Tailoring the physicochemical properties of solution-processed transition metal dichalcogenides *via* molecular approaches

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During the last five years, the scientific community has witnessed a tremendous progress on solution-processed semiconducting 2D transition metal dichalcogenides (TMDs), in combination with the use of chemical approaches to finely tune their electrical, optical, mechanical and thermal properties. Because of strong structure-properties relationship, the adopted production methods contribute in affecting the quality and characteristics of the nanomaterials, along with the costs, scalability and yield of the process. Nevertheless, a number of (supra)molecular approaches have been developed to meticulously tailor the properties of TMDs *via* formation of both covalent and non-covalent bonds, where small molecules, (bio)polymers or nanoparticles interact with the basal plane and/or edges of the 2D nanosheets in a controlled fashion. In this Feature Article, we will highlight the recent advancements in the development of production strategies and molecular approaches for tailoring the properties of solution-processed TMD nanosheets. We will also discuss opportunities and challenges towards the realization of multifunctional devices and sensors based on such novel hybrid nanomaterials.

1. Introduction

The discovery of new materials with exploitable properties has always boosted the scientific and societal progress in the history of mankind. In this regard, the latest cornerstone we faced during the past fifteen years concerns the so-called discovery of the outstanding physical and chemical properties of graphene and related 2D materials (2DMs) by Geim and Novoselov in 2004.¹ Indeed, graphene represents a veritable breakthrough in material science: its unique and exceptional properties² may be key to revolutionize existing technologies and foster the development of new ones.

The ease of graphene isolation *via* micromechanical cleavage, also known as scotch-tape method, has encouraged the scientists worldwide to isolate new 2DMs starting from the related bulk counterparts.³

As a result, a variety of atomically-thin nanosystems have been produced from layered van der Waals structures, such as black phosphorus (BP), hexagonal boron nitride (h-BN) and transition metal dichalcogenides (TMDs). Unlike graphene that exhibits a semimetallic behaviour and does not possess a bandgap in its pristine form,² TMDs offer a broad portfolio of electronic and optical properties which include, for instance, tunable bandgaps in the whole visible spectrum,^{4,5} a pivotal feature for electronic and optoelectronic applications.⁶

Noticeably, the properties of the single-layer materials are

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markedly different from those of their bulk systems because of strong quantum confinement, reduced screening and surface effects.⁷ Therefore, the discovery of exotic quantum effects and phenomena in the atomically thin limit has promoted the ever growing diffusion of 2D materials, and TMDs in particular, for applications spanning from electronics,⁶ optoelectronics⁸ and (photo)catalysis⁹ to (bio)sensing and biomedicine.¹⁰

Nevertheless, the performances of TMD-based devices are strictly connected to the inherent properties and quality of the materials, which play a paramount role in determining the final applications. More specifically, research endeavors have been devoted to the development of production techniques and successive functionalization steps to increase the quality and enhance the performances, respectively, of the afforded materials.^{11,12} Indeed, the early stages of the research based on TMDs has relied exclusively on the micromechanical exfoliation, yet, this technique has two major drawbacks concerning the lack of control during the production of samples with a specific number of layers and it is not suitable for the production at large (industrial) scale.¹³

Therefore, in order to overcome these limitations, various strategies have been developed and pursued during the last few years to foster the production of high-quality 2D materials. Remarkably, solution-processing approaches have stand out as efficient methods towards the synthesis or exfoliation of TMD nanosheets.^{14,15}

Although the production steps already contribute in affecting the quality and the characteristics of solution-processed TMD materials, in the last few years many research endeavors have been devoted to the development of molecular strategies in order to further tailor their physicochemical properties.¹² In particular, such approaches exploit non-covalent and covalent interactions through which small molecules,¹⁶ noble metal nanoparticles (epitaxial growth or

self-assembly)^{17,18} or (bio)polymers¹⁹ interact with the basal plane and/or edges of TMD nanosheets. In fact, the physisorption or chemisorption process of molecular systems onto 2D structures is driven by a variety of mechanisms, whose versatility guarantees a powerful toolbox in such an exciting area of 2D material science.

In this Feature Article, we will thoroughly discuss the foremost molecular strategies employed to finely tune the properties of solution-processed TMDs, with particular emphasis on the emerging properties of the resulting TMD-based hybrid systems and their possible applications in numerous research areas. More specifically, after a brief introduction regarding the structures and properties of TMDs (Section 2), we will explore the possibilities to employ solution-processed TMDs, obtained *via* both *top-down* and *bottom-up* strategies (Section 3), in functionalization steps *via* molecular strategies (Section 4) and leading to hybrid multifunctional materials, whose new and/or enhanced properties might be exploited in many different research fields (Section 5). Significantly, the chemical approach plays a fundamental role in designing the molecules to employ during the functionalization reactions envisaged for TMDs, tailoring *à la carte* the properties of the resulting ultrathin hybrid systems, bearing the new functionalities required for specific applications (Section 6).

