



# Integrative strategies to hybrid lamellar compounds: an integration challenge

Francisco M. Fernandes, H. Baradari, Clément Sanchez

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8 **Integrative strategies to hybrid lamellar compounds:**  
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11 **F.M. Fernandes<sup>a,b,c</sup>, H. Baradari<sup>a,b,c</sup>, C. Sanchez<sup>a,b,c,\*</sup>**

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14 <sup>a</sup> *Sorbonne Universités, UPMC Univ Paris 06, UMR 7574, Chimie de la Matière Condensée*  
15 *de Paris, F-75005, Paris, France.*

16 <sup>b</sup> *CNRS, UMR 7574, Chimie de la Matière Condensée de Paris, F-75005, Paris, France.*

17 <sup>c</sup> *Collège de France, UMR 7574, Chimie de la Matière Condensée de Paris, F-75005, Paris,*  
18 *France.*

19  
20  
21 \* Corresponding author: clement.sanchez@college-de-france.fr

## 1    **Abstract**

2    During the past decades, the potential derived from the hybridization of inorganic materials,  
3    has been widely studied and presented. The capability of tuning materials' performances, not  
4    only in terms of tailoring their physico-chemical properties to answer prerequisites of a given  
5    application, but also regarding the elaboration of novel concepts, opened a door to a radical  
6    new world in materials science. However, as a consequence of their diverse chemistry,  
7    structure, envisaged applications and historical background, each subgroup of inorganic  
8    lamellar compounds were usually discussed separately. This review intends to reflect upon the  
9    different categories of lamellar compounds and their hybridization strategies, regardless of  
10   their chemical and historical differences. The hybridization strategies of lamellar compounds  
11   are divided and presented under two main categories. Firstly, the intercalation/exfoliation  
12   approach, where the hybridization of lamellar compounds is operated in pre-formed inorganic  
13   layered materials. Secondly, the *in-situ* synthesis methods, where the hybrid character of the  
14   layered compound is imparted simultaneously along with the layered inorganic compounds  
15   synthesis routes. Finally, in order to tackle the important question of "*the place and role of*  
16   *hybrid lamellar compounds in consumer end-products, an integration challenge*", the proven  
17   concepts and potential applications defined for these organic-inorganic compounds are  
18   discussed.

## 19   **Table of abbreviations**

20   AMP: Aminopropyl-functionalized magnesium phyllosilicate

21   CSH: Calcium silicate hydrate

22   CPN: Clay polymer nanocomposite

23   DNA : Deoxyribonucleic acid

24   DS : Dodecylsulfate

25   LHDS: Layered hydroxyl double salts

26   LDH: layered double hydroxide

27   LHS: Layered hydroxide salts

- 1 LMC: Layered metal chalcogenides
- 2 Mt: Montmorillonite
- 3 PILC: Pillared interlayered clays
- 4 MX<sub>2</sub>: Metal dichalcogenides
- 5 MX<sub>3</sub>: Metal trichalcogenides

## 6 **1. Introduction**

7 Hybrid lamellar compounds are ubiquitous in materials science (Usuki et al., 1993; Giannelis,  
8 1996; Leroux and Taviot-Guého, 2005; Ruiz-Hitzky et al., 2007; Sanchez et al., 2011). Their  
9 widespread presence from laboratory benches to industrial plants is the image of a  
10 fundamental research area that has profoundly impacted numerous applied domains. A quick  
11 overview of the literature focused on lamellar hybrid materials show domains of application  
12 as disparate as heterogeneous catalysis (Okada et al., 2012), adsorption (Lagadic et al., 2001),  
13 nanocomposites (Ray and Okamoto, 2003), sensors (Aranda et al., 2006) or optics-related  
14 materials (Mane and Pinna, 2006). Such variety of application has led to a consensus around  
15 the idea that synthesizing hybrid compounds from their inorganic layered precursors is an  
16 interesting strategy to tailor many of the latter properties.

17 Most of the advances on hybrid lamellar compounds elaboration have been led by research  
18 groups previously working on the inorganic counterpart. As a consequence, much the  
19 advances in hybrid lamellar compounds were led forward in different moments and by  
20 researchers with different backgrounds. Such asynchronous interest on layered hybrid  
21 materials justifies the heterogeneous state-of-the-art presently found in the literature, both in  
22 their synthesis and their application. The clay community, for instance, has soon agreed on the  
23 potentialities of hybrid clay compounds, following the pioneer works led by Gieseking  
24 (1939), MacEwan (1948) and Jordan (1949) on organoclays. Such advances were  
25 contemporary to the description of metal phosphates' cation exchange properties (Kraus and  
26 Phillips, 1956; Alberti, 1978; Clearfield, 1988, 2012) which paved the way for the  
27 development of phosphate and phosphonate hybrid materials (Cao et al., 1992). The first

1 systematic study of the intercalation of different organic and inorganic anionic species in the  
2 interlayer space of layered double hydroxides (LDH) was not reported until the early 1980s  
3 (Miyata, 1983).

4 Despite the history of lamellar compounds hybridization, the most salient feature in these  
5 materials is a common and unifying factor: their *morphology*! Independent from the chemical  
6 nature of the inorganic structure, the strategy used by the different research groups was, in  
7 most cases, to modify the interlayer space of the inorganic layered host. Such approach arises  
8 as a consequence of the two-dimensional morphology of inorganic layered compounds.  
9 Numerous examples are available to strengthen this analysis: i) swelling of clay minerals  
10 using caprolactam to perform *in situ* polymerization of Nylon (Fukushima and Inagaki, 1987);  
11 ii) intercalation of polyoxymetalate anions in LDH to attain pillared structures (Dimotakis and  
12 Pinnavaia, 1990) or iii) the delamination of  $\alpha$ -zirconium phosphate crystals by the  
13 intercalation of alkylammonium anions (Alberti et al., 1985, 2000). In each of the preceding  
14 cases the common goal is to fine-tune the distance and relative order between the inorganic  
15 layers by the nature of the guest chemical species. It is worth underlining that the lamellar  
16 compounds are able to retain chemical species only with electrical charges compatible with  
17 those of the layers. One of the major driving forces behind the intercalation of guest species in  
18 the interlayer space of layered compounds relates to the affinity between both entities. Charge  
19 matching naturally accounts for a very important part of such affinity. Organic cations are  
20 likely to intercalate into negatively charged clay mineral layers, conversely, anionic species  
21 are efficiently intercalated within the interlayer space of positively charged layered double  
22 hydroxides lamellae. The electrostatic affinity can also be tailored by the insertion of excess  
23 cations, switching the layered compound's affinity from an anion-exchanger to a cation-  
24 exchanger or vice-versa.

25 If the hybridization of layered inorganic materials has become widespread across  
26 materials-related disciplines (with quite few yet surprising exceptions), the integration of the  
27 referred hybrid materials into devices and consumer end products is an entirely different  
28 matter. This article addresses two dimensions of hybrid layered materials. First, it briefly  
29 reviews the main strategies to fabricate hybrid layered compounds with new or improved  
30 functionality; and second, it surveys how these new building blocks are being integrated from  
31 both a conceptual and technologic point of view.

## 2. Lamellar compounds

Inorganic layered solids being the backbone of hybrid layered compounds, a brief description of the different layered solids, under consideration in this review, is appropriate. Moreover, since these compounds have been scarcely treated together (Nicolosi et al., 2013), the overview of the different inorganic layered solids selected for this review intends to present a collective analysis on their structures.

A layered compound is a crystalline material wherein the intralayer atoms are linked by covalent, ionic, ionocovalent or metallic bonds, while the interlayer atoms interact through weaker electrostatic forces mediated (when present) by interlayer species (Schoonheydt et al., 1999). The interest of such brief explanation on the nature of bonds in inorganic layered solids is two-fold. From a fundamental point-of-view, it describes the nature of the interactions between the different atoms of the inorganic solid. In a more pragmatic look, it highlights the energetic difference between the bonds within the inorganic layer and those in between adjacent layers. This latter leads the reader to the logic behind the modification strategies in this class of compounds.

In terms of lexicon, few precisions are needed, despite the different disciplines that have treated the subject of layered structures. A single layer is called a lamella, slab, or sheet (Alberti and Constantino, 1996), as a consequence, the terms interlayer and interlamellar are used to define the gap between adjacent layers.

Clay minerals, layered metal hydroxides, layered simple hydroxides known as layered hydroxy double salts, calcium silicate hydrates, layered metal oxides metal phosphonates, metal phosphates and layered metal chalcogenides are the treated compounds in this section. Simplified structures of these layered compounds are illustrated in figure 1.

### 2.1. Clay minerals

Clay minerals are at the epicenter of hybrid lamellar materials research. Even though their origin and chemical nature have been perfectly identified for decades, their exact definition is an ongoing subject of debate (Bergaya and Lagaly, 2006). The precise definition of a clay or a

clay mineral is not within the scope of this article but, given the wide variety of compounds below the clay umbrella name, it is useful to discriminate which structures are referred to as clay minerals throughout this work. Due to the layered nature/nano-morphology of the materials under discussion, clay minerals displaying a fibrous habit such as sepiolite and palygorskite, as well as clay minerals displaying rolled up inorganic layers such as halloysite or chrysotile, fall out of the scope of this work and are not discussed. Within the layered clay minerals this review focuses on planar hydrous phyllosilicates (Fig. 1a). No structural difference will be pointed out between TO or TOT clay minerals, despite the interlayer charge dissimilarity that derives from such structural differences (Auerbach et al., 2004; Bergaya et al., 2006b).

The knowledge of the crystalline structure of clay minerals is the ultimate tool to rationally design clay mineral-based materials. Insight on clay mineral structure followed the early developments in X-ray diffraction (XRD) techniques in the transition between the XIX and XX centuries (Bergaya et al., 2006a). In parallel with fundamental research on the structure of clay minerals, a variety of new applications emerged. The most notable of which were linked to the rheological (Stephenson, 1927), mechanical reinforcement of rubbers (Thies, 1925) and their adsorption properties (Bradley, 1945), both closely related to the physical and chemical phenomena occurring at the interlayer space of clay minerals. The most relevant features of clay mineral regarding their potential use as hybrid lamellar compounds are thus the layered morphology alongside with net layer charge per unit formula. Since the layer's charge varies from neutral to negative, adjacent clay mineral layers are compensated by cations that stabilize the clay particles. Knowing the cation exchange capacity (CEC) of clay minerals is an effective method to estimate which species can be used and to what extent can the interlayer space of clay minerals be modified.

## 2.2. *Layered Metal Hydroxides*

The simplest examples of this category of layered metal hydroxide compounds are brucite, *i.e.* magnesium hydroxide and gibbsite, *i.e.* aluminium hydroxide. Brucite-like structures are composed of divalent cations coordinated octahedrally by hydroxide ions, that is to say these cations are placed in the center of octahedra with hydroxide groups located in vertices.

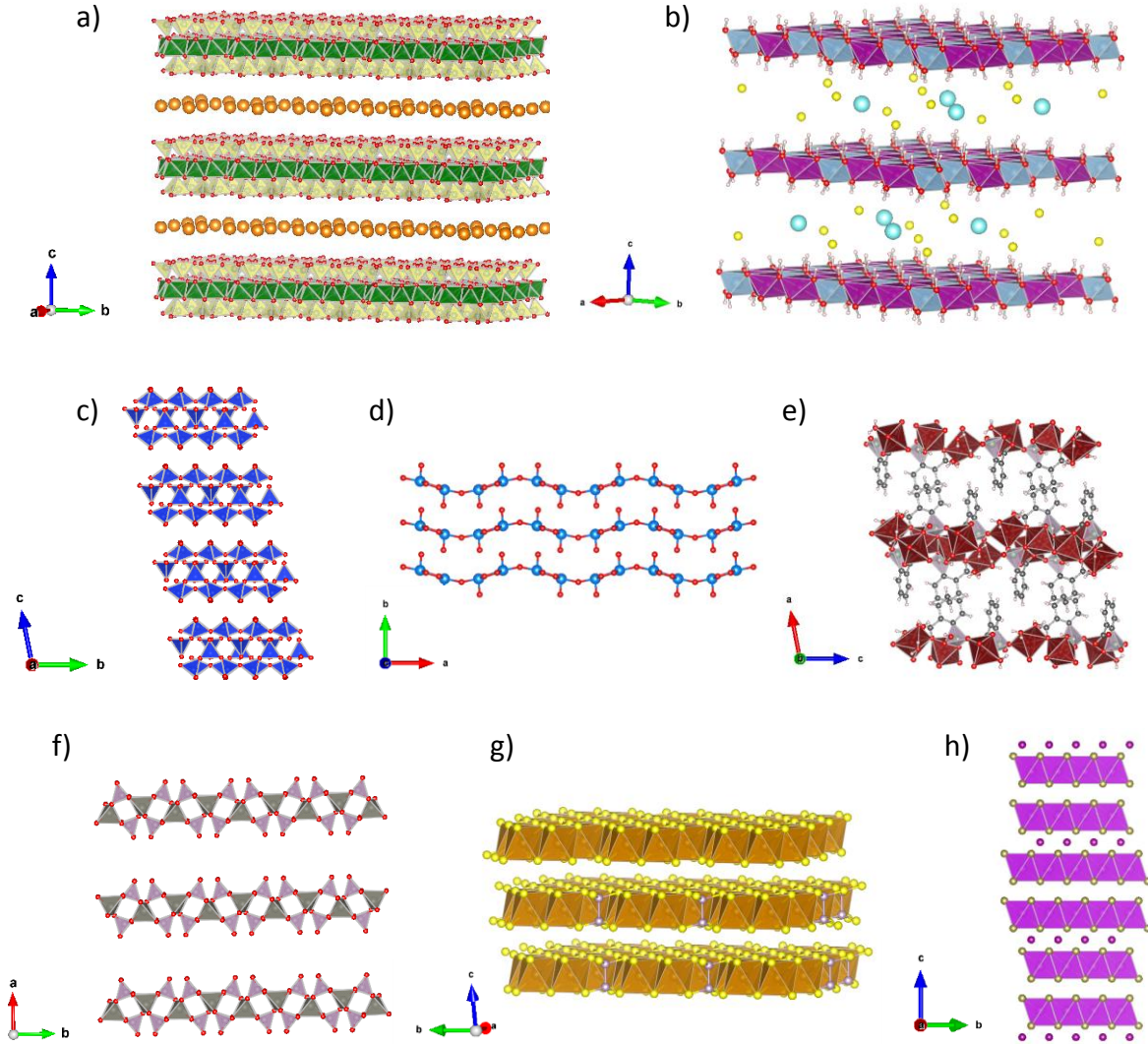
1 Octahedral units share edges to form infinite neutrally charged layers. Calcium, manganese,  
2 iron, cobalt and nickel hydroxides are well-known examples of metal hydroxides with  
3 brucite-like structures. The brucite structure can undergo chemical, as well as slight structural  
4 modifications to form more complex metal hydroxides such as layered hydroxide salts (LHS),  
5 layered double hydroxides (LDH) and layered hydroxy double salts (LHDS), also known as  
6 “double hydroxide salts” (Arizaga et al., 2007).

