Nanotechnology in Herbal Drug Delivery: - A Novel Approach in Pharmacognosy

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***Abstract*—Plant-based drugs are a rich source of useful active drugs, but they are usually impaired by insolubility, poor oral bioavailability, and wide biotransformation. Nanotechnology drug delivery systems (NDDS) are novel solutions that have augmented solubility, stabilized phytoconstituents, ensure controlled release, and ensure targeted delivery. This review identifies progress from 2019 to 2025 in nano-herbal products like liposomes, polymeric nanoparticles, solid lipid nanoparticles, Nano emulsions, nanogels, phytosomes, and green-synthesized metal nanoparticles. Mechanistic understanding, representative phytochemical case studies, green synthesis protocols, safety concerns, regulatory matters, and the future agenda in personalized nano-herbal therapeutics are discussed, giving a glimpse of this rapidly advancing topic.**

***Index Terms*—Herbal medicine; Nanocarriers; Phytoconstituents; Green synthesis; Bioavailability; Drug delivery, Pharmacognosy, Nanotechnology, Herbal drug delivery.**

I. INTRODUCTION

Herbal drugs are the foundation of medicine as they are abundant in bioactive molecules. But their poor aqueous solubility, low bioavailability, and high metabolism diminish their clinical effect. Nanotechnology-mediated drug delivery systems present an excellent method to overcome these limitations through the encapsulation of phytoconstituents, enhanced solubility, protection from degradation, and ensuring controlled and targeted release. More recent reviews of the 2019-2025 time period encapsulate that Nano formulations such as liposomes, polymeric nanoparticles, solid lipid nanoparticles, Nano emulsions, nanogels, phytosomes, and metallic nanoparticles prepared through green methods improve therapeutic effectiveness to a great extent, demonstrating their translational medicine potential .

II. NANOCARRIER SYSTEMS FOR HERBAL DRUG DELIVERY

Through nanotechnology, a number of different types of nanocarrier are available for the treatment of different diseases that could be the main reason for difficulty in herbal drug delivery.

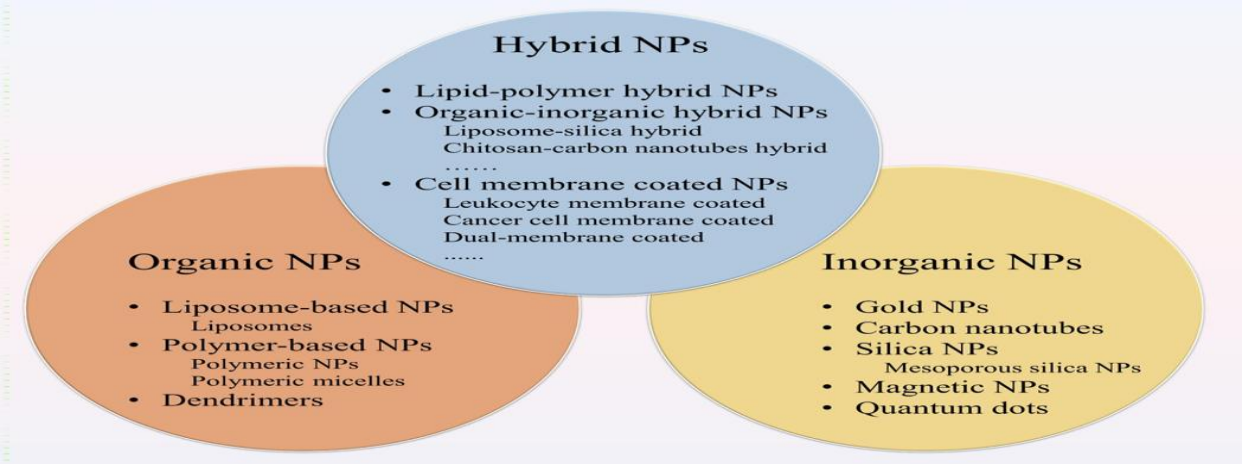

Fig.1. Shows Different types of nanoparticles (NPs)

- ❖ **Liposomes**: - Ectoplasmic bilayer spherical vesicles that are capable of enwrapping the water and the fat-loving substances. Curcumin-loaded liposomes improve bioavailability as well as anti-inflammatory potential; triptolide liposomes have by far the best ability to make tumor cells inactive.
- ➢ **Advantages**: Enhanced solubility, biocompatible, controlled release, versatile encapsulation, targeted delivery.
- ❖ **Polymeric Nanoparticles:** - Polymeric materials (PLGA, chitosan) which are biodegradable and released slowly over time are used to protect plant chemicals. Quercetin and berberine techniques improved antioxidants and antidiabetic activities.
- ➢ **Advantages**: Controlled release, protection against degradation, targeted delivery, biodegradability, enhanced uptake.