2. A brief overview about the structure-properties relationship in TMDs

The layered structure of TMDs is commonly indicated by the general formula MX_2 and consists of an atomic layer of transition metal atoms ($\text{M} = \text{Mo}, \text{W}, \text{Re}, \text{Pt}, \text{etc.}$) sandwiched between two atomic layers of chalcogen atoms ($\text{X} = \text{S}, \text{Se}, \text{Te}$).²⁰ In this regard, research endeavors in isolating thin TMD nanosheets starting from bulk systems have revealed more than 40 possible and different layered structures.²¹ More specifically, group 4-7 TMDs are predominantly layered systems, unlike some of group 8-10 TMDs which are non-layered. The atoms within individual nanosheets (typically 6-7 Å thick) are held together *via* strong M-X covalent bonds, whereas adjacent sheets interact through weak van der Waals (vdW) interactions, in the range of 10 and 10^{-2} eV per atom, respectively.²²

According to the reciprocal coordination geometry between the M and X atoms within the individual nanosheets, TMDs can manifest multiple crystal lattices and undergo phase transitions among these polymorphs triggered *via* physicochemical stimuli.²³ In particular, TMD systems exhibit a polymorphism involving three different crystal lattices (Fig. 1): hexagonal, generally indicated as 1H for single layer and 2H for multilayer (trigonal prismatic coordination for the metal center, D_{3h}) tetragonal 1T (octahedral coordination for the metal center, O_h) and rhombohedral 3R.²⁴ Noteworthy, the numerical digits in 1T, 2H and 3R indicate the number of layers in the stacking sequence, whereas the letters refer to the crystal lattices. Besides general considerations about the structure of TMDs, they possess extremely versatile properties related to their

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Fig. 1 Illustration of the different polymorph structures for TMDs. a) Depiction, in side view, of the three possible TMD polymorphs and obtained via different stacking sequence of individual layers. b) Representation, in top view, of the metal coordination geometry for the three possible TMD polymorphs. Atom colour legend: light blue, transition metal; yellow, chalcogen.

electronic structure, strongly affected by the constituent transition metal and chalcogen atoms.^{24,6}

More specifically, the electronic properties of TMDs are strongly influenced by the progressive filling of the non-bonding *d* bands from group 4 to group 10, located within the gap between the bonding and anti-bonding bands of M-X bonds.²⁴ In case the orbitals are partially filled, e.g. as in 2H-NbSe₂ and 1T-ReS₂, TMDs exhibit metallic conductivity, whereas when they are fully occupied, e.g. as in 2H-MoS₂ and 1T-PtS₂, the materials possess semiconducting properties. Moreover, even if the transition metal atoms have the major effect on the electronic properties, the bandgap between valence and conduction band decreases when the atomic number of the chalcogen increases. Indeed, the bandgap of bulk 2H-MoS₂, 2H-MoSe₂ and 2H-MoTe₂ gradually decreases from 1.2 eV down to 1.0 eV.²⁰ Nevertheless, the stability of the different polymorphs is also strongly influenced by the *d*-electron count of the transition metal atoms. Indeed, group 4 TMDs exhibit octahedral structure, whereas in group 5 and 6 both the octahedral and trigonal prismatic structures are observed. Group 6 TMDs are primarily found in trigonal prismatic geometry and group 7 are typically in a distorted octahedral structure, unlike group 10 which are all in octahedral structure.²⁴

Moreover, the ever-growing success of TMDs is particularly related to their thickness-dependent properties, which is determined by a change in band structure caused by quantum confinement effects and resulting variations in the orbital composition of the electronic states.²⁵ For example, the bulk and monolayer band structure for the semiconducting TMDs, e.g. MoS₂ and WS₂, undergoes remarkable variations with the number of layers. Indeed, at the Γ -point of the Brillouin zone the bandgap transition is indirect for the bulk material, but it gradually shifts towards direct one in the monolayer structure, whereas the direct transition at the K-point remains almost

unaffected.²⁶ Therefore, such a phenomenon makes TMD materials prime candidates for optoelectronic and photonic applications.²⁷ An additional paramount aspect to consider whenever a 2D material is exposed to an in-depth analysis concerns the inevitable presence of defects. Although defects alter the pristine properties of TMDs,^{28,29} they can act as chemically active sites during the chemical functionalization of TMDs, as proved by experimental and theoretical studies.^{30,31} In particular, due to thermodynamic considerations related to the formation energies, vacancies are the most common point defects in ultrathin TMD nanosheets and they have been observed in multiple forms, such as single or double M or X vacancies, albeit the landscape of defects and disorder in TMD systems is much more complex and might also include grain boundaries, dislocations, vacancies of Mo-S complexes and antisite defects.³²

Ultimately, the physicochemical properties of ultrathin TMD systems can vary dramatically with the 2D structure features, and such considerations cannot be overlooked during the molecular strategies aiming at finely tailoring their properties (Section 4).

3. Production of solution-processed TMDs

The successful applications of a certain 2D materials are strictly related to their quality and yield of their exfoliation processes. To date, micromechanical cleavage remains the most straightforward source of high-quality 2DMs, although it suffers from low yields and production rates that are not technologically scalable at industrial level.