7 Brucite-like structures can experience the substitution of a part of hydroxide groups by  
8 appropriate anions or water molecules, resulting in formation of a structure called layered  
9 hydroxide salt (LHS), also called layered simple hydroxides (LSH). The general formula of  
10 LHS corresponds to  $M^{2+}(OH)_{2-x}(A^{m-})_{x/m} \cdot nH_2O$  where  $M^{2+}$  is the metal cation (*e. g.*  $Mg^{2+}$ ,  
11  $Ni^{2+}$ ,  $Zn^{2+}$ ,  $Ca^{2+}$ ,  $Cd^{2+}$ ,  $Co^{2+}$ ,  $Cu^{2+}$ ) and  $A^{m-}$  is the anion (*e.g.*  $Cl^-$ ,  $NO_3^-$ ,  $SO_4^{2-}$ , dodecylsulfate,  
12 dodecylsulfonate and acetate). Briefly speaking, their structure is composed of triangular  
13 arrays of octahedral divalent cations, separated by anions, coordinating with metal ions and  
14 interlayer water molecules. In this type of structures the anion is not grafted to the inorganic  
15 layers by iono-covalent bonds to metal. Numerous organic molecules can be intercalated in  
16 the interlayer space *via* anion-exchange and form divers layered hybrids (Ghose, 1964;  
17 Stählin and Oswald, 1970; Petrov et al., 1989; Newman and Jones, 1999; Biswick et al., 2006;  
18 Arizaga et al., 2007; Rogez et al., 2011). Numerous studies were focused on the synthesis of  
19 transition-metal LHS, because of their interesting magnetic properties, which found out to be  
20 tunable by the type and the length of organic molecules, present as counter-ion (Rabu et al.,  
21 1993; Fujita and Awaga, 1996; Kurmoo et al., 2003; Forster et al., 2004; Kojima et al., 2007 ).

22 LDH are intriguing compounds. They display many physical and chemical properties that are  
23 surprisingly similar to those of clay minerals (Forano et al., 2006). However LDH are not  
24 silicates but metal hydroxides. They present bivalent and trivalent metallic cations on their  
25 lamellae according to the following general formula  $[M^{II}_{1-x}M^{III}_x(OH)_2]$ . These compounds can  
26 also be described as a brucite-like structure which undergoes an isomorphic substitution of  
27 cations, *i.e.* a part of divalent cations replaced by trivalent ones. Hence, the excess positive  
28 charge of the layers permits the interlayer space of LDH hosting anionic species that  
29 compensate the charge excess of the lamellae, according to the formula,  $[X^{q-}_{x/q} \cdot nH_2O]$  (Fig. 1-  
30 b). Such simple chemical definition explains three of the main characteristics of LDH. The  
31 first derives from the multitude of compositions which are allowed to be intercalated between

the layers. Natural LDH can be found bearing a wide variety of bivalent metal cations such as  $\text{Mg}^{2+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Mn}^{2+}$ ,  $\text{Zn}^{2+}$  as well as various trivalent cations,  $\text{Al}^{3+}$ ,  $\text{Cr}^{3+}$ ,  $\text{Mn}^{3+}$ ,  $\text{Fe}^{3+}$ ,  $\text{Co}^{3+}$ ,  $\text{Mg}^{3+}$ . The second relates to the  $\text{M}^{\text{II}}$  to  $\text{M}^{\text{III}}$  ratio. LDH found in nature tend to present fairly rigid ratio between both cations. Synthetic LDH are much more flexible in this regard displaying  $\text{M}^{\text{II}}$  to  $\text{M}^{\text{III}}$  ratio between 1 and 5 (Forano et al., 2006). The last characteristic that can be easily withdrawn from the general formula is that the layer charge of LDH layers is positive and these are thus compensated by anions which can be easily exchanged. That is why LDH have also been called “anionic clays”. The ensemble of characteristics referred to this far would make LDH an excellent candidate for hybrid compounds design. However, one last important feature renders LDH even more attractive, the multiplicity of synthetic procedures. A profusion of methods is available to prepare LDH as has been thoroughly surveyed elsewhere (He et al., 2006). It is, however, important to note that the diversity of methods allowing to obtain LDH is one of the driving forces behind the advances in LDH-derived hybrid materials and applications (Li and Duan, 2006).

LHDS are synthetic layered materials with positively charged layers. Their general formula consists in  $[(\text{M}^{2+}_{1-x}\text{Me}^{2+}_{1+x})(\text{OH})_{3(1-y)}]\text{X}^{n-}_{(1+3y)/n} \cdot z\text{H}_2\text{O}$ , where  $\text{M}^{2+}$  and  $\text{Me}^{2+}$  correspond to divalent metals, such as Cu, Co, Ni, Mn, or Zn and  $\text{X}^{n-}$  is the exchangeable anion. The LHDS structure has also been described as an LHS containing two different cations (Arizaga et al., 2007). Generally speaking, their layers are composed of divalent metal ions stabilized in the two-dimensional lattice similar to the brucite structure with some vacant octahedral and a part of the metal ions are positioned above and below the vacant sites outside the hydroxide layer to form tetrahedral coordination (Petrov et al., 1987). This coordination results in the excess of positive charge of layers. Hence, the LHDS, similar to LDH, can accommodate anionic species within interlayer space to compensate the positive layer charge by anion-exchange reactions (Meyn et al., 1993; Tronto et al., 2006; Rojas et al., 2010). Their structure can be stabilized by electrostatic interaction between layers and anions or by a hydrogen bond network between water molecules, interlayer anions and interlayer hydroxyl groups.



**Figure 1** - Simplified representations of several layered inorganic compounds: a) a calcium montmorillonite (Viani et al., 2002); b) shigaite  $[\text{AlMn}_2(\text{OH})_6]_3(\text{SO}_4)_2\text{Na}(\text{H}_2\text{O})_6 \cdot 6\text{H}_2\text{O}$ , a layered double hydroxide (Cooper and Hawthorne, 1996); c) tobermorite, a calcium silicate hydrate (Mrlino et al., 1999); d) vanadium pentoxide layered structure (Filonenko et al., 2004); e) schematic representation of  $\text{Co}_3(^{2-}\text{OOC}\text{C}_6\text{H}_4\text{PO}_3)_2(\text{H}_2\text{O})_3 \cdot \text{H}_2\text{O}$  layered metal phosphonate featuring a 2-carboxyphenylphosphonic acid as organic building block, viewed along the b axis (Wang et al., 2011); f) a layered zinc phosphate (Choudhury et al., 2002) g) a layered iron hexathiohypodiphosphate,  $\text{MPS}_3$  (Clement et al., 1986) and h)  $\text{Bi}_2\text{MnTe}_4$  chalcogenide displaying mixed interlayer space (Lee et al., 2013).

### 2.3. Calcium silicate hydrates

Calcium silicate hydrates (CSH) are mainly discussed in cement science area, because this hydrated phase of major components of cement, *i.e.* calcium silicates, is the “glue” within

concrete. Formed during the hydration of cement grains, it plays the role of binding phase between cement particles. CSH also occurs in nature *via* hydrothermal alteration of calcium carbonate rocks and/or vesicle fillings in basalts (Taylor, 1989). Owing to their interesting physicochemical properties, they were synthesized and used as catalysis for nuclear and hazardous waste disposal (Komarneni and Breval, 1986), inorganic Portland cement hardening additive (Thomas et al., 2010), to recover phosphorous from solutions (Okano et al., 2013) and to develop orthopaedic drug delivery systems (Wu et al., 2013). Different phases and respective structures of CSH have been reviewed in detail by Richardson (Richardson, 2008).

Briefly speaking, the smallest CSH unit has a layered structure, with unidirectional elongated layers, resulting in a ribbon-like structure. Each layer consists in a central CaO sheet, sandwiched between two linear chains of silica tetrahedra (Fig. 1-c). Among several structural models for CSH, the most accepted and applied models are based on the crystal structures of jennite and tobermorite minerals. The silicate chains of these minerals have *dreierkette* structure. In this structure, each pair of silica tetrahedra, called pairing tetrahedra, shares O-O edges with CaO octahedral of the central sheet and it is followed by a silica tetrahedron, called bridging tetrahedron, sharing only O vertices with CaO. This pattern is repeated at intervals of three silicate tetrahedra. In tobermorite CaO layers have bare Ca cations, protonated bridging tetrahedra forming silanol groups and the interlayer spaces contain water molecules and additional Ca cations to compensate the negative charge of the layer. In jennite Ca cations of the CaO layers are monohydroxylated causing a considerable corrugation of CaO layers; some of the O atoms in this layer are shared with dreierketten and the others with water molecules and OH groups, creating Ca-OH bonds.

CSH share several features with smectites, such as layer morphology, intrinsic negative charge of layers and hydrated interlayer spaces. However, compared to smectites, lateral extension of the layers is limited, CSH have a high stacking disorder and cations of the interlayer spaces are hardly exchangeable (Merlin et al., 2002; Van Damme and Gmira, 2006).

#### 2.4. Layered Metal Oxides

Simple and mixed metal oxides are certainly the most heterogeneous family of compounds discussed in this review. Given the large array of compounds generally described by such large definition, a large structural variability can be found. Metal oxides are commonly arranged in bulk phase where some of them can, under adequate synthesis conditions, form 2D structures. Many examples of transition metal oxides according to the formula  $MO_2$ , where M is a transition metal such as Sc, V, Cr, Mn, Fe, Ni, Mo, W, Ti, Nb, exist in 2D morphology (Osada and Sasaki, 2009; Ataca et al., 2012). In the preceding cases, the metal is hexa-coordinated giving rise to different arranged octahedral polyhedra, stacked to form layered materials, with cations or water molecules between layers to compensate the charge. According to the IUPAC definition of an oxide network (Alemán et al., 2007) and its 2D morphology, vanadium pentoxide,  $V_2O_5$ , is also a layered metal oxide. However it displays a dramatically different layered waving structure composed of vanadium in square pyramidal coordination (Fig. 1d) (Livage, 1991). Moreover, other authors have described the layered metal oxides according to the general formula  $A_xMO_2$ , where A is an alkali-metal ion and M can be one or several ions with various oxidation states (Delmas et al., 1980). This discrepancy in the basic lexicon of layered metal oxides is itself revelatory of the different approaches to these materials as well as the different research fields involved.

Regardless of the different approaches and definitions one common factor is patent: a myriad of applications such as catalysis (Kuhlenbeck et al., 2013), photocatalysis (Zou et al., 2001), thermoelectric materials (Terasaki et al., 1997), solar cells (Kim et al., 1993) sensors or superconductors (Takada et al., 2003), have been proposed for layered metal oxides.

## 2.5. *Metal Phosphonates*

Metal phosphonates with layered structures, classified as organic-inorganic hybrid solids, (Fig. 1e) represent attractive features of both hybrid and layered materials. The metal-O-P and P-C linkages, having quite good stability compared to silicon-based coupling agents, represent a good alternative in organic-inorganic hybrid materials. The versatility of phosphorous chemistry permits to tune characteristics of these materials and thus several applications such as ion exchange, proton conduction, catalysis or sensing are well-known examples.

For most of metals, metal phosphonates have a layered structure, with organic group being more or less perpendicular to the interlamellar space. One typical structure of divalent metal phosphonates, with general formula of  $MII(O_3PR) \cdot H_2O$ , consists in parallel compact layers of metal oxides, in octahedral configuration, sharing four corners with neighboring octahedra and one corner and an edge with two phosphonate tetrahedra; the oxygen atoms of the phosphonate tetrahedra are parallel with the inorganic layer and their organic moiety pointing the interlayer space, forming an organic bilayer between inorganic lamella (Fig. 1e). Therefore, the interlayer space distance, as well as its characteristics, is adjustable by the size and nature of organic molecule. Simple alkyl phosphonates create van der Waals bonding between the end groups of the alkyl chains of adjacent layers. Stronger interlayer bonding can occur by incorporation of hydrogen bonding at the ends of the alkyl chains, e.g.,  $M(O_3PCH_2CH_2COOH)_2$ . The lateral distance between organic groups can be altered by changing the metal ion used in forming the solid.

