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Review Article

Innovations in Next-Generation Pharmaceutical Packaging: Shaping the Future

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ABSTRACT

Next-generation pharmaceutical packaging has a significant impact on the evolution of the current practices in the pharmaceutical industry. The integration of emerging technologies and materials has a wide scope of implications for the packaging design and safety applications related to medication solutions. The state of innovations in smart pharmaceutical packaging in eco-friendly materials has an impact on ensuring medication safety, authenticity, and environmental protection. Moreover, the next-generation practices in pharmaceutical packaging provoke improved patient involvement and medication adherence and compliance with prescriptions. The essay outlines the importance of innovative packaging for medications by identifying the driving forces behind the innovations, specific technologies, and regulatory changes. The growing market perspectives associated with next-generation practices in pharmaceutical packaging and potential benefits for patient care can be evaluated for the current practices in the development of the industry

INTRODUCTION

The pharmaceutical packaging is key part of the healthcare industry as it is one of the main tools used to preserve, store and deliver medicines during their entire life cycle. Packaging not just provides confinement but also is determining in protecting the quality of the product, preventing contamination and helping with the correct dose.

Changing global health priorities have reinforced existing frailties within the healthcare industry such as counterfeiting, waste and sustainability issues, divergence of standards and regulations across different markets, etc. Under these circumstances, it is increasingly necessary to develop new packaging innovations that allow meeting healthcare requirements including the needs and expectations of the growing society.

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Innovation in packaging processes, technologies and materials is essential in finding a solution for problems of security, sustainability and waste reduction and regulatory compliance faced by a healthcare system.

Drivers of Innovation in Pharmaceutical Packaging

The pharmaceutical packaging industry is experiencing a dynamic transformation viz-a-viz with several intertwined factors influencing such development globally. As the foremost driver, there is an increasing need in ensuring patient safety that compel huge investments towards developing pertinent packaging technologies that could combat counterfeiting especially through namely overt, covert, and forensic features, and enhanced trace and track systems (Mittal et al., 2021). Similarly, enhanced regulatory demands exerted on stakeholders' supply chains need to ensure product integrity and compliance to

standards continue to be a major driver for child-resistant and tamper-evident packaging designs. This also applies to the dynamic technology developments facilitating interactive packaging solutions such as talking packs and timer caps that further promote therapeutic adherence and optimal patient outcomes (Mittal et al., 2021). Environmental demands as highlighted by the rising market desire for sustainable packaging materials and design continue to propel considerable innovation with respect to the development of regulatory expectations vis-a-viz with sustainable environmental practices. Table 1 highlights the major drivers behind innovation in pharmaceutical packaging, including the growing need for patient safety, strict regulatory compliance, technological advancements, environmental sustainability, and the complexity of modern drug formulations. These factors collectively push the industry toward smarter, safer, and greener packaging solutions.

Table 1: Key Drivers of Innovation in Pharmaceutical Packaging

Category	Driving Factor	Description / Impact
Patient Safety	Anti-counterfeiting measures	Use of overt, covert, and forensic technologies to ensure authenticity and reduce counterfeit risks.
Regulatory Compliance	Serialization & traceability	Mandatory barcoding, unique identifiers, and tamper-evident packaging for global tracking.
Technological Advancement	Smart & interactive packaging	Integration of IoT, RFID, and NFC for real-time monitoring and patient engagement.
Environmental Sustainability	Eco-friendly materials	Adoption of biodegradable, recyclable, and compostable materials to reduce environmental footprint.
Drug Sensitivity	Advanced biologics & formulations	High-barrier packaging materials to preserve drug stability and safety during distribution.