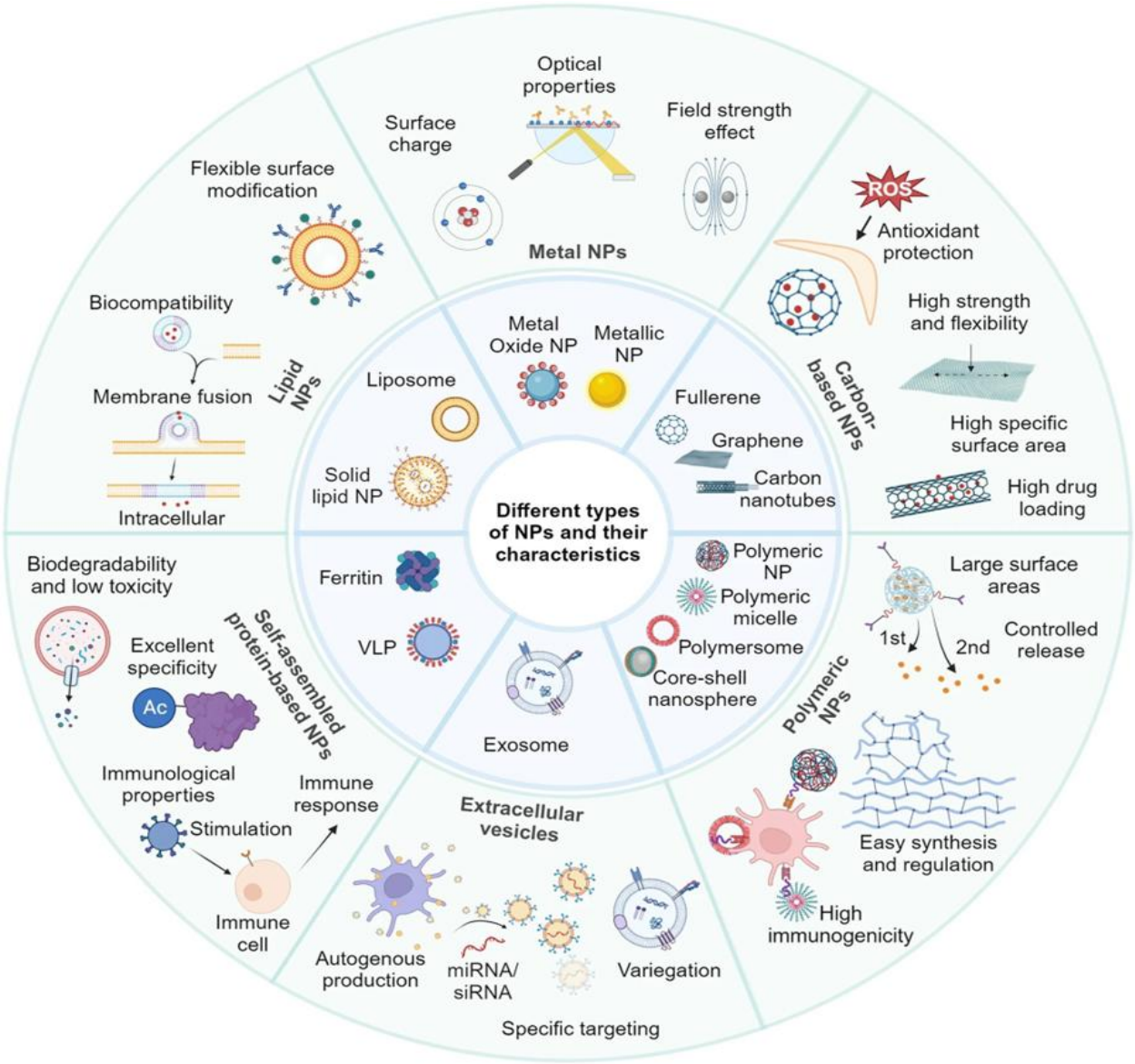

Fig.2. Shows Six common nanomaterials and their characteristics

- ❖ Solid Lipid Nanoparticles (SLNs): - Solid lipid matrices offer stability and biocompatibility. The curcumin and triptolide SLNs not only improve stability and permeability, but also increase the therapeutic effect.
- ➢ Advantages: Stability, bioavailability, protective carrier, scalable manufacture.

- ❖ Nano emulsions and Nanogels: - Nano emulsions allow the dissolution of the water-hating drugs such as andrographolide while nanogels provide a strategy for the easy release of the drugs which are one of the few types of the dull substances like curcumin and silymarin that can be released upon stimulation.
  - ➢ Advantages: Improved solubility, large surface area, scalable, stimuli-responsive release.

- ❖ Phytosomes: - Phospholipid complexes made of silybin and green tea extract are examples of naturally-derived substances that are more easily absorbed and efficacious as a result of complexation.
  - ➢ Advantages: Improved absorption, natural components, stability, suitability for chronic use.

- ❖ Green-Synthesized Metallic Nanoparticles: - More specifically, silver NPs from Azadirachta indica are a new generation of materials that, by a green-synthesis method, regard plant extracts as reducing and stabilizing agents, and such NPs are silver and gold nanoparticles from plants, e.g. nanoparticles are antimicrobial and anticancer agents that have low toxicity.
  - ➢ Advantages: - Green synthesis, biological properties, biocompatibility, synergistic effects.

III. MECHANISTIC INSIGHTS

Nanoscale carriers are drug delivery systems. These are devices that, in essence, act as amplifiers for the administration of drugs of herbal origin, as they dissolve drugs that are otherwise insoluble and they also keep the drugs away from enzymes that may break them down. Moreover, they simplify cellular uptake and targeted delivery through ligand-receptor interaction as well as through physiological barrier infiltration. In this way, controlled release, pharmacokinetics and therapeutic effects can be elevated.

IV. CASE STUDIES OF KEY PHYTOCHEMICALS