In light of such limitations, during the last decade intense research endeavors have been addressed towards the design and development of innovative solution-based strategies to achieve an efficient production of 2D structures (Fig. 2), such as TMD nanosheets, exhibiting specific structural features and

therefore electronic and spectroscopic properties. For a better understanding, the production approaches can be classified as *top-down* and *bottom-up* approaches. In the latter case, TMDs are synthesized starting from suitable precursors and by connecting atoms to each other, leading to systems characterized by minor defectivity, high chemical homogeneity and good short- and long-range ordering. In particular, this class includes processes mainly based on solvothermal,^{33,34} colloidal^{35,36} and secondarily electrochemical synthesis.^{37,38} Conversely, in *top-down* strategies, which include among the others liquid-phase exfoliation (LPE)³⁹ and electrochemical exfoliation (ECE)⁴⁰ approaches, TMD nanosheets are exfoliated from the bulk system under specific conditions and, due to the inherent features of the procedure, such an approach entails both the production of new defects in the nanosheets and the propagation of defects inherited from the bulk structure. Nevertheless, such a class of techniques is commonly employed because it represents the best trade-off among the pivotal parameters to assess a production strategy in 2DMs' science, such as costs, purity, yield, etc.⁴¹

The following sub-chapter describes the main characteristics for each of the aforementioned production strategies, pointing out the opportunities and challenges faced during the production and isolation of solution-processed TMD nanosheets.

3.1 Solvothermal synthesis

The first crystal growth under hydrothermal conditions was reported in 1845 by the German geologist Schafhäütl, who

succeeded in the production of microscopic quartz crystals.⁴² Noteworthy, the term “solvothermal” refers to the procedures which exploit an organic solvent, whereas when water or aqueous solutions are involved it is referred to as “hydrothermal” process.

Nowadays, hydro/solvothermal synthesis represents a valuable *bottom-up* approach to produce TMDs, starting from specific precursors and taking advantages of sealed autoclaves operating at high temperatures ($10 - 10^2$ °C) and controlled pressure ($1 - 10$ Pa).^{43,44,45} The main advantages of this strategy lie with the superior aptitude of materials in being induced to solubility *via* proper temperature and pressure conditions, along with the more accurate control of the operating parameters, which might influence the quality and crystal structure of the final systems.⁴⁶ Nevertheless, such an approach envisages some drawbacks related to the need of expensive autoclaves able to withstand the operating conditions (temperature, pressure, pH, solvent, etc.) and the lack of a real-time monitoring of the crystal growth (“black box”).⁴⁷

As already mentioned, the operating parameters play a fundamental role in determining the successful and efficient growth of TMDs. A prime example is represented by the solvent, whose nature might strongly affect the morphology of MoS₂ nanosheets because of the structure-directing ability of organic molecules, as reported by Feng *et al.*³³ Furthermore, Xie and co-workers succeeded with the growth of defect-rich MoS₂ nanosheets by adjusting the concentration of the precursors, namely ammonium molybdate and thiourea, stabilizing

Fig. 2 Illustration of the main production strategies to obtain solution-processed TMD materials *via top-down* (left) and *bottom-up* approaches (right). In particular, *top-down* strategies mainly rely on liquid-phase exfoliation (LPE) and electrochemical exfoliation (ECE) of bulk systems, unlike *bottom-up* approaches which essentially entail solvothermal and hot-injection synthesis starting from appropriate precursors.

ultrathin structures and enhancing their electrocatalytic activity towards hydrogen evolution reactions (HERs).⁴⁸ Interestingly, solvothermal operating conditions have been also exploited to intercalate TMDs with solvent molecules,⁴⁹ lithium ions⁵⁰ or oxygen molecules,⁵¹ promoting the subsequent exfoliation procedures. Finally, solvothermal synthesis can also be exploited to grow TMD-based hybrid systems, by making use of the synergetic effects of the components and enhancing the proprieties and performances of the resulting materials.^{52,53}

3.2 Hot-injection synthesis

Hot-injection synthesis, also known as colloidal synthesis, represents an additional valuable solution among the wet *bottom-up* chemical methods to produce TMD systems.

In particular, such an approach provides a versatile strategy towards synthesis of nanocrystals with tunable shape, lateral size and thickness. From this perspective, the choices concerning the precursors, the potential coordinating ligands (to ensure stability and control over the size and shape) and the solvent (which provides an homogeneous reaction medium and might act as capping ligand as well) are crucial.⁵⁴ Nevertheless, the hot-injection method possesses some major drawbacks related to the use of expensive, hazardous and toxic precursors and solvents, such as organometallic and phosphine-based compounds, respectively, which have hindered the large-scale synthesis for commercial production.⁵⁵

In most cases, the method envisages the use of a chalcogen precursor solution rapidly injected into a hot mixture (150–300 °C) of metal precursors and capping agents, where an accurate control over the structural features of the growing materials can be achieved by adjusting the operating conditions and the chemical species involved in the process. In particular, besides general protocols mainly adopted in the synthesis of group 4 and 5 TMDs with specific lateral size and thickness,^{56,57} researchers have developed versatile approaches to obtain materials with specific physicochemical characteristics. For instance, the lateral size of TMD nanosheets can be tuned by playing with reaction time while keeping the thickness constant, as reported by Jang *et al.* about the ZrS₂ nanodiscs synthesis by injecting carbon disulfide (CS₂) into a mixture of zirconium (IV) chloride (ZrCl₄) and oleylamine at 300 °C under argon atmosphere.⁵⁸ Analogously, even the final thickness of TMD systems can be finely tuned by either adjusting the precursors concentration,⁵⁹ or more interestingly, by changing the functional groups of the capping ligands, to exploit the different binding affinities with the TMD nanosheet edges.³⁵ Moreover, the reaction temperature can be adjusted to produce TMD defect-rich nanoflakes, as reported by Cheng and co-workers, who exploited the abundant presence of edges to obtain a WS₂-based material characterized by high catalytic activity for HERs in acids.⁶⁰ Finally, the presence of templating agents can steer the growth of TMDs towards specific structural features, introducing external chemical species⁶¹ or performing the reaction under controlled atmosphere.⁶²

Ultimately, colloidal synthesis represents an intriguing and versatile class of reactions towards the bottom-up production

of TMDs, and recently some innovative variations have been established in order to employ single precursors,⁶³ produce hybrid systems⁶⁴ and use nontoxic phosphine-free solvents.⁶⁵

3.3 Liquid-Phase Exfoliation (LPE)

The overwhelming majority of solution-processed TMD systems produced by *top-down* approaches derive from liquid-phase exfoliation techniques. Indeed, the seminal work published by Coleman and co-workers in 2008, on the first LPE of graphite towards graphene,⁶⁶ paved the way to this new method for the isolation of thin 2DMs, such as TMD nanosheets.