Although this layered structure forms with most of the trivalent metals and it is the sole existing layered structure for tetravalent metals, formation of a simple lamellar structure largely depends on the size of the organic group. The reason behind this behavior is that the structure of these materials depends on the type of bonding in the inorganic network, i.e. metal-phosphonate bonding, which makes a scaffold for organic groups to lie on (Auerbach et al., 2004; Vioux et al., 2004; Mutin et al., 2005).

## 2.6. Layered Metal Phosphates

Layered metal phosphates represent similar structural features as the layered metal phosphonates. The structure of most of the known metal phosphonates is related to a purely inorganic metal phosphate. Many of these layered materials with their rich chemistry are excellent inorganic ion exchangers with a peculiar selectivity (Clearfield, 1988).

The structural motif of metal phosphates is composed of the planar di- or trivalent metal cations, knitted together by phosphate oxygens above and below the layer plane (Cao et al., 1992). Layered metal phosphates having similar structure (Fig. 1f and 1g), have been mostly described with reference to the  $\alpha$ -,  $\gamma$ - and  $\lambda$ -zirconium phosphates. Geometrically speaking, each bi-dimensional layer is formed by concatenation through the vertices of polyvalent metal octahedral and phosphate tetrahedral. The structures similar to that of the  $\alpha$ -zirconium

phosphates are monoclinic, in which each tetrahedron bridges three different octahedral and these latter bridge six tetrahedral. The arrangement of the pendent phosphate groups in the interlayer space creates cavities, containing water molecules. In a typical  $\gamma$ -compound, metal atoms are bonded by both phosphate tetrahedral and  $\text{H}_2\text{PO}_4$ . The  $\text{H}_2\text{PO}_4$  shares two oxygens with two different metal atoms and points the remaining two OH groups to the interlayer (Alberti et al., 1999). In the  $\lambda$ -structure, a layer is composed of four different metal atoms bridged together with a tetrahedral phosphate group, compensating the residual positive charge as well as completing the octahedral configuration of each metal atom with a monovalent anionic ligand,  $\text{Cl}^-$  and a neutral monodentate ligand (Auerbach et al., 2004).

## 2.7. *Layered Metal Chalcogenides*

Owing to their interesting yet intriguing physico-chemical characteristics of these layered two-dimensional (2D) materials, layered metal chalcogenides (LMC) attracted attentions of researchers. Many interesting physical and chemical properties of LMC stem from the anisotropic nature of the layers, resulting in technologically useful mechanical, electrical, magnetic, and optical properties.  $\text{MoS}_2$ ,  $\text{NbS}_2$ , and  $\text{WS}_2$  are examples of LMCs which are used both as solid lubricants and as additives in liquid lubricants in several technological applications. Several transition metal dichalcogenides, such as  $\text{MX}_2$  ( $\text{M} = \text{Ta}, \text{Ti}, \text{V}, \text{Mo}$ , or  $\text{Cr}$ ;  $\text{X} = \text{S}$  or  $\text{Se}$ ) were used as cathodic (positive) insertion electrode in rechargeable alkali metal batteries. Transition metal trichalcogenides have demonstrated interesting electrochemical properties for battery application. The group V transition metal dichalcogenides  $\text{MX}_2$  ( $\text{M} = \text{Ta}$  or  $\text{Nb}$ ;  $\text{X} = \text{S}, \text{Se}$ , or  $\text{Te}$ ) are metallic superconductors.

LMC are usually categorized by their composition. They are either binary compounds, including metal dichalcogenides ( $\text{MX}_2$ ) and metal trichalcogenides ( $\text{MX}_3$ ), or ternary compounds, including  $\text{AM}_2\text{S}_5$ ,  $(\text{AS})_n(\text{MS}_2)_2$  (known as misfit layer) and metal phosphorus trichalcogenides ( $\text{MPX}_3$ ). LMC contain neutral layer structures except some compositions which have negatively charged layers. An LMC is either semiconductor, or semimetallic or metallic as a function of metal cation present in its structure. For example,  $\text{MoS}_2$ ,  $\text{MoSe}_2$ ,  $\text{WS}_2$ , and  $\text{WSe}_2$  are semiconductors, whereas  $\text{MX}_2$  ( $\text{M} = \text{Ta}$  or  $\text{Nb}$ ;  $\text{X} = \text{S}, \text{Se}$ , or  $\text{Te}$ ) are metallic. While  $\text{TiS}_2$  has a semiconductor–semimetallic phase transition,  $\text{TiSe}_2$  is a semimetal.

Generally speaking, LMCs structure consists in layers of covalently bounded atoms with Van der Waals interaction between layers. In each individual layer metal atoms arranged hexagonally, sandwiched between two hexagonal sheets of chalcogen, forming a two-dimensional electron bond layer. The individual 2D layers can self-assemble into face-to-face-stacked layers, forming a LMC (Fig. 1h) (Auerbach et al., 2004).

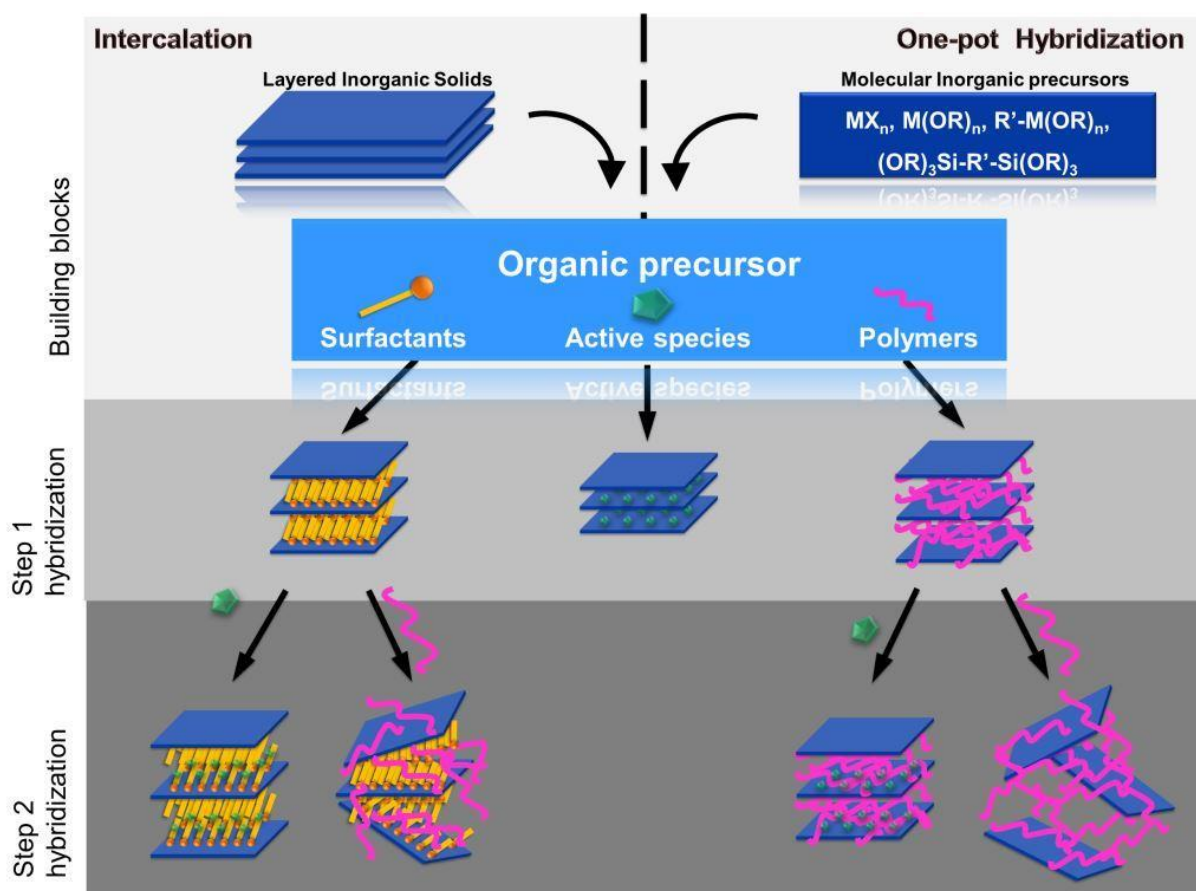
### 3. Lamellar compounds hybridization strategies and approaches

The picture of inorganic lamellar compounds beside each other, regardless of their chemical composition (*c.f.* Figure 1), can easily lead keen eyes to the one common point between them: their nano-morphology, composed of stacking inorganic layers which creates “the interlayer space”. This important observation/conclusion on the structure of a lamellar compound, notably the presence of weak electrostatic forces which governs the interlayer space interactions, is the key idea behind the hybridization of lamellar compounds.

Taking advantage of the possibility of interlayer chemistry modification, the very first strategy of organic modification of a lamellar compound was defined: inserting organic species between layers, i.e. organic modification of the interlayer space. Later, this strategy was also coined as hybridization of nano-building blocks (Sanchez et al., 2005).

The second hybridization strategy of lamellar compounds came with advent of organic-inorganic hybrid materials concept. The advantages brought by sol-gel process, allowing inorganic and organic precursors to mix at nanometric scale, was the origin of one-pot synthesis strategies. The application of this strategy to obtain hybrid lamellar compounds will be discussed in this paper.

Hybridization strategies of lamellar compounds can be depicted in two main categories: hybridization by intercalation and by in-situ integration of a given organic moiety into the forming inorganic layer (Fig. 2). While intercalation strategy consists in accommodating an organic moiety between layers, after synthesizing the inorganic host, in-situ hybridization implies self-assembly of organic and inorganic species together in the synthesis medium, forming a layered texture, containing organic guests between inorganic layers.



**Figure 2-** Hybridization strategies of inorganic lamellar compounds

### 3.1 Intercalation

The most intuitive hybridization strategy for layered inorganic compounds relates to the capacity that most layered structures display to accommodate molecular species in their interlayer space (Hendricks, 1941; Hoffmann and Brindley, 1960, 1961; Hang and Brindley, 1970; Carrado et al., 1993; Lagaly, 2001; Forano et al., 2006; Beneš et al., 2012). In fact this strategy might have been used in ancient Mayan civilization to prepare pigments such as Maya Blue, a hybrid material consisting on indigo molecules stabilized inside the tunnels of palygorskite, a fibrous clay mineral (Sanchez del Rio et al., 2011). Layered inorganic compounds have also been used throughout history as adsorbents capable of stabilizing organic molecular species. One of the most know examples is that of fuller's earth which has served since the Roman civilization as a detergent due to the adsorption properties of the clay

fraction (Ruiz-Hitzky et al., 2010). Yet another example concerns the intercalation of urea molecules that has been also used during the roman civilization to prepare hybrid layered materials from decaying urines. (Rytwo, 2008) In fact, several centuries passed until Weiss (1963) reported the intercalation of urea by layered silicates.

The first works about the intercalation of organic species in the interlayer space of layered compounds have mostly focused on clay minerals and on the basic fundamental understanding of the physical and chemical phenomena involved in the intercalation process, cation exchange or dipolar interaction (MacEwan, 1946). The first organic-inorganic hybrid layered materials have largely benefited from such fundamental works. The rationale behind most of the hybrids prepared from an intercalation process was to protect a functional species by inserting it into the interlayer space of inorganic layered solids. Although many examples concern the modification of clay minerals, other inorganic layered solids have also been modified according to the same strategy.

### *3.1.1. Molecular guests*

Strongly motivated by the chromatic quality and chemical resistance of Maya Blue pigment, the adsorption of colored dye molecules into the interlayered space of layered inorganic compounds has soon seen important advances. Organic dyes are prone to UV degradation and subsequent bleaching. The protective effect that inorganic layered hosts could induce has thus been strongly sought after. Clays (Emodi, 1949; Hang and Brindley, 1970; Carrado et al., 1993), metal layered oxides (Tagaya et al., 1993; Kuwahara et al., 2001), LDH (Miyata, 1983; Hussein et al., 2004a; Forano et al., 2006) have proven to be extremely useful scaffolds to trap and protect colored organic dyes.

One of the domains where many efforts were made in the intercalation was in the production of new herbicide and pesticide formulations, where the active species (usually highly toxic) is intercalated in the interlayer space of the layered compounds. The first understanding of the potential of clay minerals to act as a reservoir, was unveiled by Bailey and White (1964) in the context of soil science. This approach soon became widely studied. In the case of clay-herbicide hybrids, one of the biggest concerns is the reduction of herbicide leaching. Nennemann *et al.* (2001) have addressed this issue by adsorbing metolachlor in different

layered inorganic hosts from aqueous and/or alcohol solutions. Their results indicate that raw bentonites and montmorillonites can integrate up to 200  $\mu\text{g.g}^{-1}$  metolachlor. Moreover, the inorganic host is capable of tuning the release kinetics of herbicide to attain formulations that have systematically surpassed commercial formulation of metolachlor containing compounds over growth inhibition of green foxtail (*Setaria viridis*). While clay minerals seem especially well-suited for the adsorption and controlled release of cationic species, LDH do the reverse. Due to their positive layer charge, they display important anion-exchange capacity that can be useful in the adsorption of negatively charged species (Pavlovic et al., 2005; Nejati et al., 2013; Otero et al., 2013). Interestingly, in the case of LDH, the mechanism of adsorption does not seem to fully reproduce the diffusion-controlled ion exchange observed in the interlayer space of clay minerals. Since LDH have the ability to exfoliate and restack in solution (reconstruction), the adsorption of the different pesticides seems to pass through a disordered phase (where the cationic sites are easily available to the anionic pesticides) followed by the reconstruction of the LDH-pesticide hybrid (Pavlovic et al., 2005). These authors have reported very high adsorption values of 2500  $\mu\text{mol/g}$  and 1035  $\mu\text{mol/g}$  for the pesticides Clopyralid (3,6-dichloropycolinic acid) and Picloram (4-amino-3,5,6-trichloropyridine-2-carboxylic acid), respectively.

