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Redefining the functions of nanocapsule materials

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Nanocapsules are key components in new technologies related to biomedicine and materials science. However, their long-term fate after use is still largely ignored. We discuss here a sustainable approach where the products of degradation of the nanoparticles play a significant role in their application because they are also functional molecules. The polymer shell of the nanocapsules is chemically engineered so that the degradation products formed upon chemical damage are useful after their normal use.

Introduction

Nanocapsules are used as dispersions or embedded in matrices for biomedical and materials applications. However, the long-term fate of the nanoparticles after their use is still largely ignored. Moreover, most of the materials in nanoparticles and nanocapsules are actually “dead materials” in the sense that their degradation products do not play an important role. These materials are either inert or even detrimental to their applications if their degradation products are toxic or lower the properties of the matrix in which they are embedded. One possibility to overcome this issue would be to recycle nanoparticles that do not degrade easily. Metallic nanoparticles are recovered by inducing liquid–liquid phase separation by heating microemulsions,¹ decantation of inorganic nanoparticles used as catalysts and as Pickering stabilizers,² or filtering nanoparticles using a supramolecular membrane.³ However, polymer nanoparticles are difficult to re-disperse and remain intact. Moreover, recycling nanoparticles is not a concern for biomedical applications.

We discuss here a sustainable approach where the products of degradation of nanoparticles play a predominant role because they are also functional molecules. This approach considers the lifetime of the nanoparticles. Therefore nanoparticles have to be carefully designed, keeping in mind that the material composing the nanoparticles is used to yield functional degradation products. The approach can be combined with retrosynthetic analysis⁴ with additional conditions concerning the degradation products. Similarly to the renewable carbon index (RCI) for green chemistry,

we define here the active molecule index (AMI). The AMI is the percentage of active molecules within all degradation products of the nanoparticles. We briefly review here the different strategies to synthesize nanocontainers that release functional molecules upon their degradation and discuss their AMI values. We envision the future of colloid chemistry for which the Latin adage “*multum in parvo*” (much in little) will be truly applied by designing efficient nanocontainers that will serve not only during but also after their lifetime.

From classical synthesis to the design of sustainable nanocontainers

Classically, the synthetic molecules produced by industry are designed following retrosynthetic analysis taking into consideration the cost and availability of raw chemicals. Because of the new concerns of society regarding sustainability, several principles of synthesis were introduced as green chemistry labels.^{5,6} One important value linked with sustainable chemistry is the so-called renewable carbon index (RCI). The RCI is the percentage of carbon in the synthesized molecule that originates from a renewable feedstock.⁷ Typically, the carbon atoms from renewable feedstocks come from fatty acids or glycerol for example.^{8,9} Nowadays, further requirements imply that the renewable feedstock shall not compete with the food chain. This is the case for instance for L-lactide, cellulose, or terpenes. This means that the main concerns are that the raw material is cheap and is derived from renewable resources.

The function of nanocontainers can be typically fulfilled at low concentrations.¹⁰ This means that concerns about cost and renewable feedstock are less important because they do not represent a large fraction of the materials compared to the matrix in which they are embedded. The most important criteria to

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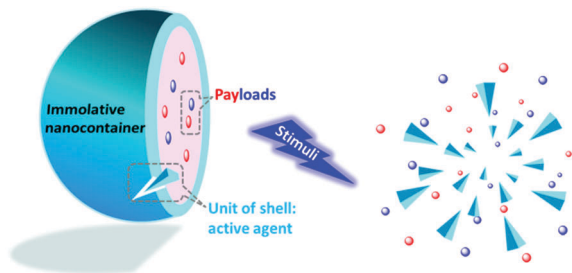


Fig. 2 Scheme of the nanocontainers with encoded active substances that are released during their degradation.

drug–drug conjugate to form nanoparticles. The hydrophilic irinotecan and the hydrophobic chlorambucil, both anticancer drugs, were conjugated *via* a hydrolysable ester linkage.³¹ The amphiphilic molecules were used to create nanoparticles, which displayed a longer blood retention half-time compared to free drugs. This allowed for the accumulation of the prodrug in tumor tissues and the ester bond could be cleaved by hydrolysis after cellular internalization. Anticancer activity was demonstrated *in vitro* and *in vivo*.

Encoding the active agents for promoting the co-release of multiple payloads from nanocontainers

The encoding of the active payload to be released in a polymer which forms the nanocontainers can be also used to release a second payload during the degradation of the nanocontainers. This approach was demonstrated by synthesizing amphiphilic copolymers with solubilizing units (polyvinylpyrrolidone) and units bearing the functional molecules to be released (Fig. 4d).³² The active payload was selected to be the corrosion inhibitor mercaptobenzothiazole that was bound with a disulfide linkage to the main chain of the copolymer. Nanoparticles were formed by self-assembly in water and were able to encapsulate an additional hydrophobic payload. The cleavage of the disulfide bonds led therefore to the simultaneous release of the corrosion inhibitor and the second payload. The AMI could be tuned between 2 and 22%, depending on the ratio of monomers in the copolymer. Such an approach was also demonstrated in the case of large poly(anhydride-ester) microparticles based on salicylic acid. The anti-inflammatory drug salicylic acid could be released from the microparticles by hydrolysis, thereby triggering the release of encapsulated insulin.³³ The AMI calculated by taking into account the produced salicylic acid and the released insulin was 70%. In this case, the encapsulated insulin was distributed inside the monolithic polymer microparticles and not encapsulated in the core of a capsule.

The ratio of active molecules to be released can be substantially increased not only by employing the aforementioned strategy but also by designing the nanocontainers as core–shell nanoparticles with a functional liquid core instead of homogeneous monolithic nanoparticles.³⁴ For this, block and random copolymers bearing corrosion inhibitors in the side-chain were used to form nanocapsules with a liquid self-healing agent physically entrapped in the core of the nanocapsules (Fig. 3). The release



Fig. 3 AFM and SEM images of block copolymer nanocapsules with corrosion inhibitors chemically encoded in the shell for a triggered release of both the corrosion inhibitor and a liquid self-healing agent present in the core of the nanocontainers.³⁴



Fig. 4 Examples of copolymers with active molecules (marked in blue) as pendant groups in their main chains or side chains showing release of these active molecules after cleavage of the corresponding bond.^{24–26,32–34}

of the corrosion inhibitors triggered a second release of the entrapped self-healing agent and the system could reach an AMI of 56%. The release rate could also be controlled by the structure of the copolymer, *i.e.* random or block.

Perspectives

The systems proposed are still far from being fully developed and many interesting properties could be implemented in new



nanocontainers to increase their efficiency and AMI value. The ideal nanocontainers would have an AMI value of 100% meaning that all materials forming the shell can be degraded to useful and active molecules (Fig. 2). The liquid core and the shell would therefore need to be degraded to form functional molecules. The functional molecules can be either chemically attached to the core or shell or physically bound. Such a concept is not only applicable to nanocontainers but also to other types of nanomaterials. The design could be combined with the self-immolative concept³⁵ so that degradation could be accelerated upon demand. For biomedical applications, the concept could also be combined with photodynamic therapy,^{36,37} so that part of the degraded material becomes phototoxic while the rest of the degraded material is active but non-toxic. Indeed, toxicity issues in circulation and *in vivo* continue to be major issues that need to be carefully investigated before a product is approved for human trials. Finally, this approach could be employed to release very fragile or reactive ingredients as is the case in biology. For instance, preprohormones are produced in the body to protect hormones such as vasopressin that possess a very short lifetime.³⁸

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