LPE entails the use of a liquid sample containing the bulk TMD crystals and a transfer of energy thereto, in order to overcome the weak vdW interactions acting within the layered systems and promote their exfoliation. Towards this end, mechanical energy is a suitable choice because of several advantages, such as low cost, user-friendliness and versatility among others. In this regard, mechanical energy can be transferred to the bulk TMD crystal *via* different strategies and forms (the latter is related to the different forces acting on the bulk structure). More specifically, shear and compression forces arise during the exfoliation steps by means of ball milling and shearing methods, fostering the separation of thinner systems.^{67,68,69} Additionally, ultrasonication approaches can also be employed to guarantee an energetic agitation of the system and the transfer of energy from the solution to the layered structure. In particular, the ultrasound waves propagate within the solvent causing alternating high- and low-pressure cycles that promote the exfoliation because of two main forms of energy inputs, namely vibration and cavitation forces. Vibrational energy arises from the generation and propagation of transverse waves through the solvent, causing vibrational modes within the layered structure with enough energy to peel the nanosheets apart. Moreover, the increasing of ultrasonication power allows the generation of cavitation forces, more energetic than vibrational forces. In fact, the formation and implosion of cavitation bubbles within the solvent promotes fast and energetic shock waves that induce high local temperature (10²–10³ °C) and pressure (from kPa to MPa) conditions. Nevertheless, such high energy cavitation forces have detrimental effects on the lateral size of the nanosheets, although they exfoliate far more effectively than vibration ones, leading to higher concentrations of dispersed material.⁷⁰ Therefore, since vibration forces help in maintaining the nanosheet size,⁷¹ a balanced trade-off between the two modes is required to tune the final structural features of the material.

Besides mechanistic considerations, several parameters play a fundamental role in determining the quality and efficiency of the exfoliation procedures, such as the power, time and the type of sonication (e.g. sonic baths or sonic probes), along with the exfoliation solvent.^{72,73} Indeed, the choice of solvent is crucial, since it plays three main roles¹¹: (1) it is the medium designed for transferring the acoustic power during the ultrasonication steps; (2) it must exhibit the correct parameters to minimize the mixing enthalpy between the liquid

and the layered structure, in some cases allowing the solvent intercalation;⁷² (3) it stabilizes the exfoliated material by providing a steric barrier with consequent inhibition of the reaggregation phenomena.⁷⁴ In this regard, new liquid-phase exfoliation approaches have been developed to employ less hazardous and lower boiling point solvents, leading to the use of solvent/surfactant mixtures.⁷⁵ The additives play a double role by modulating the surface tension of the solvent, improving the dispersibility, and creating an additional repulsive force that inhibits the reaggregation process, such as in the case of polymer solutions.^{76,77} Although the use of stabilizers provides some benefits, it results difficult to remove them completely from the exfoliated materials and this can affect their properties, especially the electrical performances.⁷⁸ Moreover, liquid-phase as-exfoliated TMDs' nanosheets display a broad polydispersity in terms of thickness and lateral size, requiring several size-sorting steps to achieve the desired structural features.⁷⁹ Ultimately, LPE strategies might possess suitable features to scale-up the production of TMDs to industrial level, paving the way to their application in several research fields.

3.4 Electrochemical Exfoliation (ECE)

An additional and extremely powerful *top-down* approach to exfoliate bulk TMD crystals exploits the intercalation of chemical species within the layers, leading to an expansion of the structure and a weakening of the interlayer vdW interactions.

Lithium-ion intercalation in TMDs has been studied since the '80s^{80,81} and the original method is still widely adopted to produce single- and few-layer TMD nanosheets. It envisages the formation of an intercalated intermediate [Li_xMoS_2] by soaking bulk TMD powder in a solution of *n*-butyllithium (*n*-BuLi) for 2–3 days under inert atmosphere, generally argon or nitrogen, at elevated temperature (c.a. 80 °C). Subsequently, the intercalated material is transferred into an aqueous or low-boiling point solvent solution and exposed to ultrasound waves to complete the exfoliation, even promoting the potential reaction between lithium ions and water to form gaseous hydrogen, which boost the separation of thin nanoflakes.⁸¹ However, some TMDs undergo structural and electronic changes upon lithium-ion intercalation (*lithiation* process), and therefore they are often referred to as chemically exfoliated TMDs (*ce*-TMDs).⁸² Nevertheless, such a technique presents considerable hazards related to the use of *n*-BuLi and safer approaches have been developed in the last years.