Regardless of the obvious differences, there is a strong resemblance between materials devised for soils and materials that are designed for drug delivery systems. In both cases the role of the prepared material is to deliver a specific functional species (a pesticide in soils, a drug in medical applications) to a very complex system. Delivery to such a complex medium necessitates protection of the functional species from undue delivery or degradation both in drug delivery systems, and in soil science. Hybrid layered materials have been intensively explored in this field of application owing to their two important characteristics: first, their capacity of accommodation a molecular specie of different nature in the interlayer space, and second the non-toxicity of many inorganic layered structures such as LDH (Forano et al., 2006; Li and Duan, 2006; Delhoyo, 2007) and clays (Carretero et al., 2006; Choy et al., 2007; Darder et al., 2007; Ruiz-Hitzky et al., 2010). These compounds have served as hosts for the controlled delivery of a wide variety of active principles such as methotrexane, a potent anti-cancer drug; diclofenac, ibuprofen and naproxen, non-steroid anti-inflammatories or vitamin C, for cosmetics (Forano et al., 2006; Li and Duan, 2006; Choy et al., 2007; Ruiz-Hitzky et al., 2010).

1 The polymer community, strongly motivated by the potential impact of inorganic layered  
2 compounds in the mechanical reinforcement of polymer-based nanocomposites, has soon  
3 embraced the layered inorganic materials field. The first works, reported by Blumstein (1965),  
4 focused on the adsorption and subsequent polymerization of different monomers by Mt such  
5 as acrylonitrile, methyl methacrylate, vinyl acetate, styrene and isoprene. This work reported  
6 the changes in basal spacing of the clay mineral according to the intercalated monomers  
7 monolayer followed by their polymerization. Despite the fundamental approach (Blumstein  
8 was interested in the study of two-dimensional polymerization phenomena more than in the  
9 preparation of materials) his findings constitute a milestone in the preparation of hybrid  
10 lamellar compounds. According to Blumstein's approach, the interlayer space in inorganic  
11 compounds could be understood not only as a reservoir of organic molecules, but also as a  
12 confined reactor capable of modulating the outcome of chemical reactions. This approach was  
13 followed by researchers working in conductive polymers such as polyaniline and other  
14 inorganic layered structures such as vanadium pentoxides (Kanatidis et al., 1989; Wu et al.,  
15 1996) aiming at the preparation of conductive composite materials.

16 Besides above mentioned considerations on layered inorganic hosts, *i.e.* reservoir, protecting  
17 shell and/or confined reactor, the combination of intrinsic properties of these hosts with a  
18 similar characteristic of an organic guest permits to accentuate a demanded property. This  
19 combination mode has been significantly used to modulate the magnetic or optical properties  
20 of layered metal hydroxides (Rueff et al., 2004; Delahaye et al., 2009). Several examples of  
21 these types of molecular magnets have been presented by different authors. A heterometallic  
22 layered structure magnet was obtained by intercalation of chiral and non-chiral salen-type  
23 Ni(II) complexes into copper and cobalt layered simple hydroxides. Pre-intercalated cobalt  
24 and copper hydroxides, *i.e.*  $\text{Cu}_2(\text{OH})_3(\text{DS})$  and  $\text{Co}_2(\text{OH})_3(\text{DSO})$ , where DS is dodecylsulfate  
25 and DSO is dodecylsulfonate, were used as host materials and salen-Ni(II) complexes were  
26 used as guest molecules to induce chirality in a non-chiral magnetic system (Delahaye et al.,  
27 2010). Intercalation of peptides by anion-exchange reactions into pre-intercalated Cu(II) and  
28 Co(II) LSH interlayer space (Copper acetate monohydrate ( $\text{Cu}(\text{CH}_3\text{COO})_2 \cdot \text{H}_2\text{O}$ ), cobalt  
29 acetate tetrahydrate ( $\text{Co}(\text{CH}_3\text{COO})_2 \cdot 4\text{H}_2\text{O}$ )), resulted in bio-hybrid compounds. Among these  
30 compounds, the copper-based tyrosine LSH bio-hybrids showed an antiferromagnetic  
31 behavior whereas the cobalt-based analogues were ferrimagnets (Si et al., 2012).

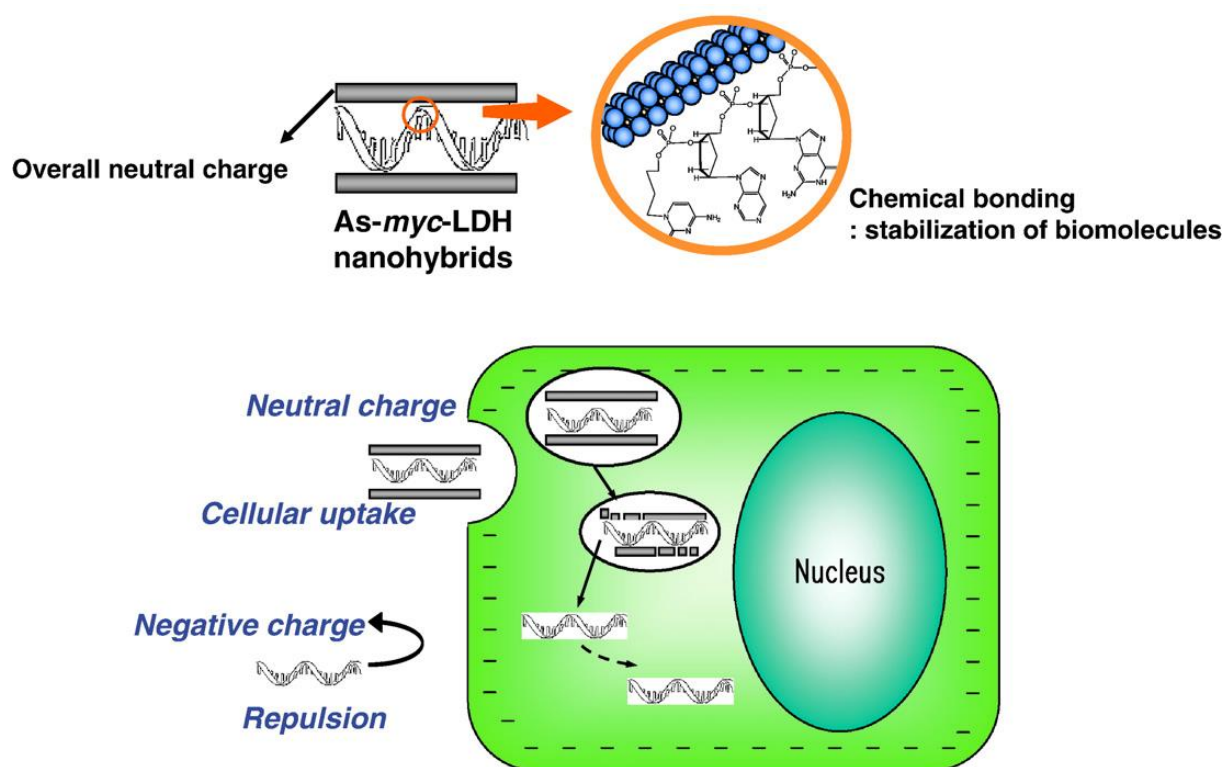
### 3.1.2 *Molecular modifiers of the interlayer space of layered materials*

The following step in the modification of inorganic layered systems was based on the enhancement of a guest molecule intercalation by the pre-adsorption of compounds which can modify the chemical environment of the interlayer space, mostly due to the use of surfactant species. Historically, alkylammonium ions were the first compounds used to render the interlayer space of clay minerals hydrophobic (Giesekeing, 1939; Jordan, 1949). Such strategy finds numerous examples in the literature where the same rationale has been applied. It was applied to vanadium oxide using the same alkylammonium organocations (Livage, 1991), to copper and cobalt simple layered hydroxides using alkyl sulfate derivatives (Eyele-Mezui et al., 2012), to layered clay minerals using phospholipids (Wicklein et al., 2010) among many other examples.

The most outstanding feature of this approach regards the capacity for highly amphiphilic molecules to self-assemble (mostly due to the interaction between alkyl chains) in a cooperative manner, thus significantly increasing the basal distance of the layered systems. This separation creates, as previously mentioned, a different chemical environment responsible for the enhanced adsorption of non-polar molecules (Miyata, 1983; Jaynes and Vance, 1999; Kwolek et al., 2003; Kozak and Domka, 2004; Rytwo et al., 2005; de Paiva et al., 2008; ; Moscofian and Airoidi, 2008; Ruiz-Hitzky et al., 2010; Wicklein et al., 2010).

Another important feature of the basal spacing augmentation is its impact on the confinement of the subsequently adsorbed species. Fukushima et al., in a series of ground-breaking works, have fully understood the potential to effectively exfoliate inorganic layered materials by polymerizing monomers such as caprolactam and methyl methacrylate in between previously expanded clay mineral layers (Fukushima and Inagaki, 1987; Fukushima et al., 1988; Kojima et al., 1993; Usuki et al., 1993; Fukushima and Tani, 1995). The result was an outstanding dispersion of the clay mineral layers within the polymer matrix, displaying a dramatic effect over the mechanical properties of the material, a clay polymer nanocomposite. Numerous contributions on the CPN field followed (Messersmith and Giannelis, 1993, 1995; Giannelis, 1996; Bafna et al., 2003; Ruiz-Hitzky and Van Meerbeek, 2006; Podsiadlo et al., 2007; Chen et al., 2008; Annabi-Bergaya, 2008; Paul and Robeson, 2008), being at present one of the fields where hybrid layered compounds have established their way into consumer end products.

Beside advances in *in-situ* polymerization of adsorbed monomers into modified interlayer space of a given clay mineral, another thrived approach concerns the diffusion of polymers directly into the modified clay minerals. This latter, technically much simpler, allows direct integration into processing units such as melt compounders or extrusion units. The rationale behind this methodology lies on the enhanced dispersibility of clay mineral particles induced by shear as well as the maximization of polymer chain mobility with temperature in thermoplastics. These two phenomena, together with an appropriate interlayer space modification, allow to fully disperse organoclays stacks to individual layers throughout the CPN (Vaia et al., 1995; Giannelis, 1996; Gilman, 1999; Lagaly, 1999; LeBaron et al., 1999; Alexandre and Dubois, 2000; Suprakas Sinha Ray and Okamoto, 2003; Lagaly et al., 2006; Tjong, 2006).



**Figure 3** – Schematic representation of DNA transfection by Layered double hydroxides (Choy et al., 2007). Reproduced with permission from Elsevier Ltd.

### 3.1.3 Polymer diffusion in raw inorganic layered materials

Another strategy devoted to the production of hybrid layered materials that has recently found an impressive development, concerns the diffusion of polymers directly into the interlayer

space. Given the hydrophilic nature of most inorganic layered materials, such diffusion is widely favored in aqueous conditions, which in turn dramatically reduces the array of polymers that are concerned by this modification approach.

Within the water-soluble polymers many have been used to produce CPN for different applications, from lithium insertion batteries to DNA transfection (Fig. 3) (Ruiz-Hitzky and Aranda, 1990; Aranda and Ruiz-Hitzky, 1992; Ray and Okamoto, 2003; Darder et al., 2005b; Ray and Bousmina, 2005; Ruiz-Hitzky et al., 2005, 2010, 2011; Choy et al., 2007; Zhuang et al., 2007; Chivrac et al., 2009; Ojijo and Ray, 2013). Analyzing these materials, one conclusion is apparent. Most of the water-soluble polymers that diffuse into the inorganic layered materials are of biological origin. In fact, the assembly of biopolymers with inorganic nanomaterials has been recently coined as bionanocomposites (Darder et al., 2007; Ruiz-Hitzky et al., 2008). These materials are presently under intensive research using a multitude of inorganic hosts such as vanadium pentoxide (Carn et al., 2010), clay minerals (Darder et al., 2008; Ruiz-Hitzky and Fernandes, 2013), LDH (Darder et al., 2005b) or phosphates (Darder et al., 2006). The strategy behind the preparation of these materials is not different from hybrid materials prepared by diffusion of molecular species. Biopolymers are usually adsorbed within the interlayer space of the inorganic host. The intercalation is often followed by the complimentary information provided by the adsorption isotherm as well as XRD patterns that clearly identifies the basal spacing changes induced by the adsorption. This technique implies a very high affinity between the inorganic host and the macromolecule being adsorbed. When the inorganic host displays a layer charge such as in the case of clay minerals or LDH, the adsorption mechanism is mediated by an ion-exchange process. One of the most prominent results concerning the direct intercalation of biopolymers within an inorganic lamellar host is that of DNA (Fig. 3) (Choy et al., 1999, 2007).

