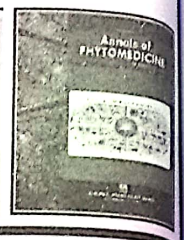
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Edible vaccines from leafy vegetables: Advances in food technology, phytochemical composition and human health

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Abstract

Edible vaccines have emerged as a promising alternative to conventional vaccination systems due to their cost-effectiveness, ease of administration and potential for large-scale production. Among various plant-based platforms, leafy vegetables are considered highly suitable for edible vaccine development because of their rapid growth, high biomass production, ease of cultivation and suitability for raw consumption. This review highlights the potential of leafy vegetables as edible vaccine platforms with emphasis on food technology, phytochemical composition and human health applications. Edible vaccines are developed by introducing pathogen-specific antigen genes into edible plant tissues through genetic engineering approaches. Upon oral consumption, these antigens stimulate mucosal and systemic immune responses, providing protection against infectious diseases. Leafy vegetables such as lettuce, spinach, cabbage, kale, mustard greens and amaranthus have been extensively investigated for the production of vaccine antigens against diseases including hepatitis B, cholera, influenza, COVID-19 and norovirus. In addition to their role in antigen delivery, leafy vegetables contain important phytochemicals such as phenolics, flavonoids, carotenoids, glucosinolates, terpenoids and alkaloids that exhibit antioxidant, anti-inflammatory, antimicrobial and immunomodulatory activities. These bioactive compounds may enhance vaccine efficacy and contribute to overall health improvement.

The review also discusses the importance of food technology approaches including freeze drying, encapsulation, spray drying and nanoformulation for improving antigen stability, shelf-life and oral delivery efficiency. Recent advances in biotechnology such as chloroplast transformation, CRISPR/Cas genome editing, synthetic biology, nanobiotechnology and artificial intelligence-based omics approaches have further strengthened edible vaccine research and development. Although, challenges related to dosage consistency, biosafety, regulatory approval and public acceptance remain, leafy vegetable-based edible vaccines hold significant potential for future applications in human and veterinary healthcare, particularly in low-resource settings and mass immunization programs.

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