The growing sophistication of drugs, in particular due to the growth of biologics and the shift to personalized medicines, also places further demands on packaging, with many factors that impact on safety and efficacy. Advanced therapies are often more sensitive to 'normal' variables, e.g., temperature, humidity, etc., which means that decisions on packaging materials and barrier properties may be even more critical than normal

(Pala et al., 2024). Simple considerations for the packaging of prescription products may no longer be adequate, and even minor leachables can now affect the stability and delivery of the fragile drug set. Manufacturers therefore have to choose primary, secondary and tertiary packaging, which has minimum reaction, provides maximum security during delivery, and can be delivered



around the world without compromising drug delivery quality (Pala et al., 2024).

Moreover, the growth of international pharmaceutical supply chains has escalated the demand for tamper-evident and ultra-secured packaging solutions. With products traveling through numerous regulatory and geographical frontiers, integrity claims on the packaging of medicines while in transit become ever more difficult to control and authenticate. Serialization regulations have taken form as a key reaction to this need, aiming to regulate the presence of unique identifiers and secured barcode upon the packaging of pharmaceuticals, which shall permit traceability through complex international networks (Sarkar, 2022). The compulsory use of tamper-proof seals and sophisticated anti-counterfeiting technologies help reduce the odds of product fraud, benefiting consumers and manufacturers alike from the repercussions of adulterated medicines. Driven not only by admiration for counterfeit goods, security-led innovations are also motivated by rising demands from regulatory entities and supply chain companions for reinforced guarantees on product originality throughout the entire supply chain (Sarkar, 2022).

Smart Packaging Technologies

Simultaneously with the rising security and regulatory requirements, smart packaging has become a novel solution within the pharmaceutical industry due to its digital capabilities maximizing product safety and monitoring. Smart packaging implies an integrated package with sensors, time temperature indicators, and wireless communication elements ensuring real-time tracking of storage, transportation, and distribution parameters. Thus, some drugs require compliance with certain conditions, including temperature and humidity. Smart packaging technologies allow

real-time monitoring of the specified parameters since the medicine may lose its properties when delivered in an adverse environment (Osadchy, 2024). Components of digital connectivity also include RFID tags and Internet data updating interfacing, ensuring better traceability and transparency across the supply chain. Smart packaging's digital capabilities help achieve stricter quality assurance and regulatory compliance and cope with new market demands for reliability, security, and product information access, signifying a breakthrough into the 4.0 Industry paradigm in pharmaceuticals (Osadchy, 2024).

Most specifically, RFID (Radio Frequency Identification) and NFC (Near Field Communication) technologies incorporated into the medicinal products' packaging contribute considerably to the industry's real-time storage and authentication capabilities. While RFID tagging allows for the identification and geolocation of medical supplies throughout the supply chain and creates a digital "footprint" that can be used for rapid identification of unauthorized access and any violations of optimal storage conditions, NFC connectivity extends this opportunity to healthcare professionals and patients. The use of smartphones and other compatible devices to identify counterfeit medications and acquire critical dosage data increase the possibility of minimizing counterfeit drugs distribution and secure the medication quality controls and drug products integrity and traceability protection during their whole lifecycle from manufacturer to end-user (Raman et al., 2023). The fusion of RFID and NFC usage corresponds to requirements set for the modern packaging trends powered by the manifold Internet of Things opportunities and capable of providing scalability for automation, transparency



throughout the supply chain, and improved patient safety (Raman et al., 2023).

Furthermore, the use of temperature and humidity sensors for pharmaceutical packaging is vital for preventing drug damage during storage or transport. Such active sensors are employed to control the environmental conditions inside the package and can send alerts when the thresholds are exceeded for specific drugs vulnerable to physical variations. These systems also allow for continuous monitoring and recording of data, which allows to enhance supply chain reliability, as the alerts of deviations, potentially influencing the drug's quality, can initiate immediate responses, such as the withdrawal or recall of affected products. The sensor-enabled packaging solutions also ensure the retention of active pharmaceutical ingredients' chemical and therapeutic properties until consumption, reinforcing a transition towards active and intelligent pharmaceutical packaging systems

