Greener, safer, and stronger: plasma ion-exchanged pharmaceutical glass vials for precision drug delivery dosing.

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This study introduces the groundbreaking synergistic influence of plasma and ion-exchange treatment (P-IET), conducted under varying conditions (450°C and 500°C for 2, 12, and 24 h), preceded by a few seconds of pre-plasma treatment using a mixed air-argon gas approach. P-IET is a cost-effective, innovative, long-lasting, and industrially scalable process designed to improve the performance of Type I borosilicate glass across a variety of pharmaceutical packaging forms and structures. This treatment produces a durable hydrophilic surface, as confirmed by FTIR analysis, which shows a broad and intense OH group peak at ~3350 cm^{-1}, along with significant structural changes that demonstrate enhanced water-attractive properties. Furthermore, P-IET significantly lowers water contact angles on the glass's inner surface, amplifying its hydrophilicity. These improvements are crucial for water-based drug formulations, facilitating efficient and waste-free drug delivery by enabling complete withdrawal and precise dosing—critical features and requirements for contemporary and modern pharmaceutical applications. Beyond hydrophilicity, P-IET also significantly enhances the mechanical strength of glass by generating a robust compressive layer, hence doubling its resistance to crushing loads by 2124 ± 21 N (e.g., at 500°C for 24h) compared to untreated standard vials available on the market today (1157 ± 91 N). Moreover, P-IET sterilizes the glass surface by removing biological contaminants and microorganisms, organic residues and improves chemical durability by reducing Na and K ion leach-out, thus assuring long-term chemical stability under various pH conditions. Notably, these are achieved without changing the colour or transparency of the glass with preserving its aesthetic or functional integrities. The proposed transformative technology effectively tackles critical challenges in pharmaceutical packaging by introducing a greener, safer, and more efficient solution. It facilitates complete drug withdrawal with precise dosing and boasts exceptional mechanical and chemical resistance. P-IET is establishing new standards related to type I borosilicate glass and is promoting the development of innovative drug delivery systems characterized by their unique reliability and sustainability.

Keywords: Plasma-Ion exchange treatment (P-IET), hydrophilicity enhancement, mechanical strength, pharmaceutical packaging, chemical durability, type I borosilicate containers.

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