A promising variation of such an exfoliation technique is the electrochemically-assisted process,^{83,84} which guarantees a fine control over the lithium intercalation within the bulk TMD crystals. One of the possible lithium sources is represented by lithium foils, usually employed as the anode of the electrolytic cell, along with the TMD crystal acting as cathode of the system (cathodic exfoliation). It is worth mentioning that the electrochemical exfoliation exhibits many advantages due to the more favorable operating conditions, such as room temperature, shorter production time and safer chemicals. Nevertheless, in order to tackle the costs concerning the use of

lithium foils, new techniques exploiting different lithium sources, such as electrolytes,⁸⁵ have been explored. By taking advantage of that, the electrochemical exfoliation can be performed using aqueous solutions⁸⁶ and under ambient conditions⁸⁷, thus representing an appealing and cutting-edge technique to produce thin TMD nanosheets.

It is worth mentioning that the lithium intercalation is not just a mechanical process in which an expansion of the structure is achieved. In fact, an electron transfer process takes place from the metal ion to the lowest lying unoccupied energy level of the metallic d-bands for the MX_2 crystal.^{88,89} The effects of this charge transfer depend on the resulting d-electron count of the metal center and they are particularly significant in Group 6 TMDs, such as MoS_2 ,⁹⁰ WS_2 ,⁹¹ etc. More specifically, the energy penalty encountered due to the electron transfer is minimized by forcing a change in the metal coordination geometry, from trigonal prismatic (2H polymorph) to the charge-stabilizing octahedral geometry (1T polymorph). As consequence, the changes in the electronic structure result in significant alterations of the properties: in the MoS_2 case, the change from the 2H polymorph to the 1T polymorph, upon lithium-ion intercalation, induces a change from semiconducting to metallic behavior, respectively. However, the pristine 2H structure and its related properties can be preserved either converting the metastable 1T phase, obtained *via* lithiation process, by means of physicochemical stimuli^{92,93} or using different intercalating chemical species,^{94,95} which promote the retaining of the starting crystal structure. Therefore, electrochemical exfoliation approaches represent an efficient and versatile tool to achieve the production of thin TMD systems with specific structural features and properties.

4. TMD functionalization strategies *via* molecular approaches

As extensively discussed in *Section 3*, synthesis and production processes already contribute in determining the final properties of exfoliated TMD nanosheets. Nevertheless, post-exfoliation treatments have raised lately to meticulously customize the physical and chemical properties of two-dimensional TMD

Fig. 3 The image illustrates the main functionalization strategies for TMDs materials *via* molecular approaches. In particular, they rely on the physisorption and chemisorption phenomena of (supra)molecular species by means of diverse mechanisms/interactions.

Fig. 4 Functionalization strategies *via* molecular approaches for solution-processed TMD nanosheets. The plethora of possible functionalizing molecules to succeed in the formation of functional TMD-based hybrid systems guarantees a wide range of possible combinations, and the different methods can be divided in five classes: physisorption, covalent, coordinative, coordinate-defects and defects.

materials (Fig. 3), where the final goal seeks the matching with the requisites envisaged for a certain type of application. In particular, many excellent review articles^{96,97} have been published on solution-based approaches to exfoliate TMD materials, although they do not provide additional information about a possible further tailoring of the physicochemical properties using molecular approaches. For this purpose, in the following paragraphs, we report on the diverse classes of functionalization strategies envisaged for solution-processed TMDs, exploiting different mechanisms and interactions (Fig. 4).

4.1 Physisorption

TMD nanosheets, like all others 2DMs, are characterized by a high surface area, hence non-covalent functionalization *via* physisorption of various molecular systems is a promising strategy to produce TMD-based hybrid structures (Fig. 5).

Such an approach is mainly adopted to increase the dispersibility of TMD nanosheets in a certain solvent, preventing aggregation of 2D sheets after the exfoliation procedures. Specifically, organic functional groups are adsorbed onto the nanosheet surface of 2DMs *via* vdW and electrostatic interactions,^{98,99} modulating the solubility parameters. From a mechanistic point of view, the stabilization in aqueous environment by means of ionic surfactants is achieved because of steric hindrance and Coulombic repulsion, which can be described within the Derjaguin-Landau-Verwey-Overbeek (DLVO) theory.¹⁰⁰ In this regard, Gupta *et al.* provided evidence on the structure and organization of ionic surfactants onto MoS₂ nanosheets, focusing on the cationic amphiphile cetyltrimethyl ammonium bromide (CTAB) and the anionic sodium dodecyl

Fig. 5 (a) Cartoon of MoS₂ nanosheet with surfactant molecules, containing ionic head-group (in blue). (b) Zeta-potential distribution of as-prepared MoS₂-CTAB and MoS₂-SDS dispersions. Reproduced with permission from ref. 100, copyright 2015 American Chemical Society. (c) Illustration of phase-transfer processes for *ce*-MoS₂ nanosheets from water to organic solvents. (e) XPS spectra evolution of MoS₂ annealed at different temperatures, with corresponding phase percentage (d). Reproduced with permission from ref. 105, copyright 2015 American Chemical Society.