(Rydzkowski et al., 2022). In such advancements, functional materials and their applications have a great potential to meet regulatory demands, improving health conditions on a global scale through ensuring product safety and efficiency at every stage of distribution (Rydzkowski et al., 2022). Table 2 outlines the emerging technologies shaping next-generation packaging. Smart packaging with RFID, NFC, and IoT sensors enhances product traceability and patient adherence. Sustainable packaging using biodegradable and recyclable materials addresses environmental concerns. Advanced materials like nanotechnology improve protection and anti-counterfeiting features, while user-friendly designs ensure safety for children and the elderly. Additionally, 3D printing enables personalized packaging and supports precision medicine. Together, these innovations signify a shift toward intelligent, sustainable, and patient-centered pharmaceutical packaging.

Table 2: Emerging Trends and Technologies in Next-Generation Packaging

Innovation Area	Technology / Material	Key Benefits	References
Smart Packaging	RFID, NFC, IoT Sensors	Real-time monitoring, enhanced traceability, improved adherence	Raman et al., 2023; Osadchy, 2024
Sustainable Packaging	Biodegradable polymers (PLA, PHA), paper-based composites	Environmental protection, waste reduction, regulatory compliance	Ibrahim et al., 2022; Ashiwaju et al., 2023
Advanced Materials	Nanomaterials, functional barrier films	Improved moisture/oxygen protection, anti-counterfeiting	Bumbudsanpharoke et al., 2025
User-Centric Design	Child-resistant & senior-friendly systems	Enhanced safety, accessibility, usability	Zhang et al., 2020
3D Printing Applications	Customized containers & delivery systems	Personalized dosing, adaptive design, integration with smart sensors	Osadchy, 2024

On top of that, the ability of smart packaging to enhance the adherence of patients with digital prompts and connected applications is also becoming a focus of the pharmaceutical sector. Thanks to breakthrough achievements, packages can now directly communicate with patients or caregivers, sending alerts through connected

mobile devices when it is time to take a dose, a medication has been missed or a refill is due. With Internet of Things (IoT) and cyber-physical systems, the smart package can connect the adherence information with a digital health record (Mukhlas et al., 2024). This allows real-time tracking of adherence by clinicians or family

members. These features directly address factors for nonadherence, such as forgetting a dose or not understanding directions, and contributes to the maintenance of therapy and its effectiveness. As an example of employing data-centric technologies to provide concrete support in ensuring optimal use of a product for improved health outcomes, these innovations demonstrate the significant impact beyond just the supply chain (Mukhlas et al., 2024).

Sustainable Packaging Solutions

On the other hand, another crucial trend emerging in the framework of innovation in pharmaceutical packaging relates to the increasing focus on sustainability, motivated by regulatory requirements and social pressures in favor of protecting the environment. Pharmaceutical companies and stakeholders are now being called to rethink certain packing practices in accordance with evolving regulations that seek to minimize the impact of waste related to healthcare on the environment. The heightened focus on this issue is strongly correlated with the fact that conventional plastics are not fully recyclable as only a small fraction of this material is currently recycled, and considerable proportions continue to accumulate in landfills or pollute oceanic waters (Ibrahim et al., 2022). As a result, stakeholders have come to show growing interest in replacing conventional materials with recyclable, bio-based or biodegradable alternatives that are capable of ensuring sustainable resource usage and contributing to recovery at the end of life. The development of innovative paper and paperboard alternatives is also becoming increasingly popular because of their cost and ecological benefits when compared to plastics, metals, and glass. Overall, it is the growing focus on sustainability is expected to redefine design criteria and priorities for the

packing of pharmaceutical products (Ibrahim et al., 2022).