Gene therapy concerns the treatment of a variety of diseases by transfection, *i.e.* delivering genetic material within the intracellular space so it can interact with the cells' own genes. To achieve this goal two criteria must be taken into account. The first one relates to the degradability of DNA and the second to the need to overcome the charge repulsion that is established between the cell walls and the DNA strands (both charged negatively). The most known strategy to address transfection consists in the use of viral capsids to penetrate the cell wall and deliver the therapeutic genetic material to the nucleus. To produce non-viral vectors for gene delivery, Choy *et al.* (1999, 2007) have adsorbed nucleotides and DNA within

1  $\text{Mg}_2\text{Al}(\text{NO}_3)$  LDH. LDH have proven effective materials to host DNA without inducing  
2 conformational or compositional changes in the DNA strands. Moreover, since the net charge  
3 of the hybrid compound is positive the electrostatic repulsion between the cell walls and DNA  
4 was circumvented.

5 Another noteworthy example of biopolymer diffusion in the interlayer space of raw inorganic  
6 layered compounds regards the intercalation of chitosan in the interlayer space of Mt. Darder  
7 *et al.* (2003) have shown that the intercalation of a biopolymer can be pushed beyond the  
8 adsorption of a monolayer in the interlayer space of the clay mineral. Based on XRD and  
9 adsorption data, the authors have demonstrated the formation of a bilayer of positively  
10 charged chitosan macromolecules in the interlayer space of the clay mineral. The result of  
11 such massive intercalation was the transformation of Mt chitosan, a cation exchanger into an  
12 anionic exchanger when the chitosan to Mt reached 5:1, respectively. This feature has been  
13 demonstrated in the form of a sensor displaying potentiometric cross-sensitivity.

14 Finally, another remarkable application for bionanocomposites prepared from layered hybrid  
15 materials concerns the mechanical reinforcement provided by the inorganic moiety to the  
16 biopolymer matrix. The key idea behind the preparation of clay polymer bionanocomposites  
17 for structural applications does not differ from the classical CPN. It is based on the difference  
18 between the mechanical properties of the inorganic layers and those of biopolymers.  
19 Moreover, the elevated aspect ratio of inorganic layers obtained by the delamination of  
20 lamellar compounds alongside with the potential to disperse thoroughly the inorganic layers  
21 has naturally attracted the interest of researchers. The strategy is, again, no different from the  
22 previous examples. The biopolymers are adsorbed into the interlayer space of clay minerals  
23 (Darder *et al.*, 2008), oxides (Carn *et al.*, 2010) or LDH (Darder *et al.*, 2006) inducing the  
24 basal spacing augmentation until the interactions between adjacent layers are comparable to  
25 the interaction with the biopolymers. This process, usually performed in aqueous solution is  
26 normally followed by shaping by solution casting, foaming or spinning techniques. Alongside  
27 with the mechanical reinforcement, bionanocomposite materials benefit from the  
28 biocompatibility of the used biopolymer. This is why bionanocomposites have special impact  
29 in two sensitive domains, health and food packaging (Armentano *et al.*, 2013). Due to the  
30 resemblance between the nature of bionanocomposites and bone composition (a natural  
31 bionanocomposite made out of collagen and nanometric hydroxyapatite sheets), these  
32 materials are often discussed in the context of tissue engineering (Armentano *et al.*, 2013;

Okamoto and John, 2013; Sowmya et al., 2013). However, the domain, where bionanocomposites are perceiving increasing attention, is that of food packaging (Armentano et al., 2013; Raquez et al., 2013; Reddy et al., 2013; Rhim et al., 2013).

#### 3.1.4 Interlayered metal nanoparticles

One of the most interesting domains discussed in the context of layered materials regards the role of such inorganic structures in the development of prebiotic life (Ponnamperuma et al., 1982). In fact this hypothesis is supported by the wide availability of inorganic layered materials such as silicates along with the morphological characteristics of layered materials that can act as confined reactors for an eventual prebiotic synthesis. Yet, the catalytic effect of the inorganic layers themselves is often overseen. In fact the inorganic layers of clay minerals such as Mt have been used to catalyze the synthesis of biomolecules from prebiotic conditions (Brack, 2006).

Modern catalysts however depend on far more complex systems due to strict technical demands in terms of efficiency, selectivity and reusability. To achieve suitable catalysts one of the most common approaches consists in the deposition of active nanometric catalytic centers on a substrate to maximize the contact between the active center and the species to be catalyzed (*i.e.* heterogeneous catalyst systems). Metallic centers displaying catalytic activity such as Ni, Pd or Cu have been introduced in the interlayer space of layered systems in form of nanoparticles (Martínez-Ortiz et al., 2003; Patakfalvi et al., 2003; Tichit et al., 2006; Gérardin et al., 2008) in the case of LDH, and as pillared structures bridging the gap between adjacent clay layers in clay minerals (Ohtsuka, 1997).

The main routes of synthesizing metal/LDH catalysts consist in 1) impregnation and/or exchange of  $M^{II}(M^{III})O$  with metal precursor, 2) partial or total substitution of  $M^{II}$  or  $M^{III}$  with transition metal *via* co-precipitation, and 3) intercalation by anion-exchange of preformed metal colloid (Tichit et al., 2006). Palladium nanoparticle loaded LDH were synthesized using these mentioned routes. The obtained results demonstrated that the catalytic system obtained from a palladium colloid nanocomposite precursor resulted in the higher performances in the one-pot synthesis of 2-methyl-3-phenyl-propanal from benzaldehyde and propanal (Tichit et al., 2007). The richness of this system concerns the diversity of active centers available inside

the interlayer space of the nanocomposite material. Basic sites induce the condensation of benzaldehyde and propanal to attain a reaction intermediary, acid sites are capable of dehydrating the reaction intermediary and finally, the palladium reactive centers selectively hydrogenate the carbon double bond. The same system has been applied to the dehydrogenation of 2-butyne-1,4-diol to 1,4 butanediol (Tichit et al., 2007).

As previously stated clay minerals are also capable of forming catalysis-relevant materials. However, most of the catalysts prepared using clay minerals as support concern pillaring the layers together via the adsorption and subsequent condensation of the catalyst center (pillared interlayered clays, PILC) to form a microporous solid. Despite the loss of the layered nature of the initial materials, (PILC materials are actually considered as two-dimensional zeolites) these materials are a paradigmatic example of the potentialities of layered systems even in the development of 3D functional materials.

### 3.2 *In situ integration of organic guest molecule*

Intercalation of organic species/guest molecules in the interlayer space of the lamellar compounds at the end of the 1950's, not only opened the discussion about the feasibility of hybridization of such inorganic hosts, but also it answered an important question: how to make the most of the lamellar compounds. Later on, in the mid 1990's, inspired by the vast possibilities given by sol-gel chemistry obtained from polycondensation of organosilanes and metal alkoxides, researchers started to pave a new road toward organic-inorganic hybrid layered materials. Shortly after, procedures based on the self-assembly of amphiphilic organic molecules in the synthesis medium and in presence of an inorganic precursor, allowed to synthesize hybrid materials with layered textures (Sanchez et al., 2005, 2011).

Sol-gel process, co-precipitation at room temperature or at hydrothermal or solvothermal conditions, are the most common one-pot synthesis methods used to elaborate hybrid layered materials.

#### 3.2.1 *Sol-gel process*

Sol-gel route has been widely used to synthesize hybrid layered silicates. The idea of using this method and its vast application stem from the self-directed assembly potential of alkoxysilanes ( $\text{Si}(\text{OR})_4$ ) and organoalkoxysilanes ( $\text{R}_n\text{Si}(\text{OR})_{4-n}$ ), where R can be an organic group. Considering each organoalkoxysilane molecule as an amphiphilic unit (depending on the length of organic moiety chain) as well as the sol-gel processing conditions, they can be self-assembled to form inorganic layers composed of silicate chains, between which organic chains are placed (Sanchez and In, 1992; Sanchez and Ribot, 1994; Judeinstein and Sanchez, 1996; Mann et al., 1997; Kuroda et al., 2014). Based on the mechanisms involved in sol-gel reaction, several organic-inorganic layered compounds have been successfully synthesized. Clay minerals analogous metal phyllosilicates (Fonseca et al., 1999, 2000, 2004; Jaber et al., 2002, 2003, 2005; Gallégo et al., 2008; Jaber and Miehe-Brendlé, 2008), CSH, oxides and metal phosphonates are well-discussed examples.

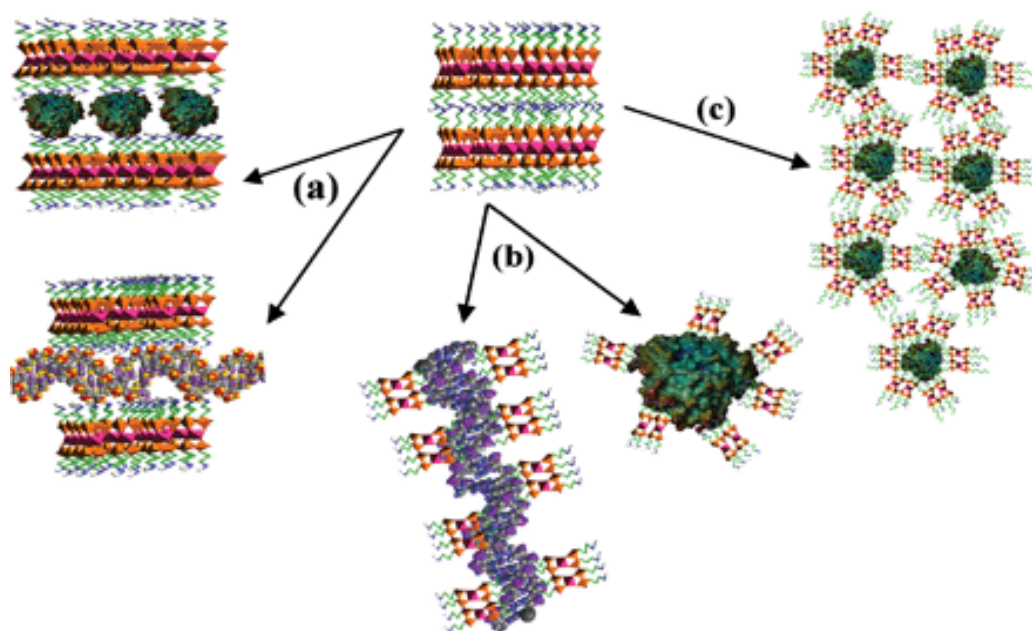
The advent of sol-gel synthesis of organic-inorganic hybrid metal phyllosilicate was in 1995, by Fukushima *et al.*, using an organosilane as silica precursor (Fukushima and Tani, 1995). The common point between numerous existing protocols for synthesizing layered organic-inorganic metal phyllosilicates through this process relies on chemical reaction between a wide variety of metal salt solutions (magnesium, aluminum, copper, zinc, calcium, lithium, nickel, etc.) and organotrialkoxysilane precursors, in basic medium. Several different alkoxysilanes were used to synthesize these compounds, including methyltriethoxysilane, octyltriethoxysilane, phenyltriethoxysilane, phenethyltrimethoxysilane, aminopropyltrimethoxysilane, N-phenylaminomethyltrimethoxysilane, (3-mercaptopropyl)trimethoxysilane, (3-aminopropyl)triethoxysilane, [N-(2-aminoethyl)-3-aminopropyl]trimethoxysilane, [(10-amino)-4,7-diazanonyl]trimethoxysilane, (3-(methacryloxy)propyl)trimethoxysilane, (3-acryloxypropyl)trimethoxysilane (Burkett et al., 1997, Carrado et al., 2001; Fujii et al., 2003; Fonseca et al., 2004; Lagadic, 2006; Gallégo et al., 2008; Badshah and Airoidi, 2011).

These organo-metal phyllosilicates were obtained in aqueous or water-solvent mixed media, at room temperature or at higher temperatures. The mechanisms invoking the formation of metal organo-phyllosilicates *via* sol-gel route depend not only on the synthesis conditions, *e.g.* pH and temperature, but also on the intrinsic characteristics of applied organotrialkoxysilane, *e.g.* organic moiety chain length/ hydrophobicity and hydrolysis and condensation kinetics (Richard-Plouet et al., 2004). This synthesis route resulted majorly in poorly crystalline

1 organo-metal phyllosilicates. Although this latter makes the structural characterization of  
2 these compounds difficult, the admitted structure for inorganic layer of organo-metal  
3 phyllosilicates consists in metallic cations centered in octahedral sites, coordinated by oxygen  
4 atoms, which are sandwiched between silicate tetrahedral sheets. The organic chains are  
5 attached to tetrahedral R-Si-O<sub>3</sub> group of the inorganic layer *via* Si-C bonds, pointing to the  
6 interlayer space (Burkett et al., 1997; Fonseca et al., 1999, 2004). Depending on the organic  
7 group bonded to Si, interlayer distance ranges from 11 to 38 Å (Richard-Plouet et al., 2004).