sulfate (SDS). It was demonstrated that the surfactant chains physisorbed flat, randomly arranged on the basal plane of the MoS₂ nanosheets, with their charged headgroup pointing out from the MoS₂ surface. Furthermore, by means of Nuclear Overhauser Effect (NOE) spectroscopy, the authors studied the dynamic interaction between the organic physisorbed molecules and the inorganic TMD nanosheets, where the former are rapidly exchanged with the free surfactants molecules in the aqueous environment.¹⁰¹ In the case of non-ionic surfactants or polymers being added as stabilizers to nanosheet dispersions,¹⁰² the stabilization process can be described in the framework of solution thermodynamics. Nevertheless, the presence of polymers during the exfoliation process can negatively affect the efficiency of the process, in terms of mean layer number and concentration. Indeed, the presence of polymers in solution influences the surface tension of the solvent (in particular, it increases with the polymer concentration), therefore some authors suggested to add gradually the polymeric system during the exfoliation procedure to overcome such an issue.¹⁰³

Another common non-covalent approach relies on the use of electrostatic interactions between ionic molecules and negatively charged *ce*-1T-TMD nanosheets, promoting the stabilization of their liquid dispersions ("inks") as well.¹⁰⁴ Taking advantage of the aforementioned interactions, *ce*-1T-TMD systems can be dispersed in high boiling point solvents, e.g. octadecene and *o*-dichlorobenzene, and undergo phase transition by heating, preventing any aggregation phenomena.¹⁰⁵ Additionally, electrostatic interactions can

represent a fruitful tool to produce multi-layered structures. On this view, layer-by-layer method allows the formation of assemblies made of TMD systems regularly spaced by polyelectrolyte layers, and where the photoluminescence properties of the nanosheets depend on the number and functional groups of the ionic layers.¹⁰⁶

4.2 Covalent

Besides physisorption phenomena, solution-processed TMD nanosheets, obtained *via* both LPE and ECE, can be chemically functionalized by taking advantage of chemisorption mechanisms (Fig. 6).

In particular, covalent modification of TMDs refers to a reductive functionalization of nanosheets with electrophiles and involves the formation of a new carbon-chalcogen bond.¹⁰⁷ The pioneering work in this direction was published by Voiry *et al.*, who exploited the reaction between *ce*-1T-MoS₂, WS₂ and MoSe₂ with alkyl halides and aryl diazonium salts, leading to dramatic changes in the optoelectronic properties of the involved TMD nanosheets.¹⁰⁸ More specifically, the authors reported on the reaction through which the electrophile species attack the negatively charged nanosheets and a new carbon-chalcogen bond is formed, with a degree of functionalization around 20%. The successful functionalization was proved by means of ¹³C-NMR, XPS, PL and IR spectroscopy, highlighting the retention of the 1T structural polymorph but exhibiting the semiconducting properties of the material after the covalent modification, due to the charge neutralization phenomenon. Taking inspiration from the aforementioned work, the covalent modification of solution-processed TMD materials has been mainly achieved by making use of alkyl/aryl halides and aryl diazonium salts. In particular, the latter approach shows a great feasibility because it exploits the inherent high reactivity of the negatively charged TMD nanosheets, obtained *via* ECE, and the diazo group, consisting of two linked nitrogen atoms at the terminal position of a molecule. In this regard, Backes and co-workers succeeded in covalent grafting of organic moieties onto the basal plane of MoS₂ nanosheets, *via* the formation of new C-S bonds. Remarkably, DFT calculation revealed that the grafting of the functional groups to the sulfur atoms of MoS₂ is energetically favorable and C-S bonds are indeed formed.¹⁰⁹ Furthermore, such an approach can be also adopted to tune the surface energy of *ce*-TMD nanosheets with fundamental consequences on their electrocatalytic activity towards HERs.¹¹⁰

Covalent modification *via* of alkyl/aryl halides represents an additional and efficient approach to tune the physicochemical properties of *ce*-TMD nanosheets. A prime example comes from the work published by Chen *et al.*, who functionalized 1T-MoS₂ nanosheets with light-sensitive Ru (II) complexes, leading to the formation of TMD-based hybrid systems characterized by higher photoresponsivity and notable performances in HERs.¹¹¹ Even though negatively charged *ce*-TMD nanosheets present higher reactivity, and therefore superior aptitude to undergo covalent functionalization, some recent works have been published on TMDs obtained *via* LPE as well. Among them, an elegant approach was published by McAdams, concerning the

Fig. 6 (a) Illustration of the functionalization reaction for *ce*-MoS₂ nanosheets using R-I, such as iodomethane or 2-iodoacetamide. (b) ATR-FTIR spectra of iodomethane (1) and functionalized 1T-MoS₂ (2), 1T-WS₂ (3) and 1T-MoSe₂ (4). Reprinted with permission from ref 108, copyright 2014 Nature Publishing Group. (d) Representation of *ce*-MoS₂ functionalization with [Ru^{II}(bpy)₃]²⁺. (c) Chronoamperometry measurements of pristine *ce*-MoS₂ (black) and [Ru^{II}(bpy)₃]-MoS₂ (red). Reproduced with permission from ref 111, copyright 2017 Wiley-VCH.

simultaneous covalent modification of MoS₂ nanosheets with Eu(III) and Gd(III) complexes, to form a stable luminescent and paramagnetic hybrid material.¹¹² Ultimately, covalent approach is a paramount tool which allows a meticulous control over the TMD properties.

4.3 Coordinative

An intriguing additional strategy to chemically functionalized solution-processed TMDs nanosheets relies on the coordination chemistry of cationic metal complexes (Fig. 7). Although the coordinative strategy is still at its infancy, some interesting works have been published in this regard, proving the high potential of such an approach.