As an illustration, the pharmaceutical industry has commenced the investigation of recyclable, biodegradable, and compostable materials as potential substitutes for single-use plastics. Biodegradable materials, including polylactic acid and polyhydroxyalkanoates, are designed to disintegrate in industrial composting facilities or in natural environmental settings, thereby curtailing waste that does not degrade and supporting circular flows of resources. Such biodegradable polymers can achieve comparable barrier performances to conventional plastics, and their degradation products are innocuous to ecosystems, rendering them ideal candidates for the packaging of sensitive drugs (Ashiwaju et al., 2023). The orientation towards biodegradable and compostable alternatives is reinforced through state-of-the-art scientific assessments and regulations, stimulating manufacturers to select materials that present lower environmental impacts. These alternative manufacturing technologies are not only embraced to fulfill compliance with regulatory instruments, but also address the expectations of consumers associated with sustainable packaging, indicating changes in the patterns of the security and delivery processes of pharmaceuticals (Ashiwaju et al., 2023).

The products have to have specific characteristics to be classified as green. Nevertheless, green pharmaceutical packaging is still a challenge for manufacturers. This is especially true for sterile and sensitive products. Even though the promising bio-composites materials are renewables and biodegradable, they still need to have the barrier properties, so the product is not compromised by the environment by where they are degraded or contaminated (Garima et al., 2024). Such properties are essential in preventing penetration



of moisture, light or microbes, and having adequate long-term stability during transport and storage. In this case, the need for recyclability and reusability may even require additional treatments or multilayer systems, which make full biodegradation or reusing the material highly unlikely. The manufacturer's choice of eco-friendly packaging is based on the principle of harmonizing environmental concerns with the uncompromising requirements for safety and efficiency for medical products (Garima et al., 2024).

The implementation of sustainable packaging practices in the pharmaceutical industry proves to be successful through collaborations between the manufacturers, suppliers and research bodies. Various case studies reveal a number of firms that have successfully employed the use of biodegradable materials and other renewable resources in their production packaging lines. While these practices have decreased the environmental impacts of the packaging materials used, they did not compromise on product safety and efficacy. Based on several case studies, commitment to sustainable packaging practices are sometimes accompanied by partnerships around supply chain logistics, where stakeholders ensure that the materials development and procurement process, the transportation cycles as well as disposal and recycling activities are performed in an environmentally conscious manner (Bhadoriya et al., 2024). Partnerships such as those emerging in this practice in the industry often lead to collaborative innovations and product developments, where knowledge is shared amongst the different partners and successful pilot studies are expanded for commercial use. Partnerships across sectors in this practice also demonstrate how progress in sustainable packaging practices is not only influenced by new technology, but rather, requires an integrated

approach to environmentally sustainable actions across the various levels of the business (Bhadoriya et al., 2024).

Advanced Materials and Design Innovations

Use of new materials technologies in pharmaceutical packaging are delivering functional enhancement and levels of protection demanded by contemporary drug products. Requirements of increased sensitivity and security of enteral and parenteral formulations are met by the integration of nanomaterials including noble metals, rare earth metal complexes, polysaccharide-based nanoparticles, carbon dots, etc. Functional nanoscale engineered barrier film is employed to regulate oxygen and moisture permeability. Active packaging materials can create software-type on-demand responses, such as antimicrobial, controlled-release of stabilizers, securing each dose in shelf-life period of the medication (Bumbudsanpharoke et al., 2025). However, addition of nanomaterials and other functional features mostly correlates with anti-counterfeiting, real-time tracking of product condition, and visual colourimetric indicators to provide parcel integrity and mark products traceability. Optimistically, use of nanotechnology and functional barriers in packaging technology is emerging as a strategic approach to address growing demands from consumer safety, regulatory affairs and performance (Bumbudsanpharoke et al., 2025).

Secondly, child-resistant and senior-friendly pharmaceutical packaging design developments are also important in preventing unintended poisonings, promoting adherence in vulnerable patient populations. Child-resistance design features such as child resistant closures and push-and-turn caps are designed to eliminate unintended access by young children but not interfere with adult access. Similarly, senior-friendly designs



address features such as limited dexterity or visual acuity by incorporating ergonomic elements, tactile indicators, and clear labeling to increase safety and ease of access for the elderly opioid user (Zhang et al., 2020). Stringent regulatory standards, especially those set by the Poison Prevention Packaging Act (PPPA), must be weighed against the need for access to the product, highlighting the importance of user testing and the application of technologies that balance these needs. Evidence shows that security technologies, informed by user-centric design principles, can markedly reduce risks associated with joint product use, leading to packaging innovations that strike a balance between safety and usability for vulnerable patient populations (Zhang et al., 2020).