8 One-pot synthesis of a hybrid layered metal phyllosilicate by applying an  
9 organotrialkoxysilane *via* sol-gel route can result in the modified structures and chemical  
10 characteristics which permit these compounds integrating various functional guest  
11 biomolecules to form bio-inorganic hybrids (Patil and Mann, 2008). Exfoliation of an  
12 aminopropyl-functionalized magnesium phyllosilicate (AMP) in water resulted in  
13 delaminated layers of 30 to 150 nm in size and about 2 nm thickness, which corresponds to a  
14 positively charged (due to protonation of aminopropyl chains) single layer of organoclay  
15 framework. Afterward, the addition of negatively charged myoglobin or glucose oxidase to  
16 the exfoliated AMP dispersion resulted in immediate re-assembly and restacking of layers,  
17 forming protein intercalated lamellar metal organophyllosilicate (Fig. 4a) (Patil et al., 2005).  
18 In order to obtain organoclay DNA-AMP (Patil et al., 2007) and organoclay drug-AMP  
19 (Holmström et al., 2007) nanocomposites the same logic were used. The organoclay layers  
20 restacking depends on the size and charge of the applied biomolecules. A positively charged  
21 biomolecule or a large negatively charged one, did not result in a lamellar bio-hybrid structure  
22 (Patil et al., 2005). Leaning on the synthetic metal organophyllosilicates potentials,  
23 synthesizing other bio-inorganic nanocomposites can be conceivable. Oligomers of a  
24 positively charged exfoliated AMP obtained after AMP layers exfoliation in water, followed  
25 by gel chromatography of the delaminated material. Adding solutions of biomolecules such as  
26 myoglobin and glucose oxidase to stable sols of the oligomeric organoclays resulted in  
27 wrapping of biomolecules by these organoclay clusters (Fig. 4b). Modification of organic  
28 moieties of metal organophyllosilicate in order to have pendent long-chain hydrophobic  
29 moieties attached to silicate layers can result in bio-inorganic nanocomposite with a high  
30 order superstructure (Fig. 4c) (Patil et al., 2004). Using similar AMP oligomers dispersion,  
31 added to λ-DNA solutions, organoclay DNA nanowires were obtained (Fig. 4b) (Patil et al.,  
32 2007).

1



2

3 **Figure 4** – (center) Proposed structure for aminopropyl-functionalized magnesium  
 4 phyllosilicate (AMP) composed of a central layer of brucite  $\text{Mg}(\text{OH})_2$  octahedra connected on  
 5 both sides to a tetrahedral silicate layer comprising covalently linked aminopropyl moieties  
 6 that are positioned in the interlayer spaces, (a) exfoliated cationic AMP sheets after  
 7 electrostatically induced reassembly of the organoclay layers with biomolecule and DNA, (b)  
 8 wrapped negatively charged proteins (bottom centre right) or DNA (bottom centre left) with  
 9 cationic organoclay clusters, (c) superstructures of organoclay-enveloped biomolecules (Patil  
 10 and Mann, 2008).

11

12 Using the same logic to synthesize a hybrid layered component, *i.e.* incorporation of an  
 13 organic group covalently bonded to a silicate layer *via* sol-gel process, Minet *et al.* (2004)  
 14 synthesized hybrid CSH. Such hybrids are obtained from co-precipitation of both  
 15 organotrialkoxysilane and tetraethoxysilane together with calcium salt in aqueous/ethanolic  
 16 solution, in basic medium. CSH accommodated the small sized organic groups, linked to  
 17 silicate chains, by co-condensation of tetraethoxysilane and trialkoxysilanes, such as  
 18 ethyltriethoxysilane, n-butyltrimethoxysilane or 3-aminopropyltriethoxysilane (Minet *et al.*,  
 19 2006). However, using only organotrialkoxysilanes with alkyl chains (from methyl to  
 20 octadecyl) as both silicon and organic group precursors, Minet *et al.* obtained a hybrid layered  
 21 calcium silicate with smectite-like layer, rather than the parent inorganic CSH structure  
 22 (Minet *et al.*, 2004).

Sol-gel route has also found its place in synthesizing multifunctional hybrid metal oxide and hydroxide nanoparticles. Pinna *et al.* (2005) presented a new hybrid layered yttria-based nanomaterial, composed of alternating layers of crystalline yttrium oxide and benzoate molecules between the layers. The synthesis procedure consisted in a non-aqueous sol-gel process, involving the reaction between yttrium alkoxide and benzyl alcohol at relatively low temperatures. Later, applying the same procedure, *i.e.* non-aqueous sol-gel reaction between Ln III ( Ln = Gd, Sm, Nd) isopropoxide and benzyl alcohol, they succeeded to obtain lanthanide-base well-crystallized lamellar nanohybrids, composed of crystalline lanthanide oxide layers regularly separated from each other by organic layers of intercalated benzoate molecules (Karmaoui and Ferreira, 2006; Karmaoui and Mafra, 2007; Karmaoui et al., 2007). This one-pot “benzyl alcohol route overcomes the main drawback of aqueous sol-gel chemistry, that is to say the low crystallinity of the final product, without the need for any template (Pinna, 2007).

Owing to the formation of both P–C and P–O–C stable bonds during hydrolysis of organophosphorus molecules, sol-gel route has been applied to synthesize metal phosphonates and hybrid metal phosphates. The precursor of organophosphorous molecules are usually acids, *i.e.* alkylphosphoric, phosphonic and phosphinic acids or mono and diesters of phosphoric acid. Briefly speaking, the synthesis of metal phosphonates *via* sol-gel route consists in a non-hydrolytic step followed by a hydrolytic step. First, a mixture of metal-alkoxide precursor and a solution of organophosphorous acid in an organic solvent go through the heterocondensation between P–OH and M–OR groups with release of alcohol. Then, by adding water, M–O–M bonds form *via* hydrolysis/condensation of residual alkoxide groups (Vioux et al., 2004; Mutin et al., 2005). Titanium oxide/phenylphosphonate hybrids (Guerrero et al., 2000) and layered zinc phenylphosphonate (Deemie et al., 1999) are two examples of these materials obtained by sol-gel process.

### 3.2.2 Co-precipitation method

This well-known method is widely used to synthesize hybrid materials, layered compounds included. It is the major one-pot synthesis method defined and applied to obtain layered compounds such as LMH and LMC.

1 A wide variety of hybrid LDH were synthesized *via* co-precipitation method (Whilton et al.,  
2 1997; Hussein et al., 2004b; Roland-Swanson et al., 2004; Tronto et al., 2004a, 2004b; Leroux  
3 and Taviot-Guého, 2005). A simple scheme of hybrid LDH synthesis through co-precipitation  
4 consists in mixing a solution of organic precursor with that of bi-and trivalent metallic cation  
5 salts in a basic medium. In some cases, in order to accommodate organic specie between LDH  
6 layers, one should overcome the guest selectivity of LDH interlayer space, determined by the  
7 charge and the size of anions. Using metal hydroxides as inorganic precursors in hybrid-LDH  
8 synthesis by co-precipitation is one of the applied solutions (Ogawa and Asai, 2000).

9 A wide range of organic molecules were integrated between LDH layers *via* co-precipitation  
10 method. By mixing a solution of commercially blue dye molecules (Evan blue, Chicago sky  
11 blue, Niagara blue) with aqueous solutions of  $\text{ZnCl}_2$  and  $\text{AlCl}_3$ , Marangoni *et al.* synthesized  
12 successfully an organic-inorganic LDH assembly, applied as filler for polystyrene, resulted in  
13 a blue plastic nanocomposite film (Marangoni et al., 2008). A “bio-assisted” nanocomposite  
14 of  $\text{Zn}_2\text{Al}$ /alginate was precipitated from a mixed solution of alginic acid and Zn and Al salts  
15 at room temperature (Leroux et al., 2004). Hybrid UV absorbent-LDH nanocomposites were  
16 also obtained from a mixed aqueous solution of caffeic acid (or sinapic acid or  
17 4-nitro-2-(trifluoromethyl)benzoic acid),  $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ , and  $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$  (Khan et al.,  
18 2011). LDH were also considered as nano-drug carriers for drug delivery systems and the  
19 hybrid LDH drug nanocomposite can also be obtained by this direct synthesis method (Choi  
20 et al., 2008). Désigaux *et al.* (2006) described co-precipitation method as a proper chemical  
21 synthesis, enabling DNA molecules entrapment into a supramolecular assembly.

22 Beside integration of individual organic molecules by co-precipitation method, polymer  
23 incorporation between LDH layers, *via* the same method has been reported too (Leroux and  
24 Taviot-Guého, 2005; Vieille et al., 2004, 2003). LDH containing Poly(acrylic acid),  
25 poly(vinylsulfonate) and poly(styrenesulfonate) were synthesized by reacting mixed aqueous  
26 salt solutions with a basic solution containing dissolved polymer. The obtained sheets of  
27 LDH, composing of  $\text{M}_{1-x}\text{Al}_x(\text{OH})_2^+$  ( $\text{M} = \text{Mg}, \text{Ca}, \text{Co}$ ) and  $\text{Zn}_{1-x}\text{M}'_x(\text{OH})_2^+$  ( $\text{M}' = \text{Al}, \text{Cr}$ ),  
28 were grown in a solution containing the desired polymer with polymer bilayers between them  
29 (Oriakhi et al., 1996).

30 Using the same method, other hybrid metal hydroxides were also synthesized and applied in  
31 different domains. Namely, layered zinc hydroxide salts (zinc LHS) - anionic orange azo dyes

(methyl orange (MO) and orange II) hybrid was precipitated from a mixture of  $\text{ZnCl}_2$  and each dye aqueous solutions (da Silva et al., 2012). A simple direct reaction between cobalt hydroxide and ethanedisulfonic acid under hydrothermal conditions resulted in crystalline  $\text{Co}_7(\text{H}_2\text{O})_2(\text{OH})_{12}(\text{C}_2\text{H}_4\text{S}_2\text{O}_6)$  with ethanedisulfonate anions packed tightly between the layers (Forster et al., 2004).

One-pot synthesis of hybrid layered metal chalcogenides followed mainly an approach consisting in using metal complexes as structure-directing agents (Ralph Stähler, 2001; Stähler et al., 2003). Zheng *et al.* (2005) obtained a layered chalcogenide framework structure templated by a chiral complex, by mixing the aqueous solutions of  $\text{GeO}_2$ ,  $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ , sulfur and tris(2-aminoethyl)amine. The obtained structure consisted in a layered framework with the composition of  $[\text{Ge}_3\text{S}_6\text{Zn}(\text{H}_2\text{O})\text{S}_3\text{Zn}(\text{H}_2\text{O})]^{2-}$  and a divalent charge-balancing complex ion (*i.e.*,  $\text{Zn}(\text{C}_6\text{N}_4\text{H}_{18})(\text{H}_2\text{O})^{2+}$ ) in the interlayer space.  $(\text{Haep})_2 \cdot \text{Ga}_2\text{Sb}_2\text{S}_7$  bimetallic layered sulfide, where aep = 1-(2-aminoethyl)piperazine, is another example of these hybrid layered chalcogenides, synthesized by dissolving and homogenizing Ga, Sb and S in 1-(2-aminoethyl)piperazine, reacted at 443 K during 7 days. The inorganic layers of the obtained structure had  $[\text{Ga}_2\text{Sb}_2\text{S}_7]^{2-}$  composition, with two monoprotonated aep cations per formula unit (Lin et al., 2010). A mild solvothermal reaction between  $\text{Co}(\text{Ac})_2 \cdot \text{H}_2\text{O}$  and  $\text{Na}_2\text{SeO}_3$  in a mixed solution, composed of deionized water and diethylenetriamine, resulted in the formation of  $\text{CoSe}_2$ -amine(protonated) nanocomposite belts with multiple stacked layers of  $\text{CoSe}_2$  slabs and protonated amine (Gao et al., 2009).

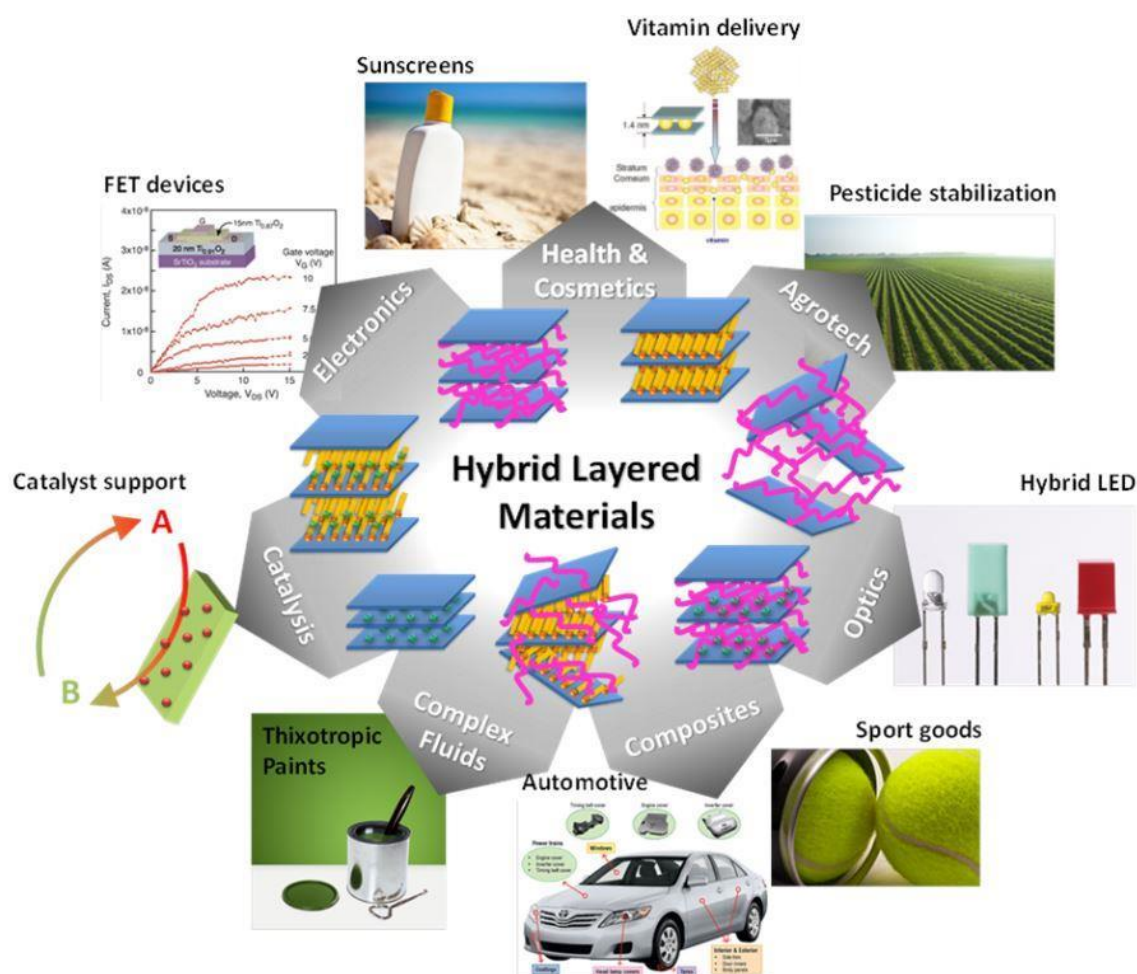
Some organic-inorganic metal organophosphonates were also successfully synthesized *via* co-precipitation method, usually in hydrothermal conditions (Frink et al., 1991; Malaman et al., 2010; Lagadic et al., 2012). This method consisted in mixing the metal salt (*i.e.* carbonate, chloride or nitrate) with the phosphonic acid in aqueous media, with the right stoichiometric ratio and placing the mixture in an autoclave, heating it around 140–190°C. The details of this synthesis method, obtained materials and their characteristics are presented and discussed elsewhere (Bellitto et al., 2008).