The pioneering work in this direction was reported by Tahir *et al.*,¹¹³ who succeeded in the functionalization of hybrid MoS₂/fullerene nanoparticles using the inherent principles of coordination chemistry and Lewis theory of acid-base reactions. More specifically, the authors exploited a multifunctional polymer possessing a tetradentate ligand capable of anchoring Ni²⁺ ions, whose octahedral coordination is completely blocked on one side with an umbrella-type chelating ligand (polymer), while the other part of the coordination sphere remains open to bind the sulfur layer of the MoS₂/fullerene system. Therefore, the coordination geometry and sulfur affinity are crucial parameter to allow the transition metal ions to simultaneously bridge the inorganic (MoS₂/fullerene

Fig. 7 (a) Illustration of the Cu^{II}-coordinated MoS₂/PMMA paper and (b) comparison of its tensile strength, Young's modulus and elongation at the break with bare MoS₂ and MoS₂/PMMA paper. Reproduced with permission from ref. 114, copyright 2012 Wiley-VCH. (c) Depiction of MoS₂-rGO hybrid paper cross-linked by PEO. (d) Cycle performance of MoS₂-rGO-PEO film anodes at different wt ratios. (e) Rate capability of the MoS₂-rGO-PEO film anode with wt ratio 6/3/1. Reproduced with permission from ref. 115, copyright 2013 Royal Society of Chemistry.

nanoparticles) and organic (polymer) moieties, and so promoting the formation of the hybrid system.

In the same vein, Xie and co-workers have reported the production of MoS₂-based nanocomposites¹¹⁴ and hybrid systems¹¹⁵ exploiting the coordination chemistry of Cu²⁺ ions and their interaction between sulfur layers and oxygen functionalities, found in polymer matrices or graphene-related materials, such as graphene oxide (GO) and reduced graphene oxide (rGO). Indeed, MoS₂-graphene hybrid paper, cross-linked by polyethylene oxide (PEO) and Cu²⁺ ions, can be exploited to fabricate high-performance anode materials that show great potential for lithium-ion batteries.¹¹⁵ Furthermore, it has been proved that a similar approach could be adopted to enhance the mechanical properties of nanocomposites, due to the direct and strong nanofiller/matrix interaction. Hence, solution-processed MoS₂ nanosheets can be dispersed in polymer matrix of PMMA

(polymethyl methacrylate), along with Cu²⁺ ions, to increase the Young's modulus of the resulting hybrid systems thanks to the bridging action of the inorganic cations between the organic and inorganic moieties.¹¹⁴

Recently, Backes *et al.* developed a facile approach to functionalize solution-processed 2H-MoS₂ nanosheets, taking advantage of their reaction with a variety of metal carboxylate salts.¹¹⁶ In particular, the successful functionalization was proved by XPS, Diffuse Reflectance Infrared Fourier Transform spectroscopy (DRIFT-IR) and Thermogravimetric Analysis (TGA), thereby showing strong evidence about the coordinative interaction between the sulfur atoms in the MoS₂ nanosheets and the Lewis acid metal atoms of the organic molecular systems. Moreover, the functionalization approach guarantees the retention of the initial semiconducting crystal phase and a tuning of the surface energy, proved by the superior dispersibility of the material in non-conventional solvents such as acetone and isopropanol. Finally, coordinative strategy has been recently adopted to tune the optoelectronic properties of mechanically exfoliated TMD materials,¹¹⁷ encouraging the use of a similar approach to solution-processed material as well, aiming at meticulously tuning and enhancing their electrical performances.

4.4 Coordinative-defect

The majority of the chemisorption-based functionalization approaches for solution-processed TMD nanosheets exploits the inevitable presence of chalcogen atom vacancies, mainly produced during the exfoliation procedures (Fig. 8).

The seminal work was published by Dravid and co-workers in 2013,¹¹⁸ where *ce*-1T-MoS₂ nanosheets were subjected to reactions with several different thiol-terminated polyethylene glycol derivatives bearing ionic and non-ionic headgroups. More specifically, the authors exploited the high reactivity of *ce*-MoS₂ nanosheets and their structural defects, especially sulfur vacancies located at both internal and perimeter edges. The outcome of the ligand affinity tests shows that the thiol group of the molecular systems explored is responsible for the MoS₂ modifications, as proved by XPS, FT-IR and Dynamic Light Scattering (DLS) measurements. Alongside, the authors have explored the effects of the ligand structure on the properties of the 2D systems, changing the polarity of the headgroup (neutral, cationic or anionic) and the ligand conjugation. In this manner, fundamental knowledge over the colloidal stability, catalytic activity and chemical affinity towards specific molecules could be achieved, promoting a vast use of functionalized TMD materials in many different research fields. To functionalize TMD nanosheets *via* coordinative-defect approach two main distinct strategies can be adopted, dealing with either the direct functionalization of TMD liquid dispersions containing the exfoliated materials,^{119,120} or the simultaneous exfoliation of the bulk TMD crystals and functionalization of the resulting exfoliated systems.¹²¹ Nevertheless, some works have also been published about the functionalization of substrate-supported solution-processed TMD nanosheets.⁸⁷ To date, the majority of works reported in

Fig. 8 (a) Graphical illustration depicting the ligand conjugation of *ce*-MoS₂ nanosheets with different thiolated molecules by means of sulfur vacancies. (b) Zeta potential of *ce*-MoS₂ nanosheets functionalized with thiolated molecules bearing diverse functional groups. (c) FT-IR spectra showing all the peaks and (d) zoom in the region of S-H stretching for native *ce*-MoS₂, functionalized-MoS₂ and free ligand species. Reproduced with permission from ref. 118, copyright 2013 American Chemical Society.

literature envisages treating the exfoliated materials with the functionalizing molecular systems after the exfoliation steps.