Furthermore, the latest developments in pharmaceutical packaging design trends are particularly aimed at enhancing dose precision and safety through the use of advanced containers and delivery systems. Pre-filled syringes are an example of packaging solutions that allow for the consistency of dosage since, by their nature, these containers dispense accurate volumes of drug product and so they spare patients and health professionals from any manual dose determination. Blister packs and unit-dose containers are also extensively used to segregate particular single doses and provide contamination safety while supporting patient adherence as they allow for more accurate schedule monitoring by consumers. The mentioned above packaging solutions also comply with the safety regulatory standards and enhance the efficiency of drug dispensing operation in both clinical and household applications (Mukhlas et al., 2024). The use of the technology-driven designs empowers the pharmaceutical packaging industry to preserve medications from hazards compromising their therapeutic value while also improving customers'

experience and clinical outcomes (Mukhlas et al., 2024).

In addition, the use of 3D printing in pharmaceutical packaging creates new opportunities for an increased level of customization and requirements to meet special patient needs. The so-called personalized medicine—medicines with individual dosing schemes or those based on specific genetic characteristics—will reap benefits from individually designed packaging, produced on demand. Using 3D printing, manufacturers will be able to create unique containers, adaptive delivery systems, and packaging configurations that match the specifically defined by a patient size, required time therapy schedule, and user abilities. This can also allow for integrating identification tags, wireless systems, or smart sensors into an individual package to aid product traceability and a patient's continuous field monitoring during the entire lifetime (Osadchy, 2024). Evolving smart packaging, based on the widespread impact of 3D printing will keep in line with Industry 4.0 requests for faster cycles of rapid development and clinical feedback, feasible delivery of safer and user-friendly pharmaceutical products (Osadchy, 2024).

Regulatory and Compliance Considerations

The regulatory environment for pharmaceutical packaging is becoming increasingly complicated and involves strict requirements to guarantee the safety and authenticity of medicinal products. In this context, the authorities of most countries all over the world require the use of detailed labeling, including linear and non-linear codes, serialization and traceability to eliminate the entry of counterfeit drugs and ensure the integrity of supply chains. The regulatory requirements for pharmaceutical serialization obligate the use of unique identifiers, tamper-evident and compliant



barcoding on each unit of sale and distribution. These measures are aimed at ensuring the movement and safe management of pharmaceuticals from the manufacturer to the treating doctor and patient (Sarkar, 2022). The regulatory requirements outlined above in detail and in their practical aspects require significant investment in packaging infrastructure and data management, as well as the standardization of procedures to comply with domestic and international requirements of the regulatory environment. The packaging industry in this regard is subject to demands to continuously improve its packaging systems to ensure their efficiency in terms of reducing human health risks and legal regulations (Sarkar, 2022).

Within this perspective, the international harmonization of pharmaceutical serialization standards emerges as a critical strategy to address counterfeit medicines, as well as to allow the preservation of complex supply chains. Serialization refers to the assignment of unique identifiers to each packing unit so it is possible to secure its verification at all distribution points and enable quick identification of counterfeits. Despite being effective in major economies, the implementation of this digital traceability is yet a challenge in developing countries because insufficient technical infrastructure, the poor enforcement of regulatory practices, and economic restraints prevent the wide adoption of the technological method (Sarkar, 2023). Also, industries located in regions affected by geopolitical instability or public health emergencies - like the impact of the communicable COVID-19 pandemic - are particularly vulnerable to the serialization system failures, ultimately exposing more weaknesses of the pharmaceutical supply chain. Thus, the success of the serialization policy adoption hinges on the ability of specific countries to devote investments to the adequate

technological, regulatory, and operational models that the type of strategy demands, and these factors are still globally-distributed (Sarkar, 2023).