#### 4. Integration of hybrid lamellar compounds

Inorganic lamellar compound is a large definition comprising compounds that display different chemistry, different intrinsic properties and even a different history. Moreover, these compounds have been addressed by actors from different domains of knowledge, which justifies their asymmetric development. However, the emergence of hybrid materials, has led to extraordinary advances in the manipulation of the interlayer space of layered compounds and eventually to the development of hybrid layered compounds. This new class of compounds, composed of an inorganic layered structure in close connection with an organic moiety, has widened the range of potential applications of inorganic materials. Surprisingly, this approach has had different feedbacks in the different research communities. While clays and LDH have been widely hybridized, few research efforts have been directed towards the development of other types of hybrid layered compounds. Table 1 briefly analyses the development of hybrid layered materials and their applications as a function of the inorganic host. Regardless of the heterogeneous development of organic-inorganic hybrid lamellar materials, these compounds have found their place in different domains of application as is illustrated in figure 5. Composites, electronics and optics, catalysis, health, cosmetics and environment are the major discussed areas of application. However, the distance between potential applications of hybrid lamellar compounds and technologically ready materials is still considerably large. The main purpose of this section is thus to discuss processing of hybrid lamellar compounds, (*i.e.* their integration as consumer-end products) *via* underlining the major potential applications and their bottlenecks.

Among the materials that are actually applied in day to day objects, the most successful are clearly CPN. They can be found from the gas-tight rubber in tennis balls to automobile engine covers and their market value is expected to reach \$2.4 billion by 2016 (Ciesla and Werner, 2012). Most of the other layered hybrid materials however have not been industrialized. It is instructive to analyze the differences between these outcomes from a technological perspective. CPN are most frequently prepared by shearing the organoclay in the polymer melt in a compounder or and extrusion unit, *i.e.* during the polymer processing. The ability to prepare an enhanced material without dramatically changing the processing, accounts for the huge success behind these materials. In fact, the key is the integration of the outcome of years of research directly into the shaping of the material. Somehow, the bottom-up process that

1 accounts for the fine tuning of clay mineral intercalation and exfoliation is held  
2 simultaneously with the standard top-down approach of shaping the melt into a solid of  
3 desired dimensions and properties. This integrative approach allows for the multi-scale  
4 architecture of the CPN while ensuring its processing cost-effectiveness (Backov, 2006;  
5 Scaffaro et al., 2013). Other materials, regardless of their implantation on the market, have  
6 forwarded this integrative approach (Pradhan et al., 2012; Birjega et al., 2013; Yoshitake et  
7 al., 2013). For instance, Coiai *et al.* (2011) fabricated low-density polyethylene/layered  
8 double hydroxide (LDPE/LDH) nanocomposites with intercalated/exfoliated morphology *via*  
9 melt extrusion. The fabricated materials showed a remarkable increase of the thermal-  
10 oxidative stability even with a low LDH concentration, and a reduction of oxygen  
11 permeability mainly depending on the aspect ratio. Tang *et al.*, (2003) have increased the  
12 adsorption affinity between clay mineral layers and polyelectrolytes through an automated  
13 layer-by-layer procedure. Such approach allowed developing macroscopic bionanocomposite  
14 films with controlled nanometric ordering and extraordinary mechanical properties (Tang et  
15 al., 2003). Likewise, Posati *et al.* (2014) developed transparent bionanocomposite films,  
16 composed of  $\text{Zn}_2\text{Al}$  LDH-silk fibroin by drop casting of a dispersion of hydrotalcite-like  
17 compound in silk fibroin solution with remarkably enhanced mechanical resistance.

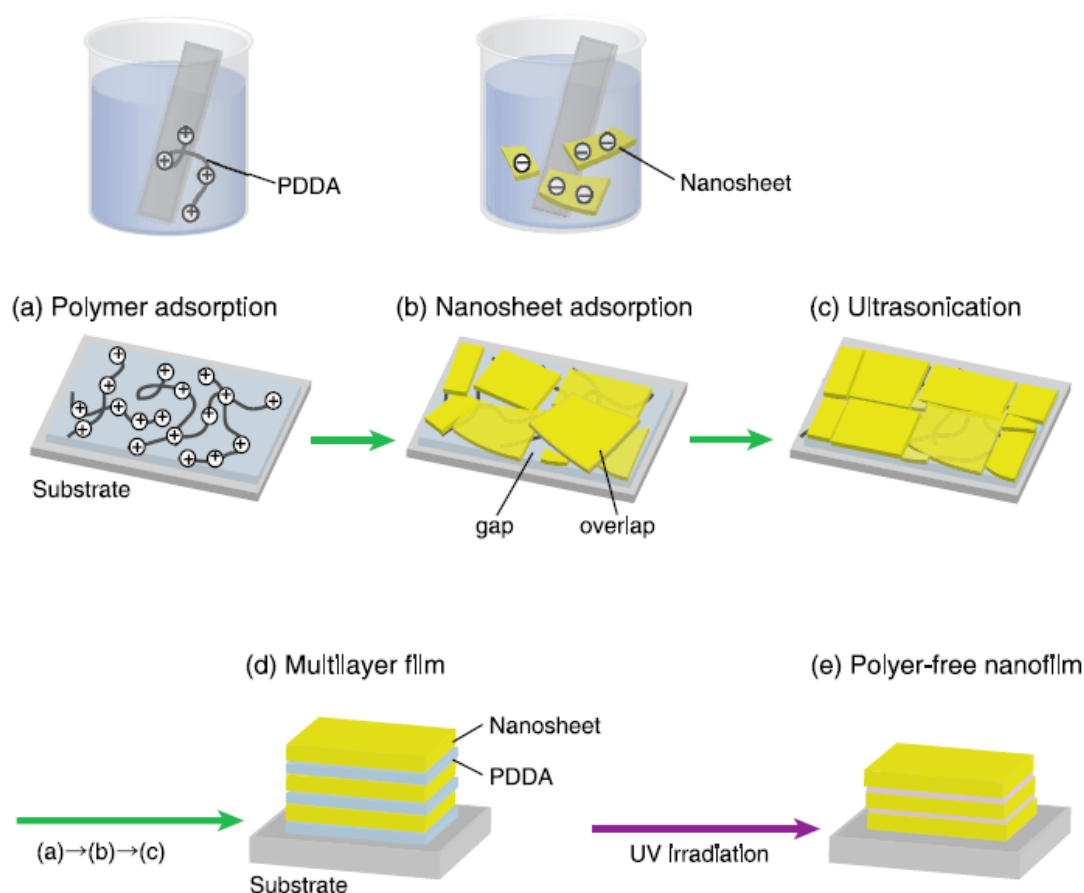


**Figure 5** – Major applications and technological sectors using hybrid layered compounds.

The focus in the field of electronics, historically, is on top-down approaches such as patterning through ion-beam lithography. Following this approach, hybrid lamellar compounds have been elaborated to be integrated in different type of devices. The nanocomposites of LMC-polymer were proven to be potentially good choices to develop hybrid-photovoltaic materials (Saikia et al., 2011). Maier *et al.* (2011) synthesized CdS- and ZnS-P3EBT (poly(3-(ethyl-4-butanoate)thiophene)) composites, through *in-situ* formation of inorganic nanostructures within the polymer matrix. The substrate was spin coated by the polymer-inorganic precursor solutions and subsequently integrated in a solar cell showing the desirable photovoltaic activity. Xu and Mitzi (2003) obtained a non-perovskite-based semiconductor lamellar hybrid  $[\text{CH}_3(\text{CH}_2)_{11}\text{NH}_3]\text{SnI}_3$  which can be solution-processed into thin films at ambient temperatures. Recently, increasing attention is devoted to the delamination of different layered oxides for direct device integration as can be seen in Fig. 6

(Osada and Sasaki, 2009, 2012). Using this approach, thin films based on alternate assembly of zinc phthalocyanine complex and LDH monolayers, with enhanced optical properties, were obtained. Exfoliated Mg-Al-LDH monolayers and zinc tetrasulfophthalocyanine, having long fluorescent lifetimes and high quantum yields, were used as building blocks and were assembled by layer-by-layer method. This integrated approach resulted thin films with properties such as polarized luminescence, while LDH monolayers functioning as an energy well layer, were applied to various opto-electrical devices (Yan et al., 2010). Although several organic-inorganic hybrid lamellar compounds with interesting electric, magnetic and/or optic characteristics have been presented, they have not found their way to be processed and applied to electronic, opto-electronic or magneto-electronic devices, yet. The case of hybrid LHS with important magnetic and optical properties is a striking example. A considerable number of research works were dedicated to study different synthesis methods of various functional molecules and metal complexes into metal hydroxide layers. Other studies succeeded to define mechanisms which govern magnetic and optical characteristics of these hybrid layered compounds. The correlations between the layered structures and magnetic properties of these hybrid layered compounds were also established (Drillon and Panissod, 1998; Laget et al., 1998; Rogez et al., 2011). Nevertheless, they are still not processed to be used as magnetic devices.

1



2

3 **Figure 6** – Mixed layer-by-layer and ultrasound strategies for the preparation of layered  
 4 perovskites superlattices. Reproduced with permission from the Wiley (Osada and Sasaki,  
 5 2012).

6 Hybrid lamellar compounds have also shown remarkable catalytic characteristics and thus  
 7 some of them, LDH and clay minerals, have been extensively studied as catalysts. LDH are  
 8 well-known precursors for elaboration of multifunctional catalysts. These materials can  
 9 potentially possess acid, basic and redox sites. A proper LDH synthesis method potentially  
 10 results in formation of mixed oxides that exhibit a homogeneous inter dispersion of the  
 11 elements, high specific surface areas and basic required properties (Tichit et al., 2006).  
 12 Moreover, after appropriate treatments these mixed oxides contain well dispersed metal  
 13 particles in strong interaction with the mixed oxide support (*e.g.* Pd/ Mg(Al)O) (Takehira and  
 14 Shishido, 2007; Tichit et al., 2007; Gérardin et al., 2008; Shi et al., 2012; Cunha et al., 2013).  
 15 However, hybridized lamellar compounds have been merely used as catalyst precursor. LDH  
 16 have been hybridized by organic molecules to enhance the catalytic activity of some organic  
 17 molecules. The intercalation of thiamine pyrophosphate (TPP) into Zn–Al and Mg–Al LDH

