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Phytotoxicology of botanical pesticides in medicinal crops: Mechanisms, multitrophic effects, and residue implications for high value phytomedicines

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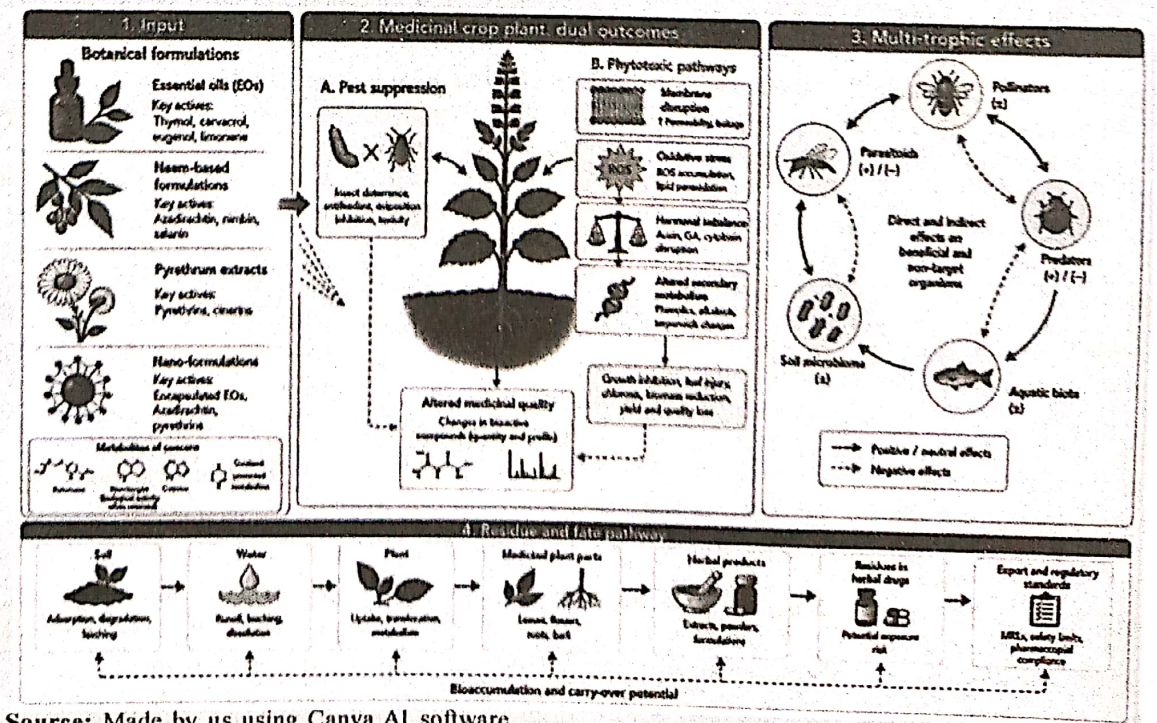
Essential oils

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Abstract

Botanical pesticides are increasingly used in medicinal and aromatic plant (MAP) production as sustainable alternatives to synthetic pesticides due to their biodegradability, broad-spectrum activity and compatibility with organic and integrated pest management systems. However, growing evidence shows that many plant-derived compounds can cause significant phytotoxic, ecotoxicological and toxicological effects depending on formulation, concentration and exposure conditions. Major botanical groups, including limonoids, pyrethrins, rotenoids, alkaloids, and essential oil constituents, may disrupt membrane stability, photosynthesis, mitochondrial activity, redox balanceand hormonal signalling. These disruptions can alter the biosynthesis of alkaloids, terpenoids, phenolics and essential oils; thereby affecting medicinal quality, pharmacological efficacy and pharmacopeial compliance of MAPs. Low-dose exposure may stimulate defence-related secondary metabolism; whereas higher concentrations can induce oxidative and metabolic damage. In addition, the persistence of residues and degradation products, as well as their ecological impacts on beneficial arthropods and aquatic organisms, remains insufficiently understood. Advances in metabolomics, transcriptomics, nanoformulations, analytical chemistry and AI are improving understanding of phytotoxicity mechanisms and residue dynamics. Sustainable use of botanical pesticides; therefore, requires mechanistic phytotoxicological evaluation, standardised residue monitoring, ecological safety assessment and harmonised regulatory frameworks. This review provides a comprehensive framework for understanding the safe and sustainable use of botanical pesticides in medicinal crop production while maintaining medicinal quality and environmental safety.



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