- ➢ Curcumin: By liposomes and SLNs the bioavailability and anti-inflammatory activity were raised.
- ➢ Quercetin: The antioxidant capacity of polymeric nanoparticles was enhanced.
- ➢ Epigallocatechin-3-gallate (EGCG): The use of nanocarriers stopped metabolism and as a result, chemoprevention was lifted.
- ➢ Resveratrol, Berberine: - The pharmacokinetics and targeted effects were improved.

V. GREEN SYNTHESIS AND SUSTAINABILITY

In fact, green methods are not only relying on plant extracts as reducing and stabilizing agents for the green production of metal nanoparticles but also for the substantial reduction of toxicants and the increase of biocompatibility. Nevertheless, the problem of quality control over time and scale still exists.

VI. SAFETY, TOXICITY, AND REGULATORY CHALLENGES

The toxicities of nanomaterials depend largely on the nano formulation size, the material used, and the surface properties of the material. In case we want to really make sure that the use of nano-herbal medicines in clinical practice is safe, then a complete toxicological evaluation as well as the establishment of the regulatory framework is necessary.

VII. FUTURE PERSPECTIVES

The future sees the combination of nanotechnology and personalized medicine, artificial intelligence, and pharmacogenomics as the major factors that will bring the precision and effectiveness of herbal therapies to a level never before. Among other things, the focus on clinical trials, eco-friendly production, and the establishment of global regulatory standards will result in a quicker clinical uptake of this technology.

VIII. CONCLUSION

Nanotechnology is one of the game-changing innovations in herbal drug delivery that has a perfect fit for the problems of solubility, stability, and targeted delivery of drugs. The degree of progress made from 2019 to 2025 is a vivid representation of the potential of herbal nanomedicines not only to be effective and safe but also to be personalized. The main factors that largely determine the clinical mainstream practice are

the continuous interdisciplinary research along with the regulatory harmonization.

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