Notably, significant obstacles are faced by manufacturers when they endeavor to adhere to the inconsistent international regulations governing the packaging of pharmaceutical products. The main challenges arise from the discrepancies in the specifications of individual countries concerning materials, labeling, serialization, language, and child-proof packaging, with some of these factors varying significantly from market to market (Mukhlas et al., 2024). A Siamese twin problem is posed by the need for companies to consistently monitor, interpret, and implement frequently updated standards by regulatory authorities responding to emerging technologies and publicly reported health incidents, often involving a significant financial commitment (Mukhlas et al., 2024). Inconsistencies in the regulatory environment, or the failure to produce a harmonized framework concerning the acceptability of novel technologies used to the packaging process such as data analytics, IoT-based serialization, and cyber-physical systems generally result in adverse effects on the emergence and extensive use of these innovations, especially in markets with less resource availability (Mukhlas et al., 2024). Fragmentation in the regulatory environment complicates the process of releasing pharmaceuticals to global markets; for this reason, manufacturers are conclusively engaged in the challenge of committing their resources to the exclusive expertise in their compliance with such regulations and multidimensional coordination to their global supply chains (Mukhlas et al., 2024).

Future Trends and Market Outlook

Future Trends: Pharmaceutical packaging will continue its trend towards broad automation,



digitalization, and personalized solutions. Smart packaging will enhance this trend; intelligent packaging with sensors, RFID tags, and real time monitoring systems will allow a better control of the conditions during storage and distribution of pharmaceutical goods. The adoption of these digital solutions will protect the security and quality of the pharmaceutical goods, but also react to the increased demand for products with traceability features and with transparent and effective communication channels with the end user (Osadchy, 2024). Therefore, producers will increasingly use connected solutions, where the packaging systems are integrated with other supply chain control and patient engagement devices. This new interconnected approach will impact industry standards, driven by the increasing need of customization according to specific therapies or patient groups and the adjustment of product supply constantly to changing regulatory and market demands (Osadchy, 2024).

In this way, the intersection of packaging intelligence, sustainability, and design sophistication is expected to generate tangible advantages throughout the pharmaceutical sector. Innovative monitoring and protection technologies applied to drugs and pharma products could increase adherence, safety, and efficacy with consequent reduction of adverse drug events (Rydzkowski et al., 2022). From an operational standpoint, automated processes and digitalized practices would be expected to optimize logistics, limit supply chain breakdowns, and decrease related loss from errors or goods with compromised quality. Further, companies that promptly adopt active, and eco-friendly packaging solutions can also benefit from a competitive edge in their respective markets by addressing regulatory and consumer pressures for safer, more practical convenience-oriented, and environmentally-friendly products. While this

may entail upfront costs and adjustments to existing processes, the impact of these trends may go beyond the immediate packaging benefits, by establishing improvements in operational efficiency, patient welfare, and market differentiation in ever-tighter pharmaceutical marketplaces (Rydzkowski et al., 2022).

CONCLUSION

Pharmaceutical packaging has continued to develop through a range of technological and societal trends that are revolutionizing the way medicines are safeguarded, tracked and supplied. These technological developments include smarter, safer and more user-friendly primary and secondary packaging solutions that utilize advanced digital technologies, sustainable materials and design principles to address the needs of the current healthcare model and environmental issues. The next-generation pharmaceutical packaging critically contributes to the improvement of engagement and adherence of patients, greater supply chain security, enhanced transparency, and compliance with the ever-changing regulatory standards, thereby attaining a transformation in operational efficiency, patient's outcomes, and the market positioning of the industry regarding new standards in the quality and effectiveness of medicine delivery. It is the progress in the packaging design and development that will retain its important position in the pharmaceutical value chain to address the emerging therapies and global health needs, thereby defining the pharmaceutical packaging as one of the vital elements of the modern healthcare system establishing new standards.

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