Biodegradability assessment of food additives using OECD 301F respirometric test', *Chemosphere*, 241. doi: 10.1016/j.chemosphere.2019.125071.

Global Chewing Gum Market Size, Share, and Trends Analysis Report – Industry Overview and Forecast to 2032 (2024). Available at: https://www.databridgemarketresearch.com/reports/global-chewing-gum-market (Accessed: 5 February 2025).

Global Natural Gum Base Supply, Demand and Key Producers, 2025-2031 (2025). Available at: https://www.globalinforesearch.com/reports/2542342/natural-gum-base (Accessed: 5 February 2025).

Great Central Plastics Ltd. (n.d.) *About Gum-tec®*. Available at: https://www.greatcentralplastics.com/eco/gumtec-sustainable-material (Accessed: 5 February 2025).

Gum Base Market by Type (Natural Rubber, Resins, Synthetic Rubber), Application (Bubble Gum, Chewing Gum, Dental Gum) – Global Forecast 2025-2030 (2024). Available at: https://www.giiresearch.com/report/ires1615473-gum-base-market-by-type-natural-rubber-resins.html (Accessed: 5 February 2025).

Gum Base Market Size, Demand, Competitive Insights & Forecast 2033 (2025). Available at: https://www.verifiedmarketreports.com/product/gum-base-market/ (Accessed: 5 February 2025).

Hartel, R.W., von Elbe, J.H. and Hofberger, R. (2018) *Confectionery Science and Technology*. Cham: Springer International Publishing, pp. 391-420.doi: 10.1007/978-3-319-61742-8.

Hosseini, H., Hosseini, F., Bolourian, S., Sarvestani, H.S., Assadpour, E., and Jafari, S.M. (2024) 'Functional chewing gum: Transition from a conventional chew to a novel matrix delivering encapsulated bioactives with health-promoting properties', *Future Foods*, 100482. doi: 10.1016/j.fufo.2024.100482.

Imai, S., Ichikawa, K., Muramatsu, Y., Kasai, D., Masai, E., and Fukuda, M. (2011) 'Isolation and characterization of Streptomyces, Actinoplanes, and Methylibium strains that are involved in degradation of natural rubber and synthetic poly(cis-1,4-isoprene)', *Enzyme and Microbial Technology*, 49(6–7), pp. 526–531. doi: 10.1016/j.enzmictec.2011.05.014.

Kalinenko, V.O. (1938) 'The role of actinomyces and bacteria in decomposing rubber', *Mikrobiologiia*, 17, pp. 119–128.

Kaveh, M., Yeganehzad, S., Rabie Ashkezary, M., Hesarinejad, M.A., Todaro, A., and Nishinari, K. (2023) 'Chewing gum base: A comprehensive review of composition, production, and assessment methods: Advances and approaches in biodegradability', *Journal of Texture Studies*, 54(6), pp. 789–807. doi: 10.1111/jtxs.12793.

Konar, N., Palabiyik, I., Toker, O. S., and Sagdic, O. (2016) 'Chewing gum: Production, quality parameters and opportunities for delivering bioactive compounds', *Trends in Food Science and Technology*, 55, pp. 29–38. doi: 10.1016/j.tifs.2016.07.003.

Kwiatkowska, D., Zyska, B.J. and Zankowicz, L.P. (1980) 'Microbiological deterioration of natural rubber sheet by soil microorganisms', *Biodeterioration*, 4, pp. 135–141.

Milov, D.E., Andres, J.M., Erhart, N.A., and Bailey, D.J. (1998) 'Chewing gum bezoars of the gastrointestinal tract', *Pediatrics*, 102(2). doi: 10.1542/peds.102.2.e22.

More, A.B. (2025) *Chewing Gum Market*. Available at: https://dataintelo.com/report/chewing-gum-market (Accessed: 5 February 2025).

Palabiyik, I., Güleri, T., Gunes, R., Öner, B., Toker, O.S., and Konar, N. (2020) 'A fundamental optimization study on chewing gum textural and sensorial properties: The effect of ingredients', *Food Structure*, 26. doi: 10.1016/j.foostr.2020.100155.

Rieger, B., Künkel, A., Coates, G.W., Reichardt, R., Dinjus, E., and Zevaco, T.A. (Eds.) (2012) *Synthetic Biodegradable Polymers*. Berlin/Heidelberg: Springer, pp. 137-168. doi: 10.1007/978-3-642-27154-0.

Rose, K. and Steinbüchel, A. (2005) 'Biodegradation of natural rubber and related compounds: Recent insights into a hardly understood catabolic capability of microorganisms', *Applied and Environmental Microbiology*, 71(6), pp. 2803–2812. doi: 10.1128/AEM.71.6.2803-2812.2005.

Roy, A.S. (2021) 'Improper Disposal of Non-biodegradable Chewing Gum is One of the Biggest Threats to Our Ecology: A Review', *Current World Environment*, 16(3), pp. 916–927. doi: 10.12944/cwe.16.3.22.

Satari, L., Guillén, A., Vidal-Verdú, À., and Porcar, M. (2020) 'The wasted chewing gum bacteriome', *Scientific Reports*, 10(1). doi: 10.1038/s41598-020-73913-4.

Shah, A., Hasan, F., Shah, Z., Kanwal, N., and Zeb, S. (2013) 'Biodegradation of natural and synthetic rubbers: A review', *International Biodeterioration and Biodegradation*, pp. 145–157, doi: 10.1016/j.ibiod.2013.05.004.

Smith, A.P. (2009) 'Chewing gum, stress and health', *Stress and Health*, 25(5), pp. 445–451. doi: 10.1002/smi.1272.

Thivya, P., Durgadevi, M. and Sinija, V.R.N. (2021) 'Biodegradable medicated chewing gum: A modernized system for delivering bioactive compounds', *Future Foods*, 4, 100054. doi: 10.1016/j.fufo.2021.100054.

Torma, A.E. and Raghavan, D. (1990) *Biodesulfurization of rubber materials*, EGG-M-90382; CONF-901194-11. EG and G Idaho, Inc., Idaho Falls, ID (USA).

Tran, T.N. (2018) *Bio-based elastomeric composites for antibacterial and antifouling applications. Methodology for the synthesis and grafting of functionalized oligomers issued from natural rubber*. Doctoral dissertation. Le Mans Université.

Williams, G.R. (1982) 'The breakdown of rubber polymers by microorganisms', *International Biodeterioration Bulletin*, 18(2), pp. 31–36.

Yang, X., Wang, G. and Zhang, X. (2004) 'Release kinetics of catechins from chewing gum', *Journal of Pharmaceutical Sciences*, 93(2), pp. 293–299. doi: 10.1002/jps.10564.

Zeb, S. (2009) *Vulcanized Rubber Degrading Paecilomyces variotii Strain SFA-25 Isolated from Hot Spring in Pakistan*. Doctoral dissertation. Quaid-i-Azam University.

Praca wpłynęła do redakcji: 29.06.2025 r.
Zrecenzowano: 20.10.2025 r.
Przyjęto do druku: 25.10.2025 r.