1 resulted in high catalytic activity of pyruvate decarboxylation as an active biocatalyst  
 2 (Baikousi et al., 2013). The preparation of  $[\text{Ni}(\text{C}_6\text{O}_7\text{H}_3)_x(\text{OH})]_y^{y(3x-1)-}$ -LDH nanocomposites  
 3 by anion exchange between Mg/Al LDH host structure and  $\text{Ni}(\text{C}_6\text{O}_7\text{H}_3)_x(\text{OH})_y^{y(3x-1)-}$  clusters,  
 4 permitted to control both the Ni loading and the size of the particles in  $\text{Ni}^0/\text{Mg}(\text{Al})\text{O}$  metal  
 5 supported catalysts after the nanocomposite reduction (Gérardin et al., 2008).  
 6 In this context, also clay minerals can be engineered into various functional solid catalysts.  
 7 Depending on the design and their preparation, clay minerals can play four major roles: (1)  
 8 catalytic activity of the framework of clay, (2) exchangeability of the interlayer ions for  
 9 catalysis purpose, (3) interlayer modification by functional nanoparticles and (4) the use of  
 10 clay minerals or their derivatives used as catalyst supports (Zhou, 2011; Zeng et al., 2013).  
 11 Hybrids of clay- manganese species, obtained from the adsorption of manganese (III) salen  
 12 complexes, showed a good activity to catalyse water oxidation (Berends et al., 2011) and  
 13 epoxidation of olefins (Kuźniarska-Biernacka et al., 2011). Another example consisted of  
 14 cyclic poly(L-lactide) (PLLA) used as stabilizer of palladium nanoparticles to prepare PLLA-  
 15 clay hybrid material as recyclable catalyst support. The obtained nanocomposite was reported  
 16 to be a highly efficient and recyclable catalyst for the aminocarbonylation reactions of aryl  
 17 halides with various amines (Prasad et al., 2013). Despite the advances shown by the isolated  
 18 proofs of concept, the absence of an integrative strategy (that could transfer the reported  
 19 results into the relevant context) hampers an extended application of these advances.  
 20 Owing to their biocompatibility, ion-exchange ability, and low cytotoxicity, LDHs and clays  
 21 have also found great potential application as inorganic nanoparticles for drug delivery.  
 22 Different ionic pharmaceutically active molecules can be intercalated into the interlayer space  
 23 of LDHs and clays by ion-exchange. The interlayer space of these materials can be considered  
 24 as a reservoir for drug, protecting it from the reaction of light and oxygen. After the cellular  
 25 uptake of these particles by clathrin-mediated endocytosis, the drug may be released through a  
 26 deintercalation process because of anion exchange or displacement reactions. The drug  
 27 release can be controlled by tuning the host–guest interactions, which can be obtained by  
 28 hybridizing clay minerals or LDH. The synthesis and potential applications of these hybrid  
 29 lamellar drug carriers are discussed in detail in other review articles (Li and Duan, 2006; Patil  
 30 and Mann, 2008; Zhao et al., 2012; Ruiz-Hitzky et al., 2013). A good example in this area is  
 31 the research work of Miao *et al.* (2012) concerning a drug delivery system based on the fibers  
 32 of LDH/biopolymer. Ibuprofen intercalated Mg-Al LDH was dispersed in polycaprolactone  
 33 (PCL) or polylactide (PLA) solutions, obtaining electrospinning suitable solutions. The

1 electrospun fibers of ibuprofen-LDH/biopolymer, comparing to ibuprofen/LDH system,  
2 brought a remarkably enhanced control over the *in vitro* ibuprofen release.

3 Except for composite materials that are steadily growing as a fully operational domain, most  
4 of the classes of hybrid layered materials discussed in this review article have not passed the  
5 “proof of concept” stage. As an example (*c.f.* table 1), an important feature of hybrid lamellar  
6 compounds such as hybrid metal phyllosilicates, hybrid LDH or hybrid zirconium phosphate,  
7 is their capacity of heavy metal cation adsorption from water. This characteristic led these  
8 materials to be presented as potential water decontaminants. However, a glance at actual  
9 water decontamination technologies shows the absence of hybrid layered materials among  
10 them. We believe that further efforts should be oriented towards the mutual adaptation  
11 between the scientific breakthroughs and the practical technological aspects of each domain.  
12 This convergent movement should facilitate the advancement of the present state of the art in  
13 hybrid layered materials.

14 Another interesting point in the context of layered materials consists on a, until now, fairly  
15 discrete domain: the intersection between physical processing techniques and chemical  
16 synthetic routes. New approaches, using monolayer deposition of materials that are usually  
17 obtained in bulk, are bringing new and exotic layered materials to the game of hybrid layered  
18 compounds (Ohtomo et al., 1999; Umar and Hahn, 2006). This perspective will not only  
19 strengthen the role of physical processing routes in the development of new materials, but will  
20 surely widen the range of materials and applications that can be envisaged by hybrid materials  
21 research.

Host inorganic structure	Guest molecule	Integration method	Properties	Applications / Status	References
<b>Clays</b>					
Mt	Organocations	Intercalation	Enhanced dispersion in polymer matrices, enhanced adsorption of hydrophobic molecules.	Additive for composite materials / Fully commercial (Nanocor, Southern Clay Products, Clariant, Laviosa Chimica Mineraria, etc.)	(Patel and Mahajan, 2012) (Scaffaro et al., 2013)
	Organocations + thermoplastics	Intercalation / exfoliation	Mechanical reinforcement and flame retardant properties	Structural nanocomposites / Fully commercial (Toyota, Dupont, LyondellBasel, Ube Industries, etc.)	(Patel and Mahajan, 2012)
	Organocations + Elastomers	Intercalation / exfoliation	Structural properties, abrasion resistance,	Tyres reinforcement / Fully commercial	(Patel and Mahajan, 2012)
	Polyethylene oxide	Intercalation	Ion conductivity	Fundamental	(Aranda and Ruiz-hitzky, 1992)
	Chitosan	Intercalation	Conductive anionic and cationic exchanger	Potentiometric sensors / POC	(Darder et al., 2005)
	Sucrose	Intercalation In situ polymerization	Electrical conductivity	Fundamental	(Darder and Ruiz-Hitzky, 2005)
	(3-mercaptopropyl)trimethoxysilane)	Intercalation / grafting	Heavy metal adsorption	Pb, Zn, Cd adsorption / POC	(Mercier and Detellier, 1995)
<b>Metal phyllosilicates</b>					
Mg-phyllosilicate	N-trimethoxysilylpropylthiopropylamidomethylacrylamide	Sol-gel	Heavy metal cation sorption	POC	(Badshah and Airoidi, 2013)
	Organosiloxanes	Sol-gel	Gold nano-particle synthesis	POC	(Burkett et al., 1997)
	Mercaptopropyltri-methoxysilane	Sol-gel	Heavy metals adsorption	POC	(Lagadic et al., 2001)

	2-aminophenyldisulfid	Sol-gel	Heavy metal absorbent	POC	(Moscofian and Airoldi, 2008)
Ni-phyllsilicate	3-aminopropyltriethoxysilane + Cu phthalocyanine	Hydrothermal	Magnetic properties	Fundamental	(Richard-Plouet et al., 2002)
	New silyating agent with ethanolamine and diethanolamine functions	Sol-gel	Barium adsorption	POC	(Melo et al., 2008)
<b>Layered Metal Hydroxides</b>					
<b>LHS</b>					
$\text{Cu}_2(\text{OH})_3(\text{CH}_3\text{CO}_2)\text{H}_2\text{O}$ $\text{Co}_2(\text{OH})_3\text{NO}_3$	Olygothiophenecarboxylates	Hydrothermal	Magnetic properties	POC	(Demessence et al., 2010)
$\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$	Oligophenylenevinylene	Ion-exchange	Magnetic & photoluminescence properties	POC	(Rueff et al., 2004)
$\text{Co}_2(\text{OH})_3(\text{CH}_3\text{COO}) \cdot \text{H}_2\text{O}$	Diarylethene	Ion-exchange	Photomagnetism	POC	(Kojima et al., 2007)
<b>LDH</b>					
$\text{Mg}_2\text{Al}$	5-fluorouracil (5-Fu)	Co-precipitation	Drug encapsulation	Drug Delivery System / POC	(Choi et al., 2008)
	Nucleoside monophosphates Deoxyribonucleic acid (DNA)	Ion-exchange	Encapsulation	Gene Delivery System / POC	(Choy et al., 1999)
	Dodecyl sulfate	Microemulsion method	Rheological properties of DLH dispersion in polypropylene	Fundamental	(Wang et al., 2012)
	DNA	Co-precipitation	Encapsulation	Gene Delivery System / POC	(Desigaux et al., 2006)
$\text{Zn}_2\text{Al}$	4[12-(methacryloylamino)dodecanoylamino] benzenesulfonate acid	Co-precipitation	Thermal and rheological properties of DLH dispersion in polystyrene	Fundamental	(Illaik et al., 2008), (Leroux et al., 2009)

	3,4-dihydroxycinnamic acid, 4-hydroxy-3,5-dimethoxycinnamic acid, 3-amino-5-trifluoromethylbenzoic acid	Co-precipitation	UV-absorption	Sunscreen / POC	(Khan et al., 2011)
CSH	acrylic acid, 2-(phosphonoxy)-ethyl-methacrylate	Co-precipitation	Cement additive	Cement hardening acceleration / Fully commercialized	(Nicoleau et al., 2013)
<b>Oxides</b>					
Vanadium oxide	Piperidinium	Intercalation	Magnetic properties	Fundamental	(Zhang et al., 1998)
Vanadium oxide	poly(N-[5-(8-hydroxyquinoline)methyl]aniline)	In situ polymerization	Electrically conductive and fluorescence properties	Fundamental	(Wang et al., 2009)
Vanadium oxide	Phenylacetate	Co-precipitation	High electrical charge storage, good dispersion in electrolyte	Li ion batteries / POC	(Sun et al., 2011)
Vanadium pentoxide xerogel	Poly(ethylene oxide)	Intercalation	Electrochemical properties	Li ion batteries / POC	(Guerra et al., 2006)
Lanthanide oxide (Y, Gd, Er)	Benzoate molecules	Sol-gel	Optical properties	Fundamental	(Sá Ferreira et al., 2006) (Karmaoui et al., 2007)
Lanthanide oxide (Gd, Sm, Nd)	Benzoate molecules	Sol-gel	Optical properties	Fundamental	(Karmaoui and Ferreira, 2006)
	Biphenyl molecules	Sol-gel	Optical properties	Tunable the emission chromaticity / POC	(Karmaoui and Mafra, 2007)
$\gamma$ -ZrP	n-Alkyl Monoamines	Intercalation	Enhanced adsorption capacity	Fundamental	(Alberti et al., 2000)
$\alpha$ -ZrP	Polyaniline	Intercalation, in-situ polymerization	Electric properties	Fundamental	(Takei et al., 2006)
Cobalt phosphonate	Carboxylates	Co-precipitation	Magnetic properties	Fundamental	(Yang et al., 2008)

Hydrated vanadyl phosphate	Polyaniline	Intercalation	Proton conductivity	Fundamental	(De et al., 2007)
M-hydroxyl-carboxylate-phosphonates (M= Mn, Fe, Co)	[(CH-(OH)(CO <sub>2</sub> )(PO <sub>3</sub> H))(H <sub>2</sub> O) <sub>2</sub> ] <sup>-</sup>	Co-precipitation	Antiferromagnetic properties	Fundamental	(Ruibiao Fu, et al., 2005)
Zirconium phosphite	Bis(triphenylphosphine)palladium(II) dichloride complex	Co-precipitation	Supported catalyst	POC	(Villemin et al., 1997)
Bimetallic sulfides (M <sub>1</sub> =Ga or Mn, M <sub>2</sub> =Sb)	1-(2-aminoethyl)piperazine	Co-precipitation	Good semiconductors, photoluminescent and antiferromagnetic properties	POC	(Lin et al., 2010)
MPS <sub>3</sub> (M=Mn, Cd, Zn)	1,10-phenanthroline 4-[4- (dimethylamino)-R-styryl]-1-methylpyridinium iodide	Intercalation	Non-linear optics	POC	(Coradin et al., 1996)

\* POC: Proof of Concept

## 5. Concluding remarks

The number of research works dedicated to understanding old and new lamellar compounds, the efforts made in integrating organic guests in between the different inorganic layered hosts, as well as the conceptual and technological framework that surrounds these materials is breathtaking! In no more than half a century, researchers from different domains have constructed a solid collection of knowledge and have started to conceive materials that are (in variable degree) present in our day-to-day life.

Hybrid layered materials benefit from a vast research community with diverse background and objectives. This has led to the development of **new ideas** for hybrid layered materials. Mann *et al.* for instance, went farther than uniquely modifying the interlayer space of talc like compounds; they have addressed the size of formed two-dimensional hybrid building blocks (Burkett *et al.*, 1997; Patil *et al.*, 2005). By separating the layered nanobuilding blocks by size they were able to wrap around different biological entities providing *ad-hoc* protecting structures around enzymes, DNA or proteins. Also Tang *et al.* (2003) have instilled new breath to the preparation of layer-by-layer bionanocomposite material with a structure resembling that of mother of pearl (Tang *et al.*, 2003). Charge matching between clay lamellae in dispersion and the selected biopolymer, plus the alternating layer-by-layer procedure, allowed developing bioinspired nanocomposites with morphological control in the nanometer range. In both cases their making of hybrid lamellar compounds was compatible with processing tools/techniques and *vice versa* which led to exciting new results.

Another important landmark in the context of hybrid layered materials concerns **new materials** related to the discipline. Graphene and graphene-like materials, which can still be considered as emerging materials, are of dramatic importance to the advancement of hybrid layered materials. The prescient work by Kyotani *et al.* (1988) who carbonized polyacrylonitrile to form graphite (or most likely few layers of graphene) in the interlayer of clay mineral has paved the way to develop new hybrids displaying tunable chemistry and physical properties (Darder and Aranda, 2010; Ruiz-Hitzky *et al.*, 2011). Also graphene-like materials such as fluorographene, boron nitride, molybdenum disulphide, silicene or germanene are capturing increasing attention in materials science (Radisavljevic *et al.*, 2011;

1 Geim and Grigorieva, 2013; Xu et al., 2013). The association of these materials with  
2 “traditional” inorganic layered compounds as well as their hybridizations opens up new  
3 exciting perspectives in the field of layered materials.

4 Finally, a deep survey on the state of the art of hybrid layered compounds shed light on the  
5 considerable gap between the proven concepts of potential applications and consumer  
6 products. Bridging this gap depends on the ability to integrate the new materials in  
7 technologically relevant contexts according to the requirements of each domain. In one word,  
8 the challenge is integration!

9

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