In this regard, 2D transition metal disulfide systems have drawn a great attention because of their versatility and aptitude to undergo healing reactions, in which thiolated molecules are exploited to fill the sulfur vacancies contained in the crystal structure and produced during the exfoliation procedures. In particular, transition metal disulfide have been extensively studied and processed with dithiolane derivatives and thiolated molecules, in order to produce hybrid systems characterized by

new or enhanced physicochemical properties and superior performances, for applications spanning from biosensing¹²² to electronics.⁸⁷

Nevertheless, the sulfur healing phenomenon is not always the most favorable process. Indeed, McDonald and co-workers demonstrated that the disappearance of the S-H vibration in the IR spectra, considered the main proof of the functionalization reaction, can also be due to a TMD-mediated dimerization of thiolated molecules to form disulfide species.¹²³ In this light, no chemisorption phenomena take place, and disulfide molecules are just physisorbed onto the TMD nanosheets *via* weak vdW interactions. This was demonstrated by DFT calculations and recent theoretical works,^{124,125} showing how the nature and the amount of defects influence the interaction between thiolated molecules and sulfur vacancies. Therefore, the aforementioned process, whose mechanism is still under debate, can result in either chalcogen defect healing or the formation of disulfide and hydrosulfide molecules weakly interacting with the 2D TMD systems.

4.5 Defects

An additional and appealing molecular strategy commonly used to functionalize solution-processed TMD nanosheets envisages the growth of noble metal nanoparticles (NPs), mainly Au,^{126,127} Pd,^{128,129} Pt^{130,130} and AgNPs,^{131,132} and their interactions with the 2D systems (Fig. 9).

In fact, NPs can interact with both liquid-phase exfoliated and *ce*-TMDs *via* covalent¹³³ and non-covalent¹²⁷ interactions, resulting in hybrid systems characterized by exceptional performances for (photo)catalysis^{134,135} and biomedicine^{131,136} applications. The growth of NPs takes place after the reduction of a noble metal precursor salt,¹⁷ due to an addition of reducing agent¹³⁷ or spontaneous formation.¹²⁷ In the latter case, Kim *et al.* succeeded in decorating *ce*-MoS₂ and *ce*-WS₂ nanosheets with AuNPs, using hexachloroauric acid (HAuCl₄) in water as precursor.¹²⁷ The functionalization takes place preferentially on the defect sites, located at the edges and basal plane of the nanosheets, which are in general more reactive than bulk crystals. More specifically, a redox reaction is involved between gold ions and TMD materials, encouraged by the position of the TMD Fermi level (5.2 eV and 5.1 eV for MoS₂ and WS₂, respectively),^{138,139} well above the reduction potential of the trivalent gold ions (+1.0 V vs. SHE). Remarkably, it was found that AuNPs play a double role, acting as a spacer to inhibit restacking phenomena in *ce*-TMDs and improve the charge transport among adjacent nanosheets, as proved by impedance spectroscopy.

As a consequence, the resulting MoS₂/AuNPs and WS₂/AuNPs hybrid systems possess superior electrocatalytic performances toward HERs.

Nevertheless, the synthesis and growth of noble metal NPs can also be induced by the use of a proper reducing agent. In this regard, Huang *et al.* exploited solution-processed MoS₂ nanosheets to direct the epitaxial growth of Pd, Pt and Ag nanoclusters in ambient conditions, using different reduction methods according to the metal precursor.¹⁷ Interestingly, the

Fig. 9 (a-b) TEM images of (a) MoS₂ and (b) WS₂ nanosheets decorated by AuNPs. (c) HER performances of hybrid MoS₂/AuNPs show a decrease of the overpotential and increase of current density when the gold loading level increases, along with a decrease of the charge-transport impedance (Z'), as reported in (d). Reproduced with permission from ref. 127, copyright 2013 American Chemical Society.

TMD nanosheets are able to address NPs towards an epitaxial growth and the major orientations arising are (100) and (111). Moreover, besides providing plenty of nucleation sites in the defective areas, 2D epitaxial template stabilize small NPs and prevent them from aggregation. It is worth mentioning that in the case of MoS₂/PtNPs hybrid systems, the nanomaterials had been tested as promising catalysts for HERs and exhibited much better electrocatalytic activity than commercial Pt catalyst, at the same Pt loading, likely due to the presence of additional {110} and {311} facets which promote the catalytic reactions.¹⁴⁰ Ultimately, solution-processed TMD nanosheets might be also subjected to prior functionalization exploiting thiol¹³² or organohalide¹³¹ chemistry, in order to active the 2D structure and make it more reactive during the following growth of NPs. Finally, such an approach represents a cutting-edge molecular strategy to produce novel versatile hybrid functional material.

5. Paramount applications of multifunctional and hybrid materials based on solution-processed TMDs

5.1 (Opto-)electronics

Semiconducting single- and few-layer TMD nanosheets are very attractive for the fabrication of electronic devices, such as metal-oxide-semiconductor field-effect transistors (MOSFETs), photodetectors and photodiodes, exhibiting a great potential for (opto-)electronic applications (Fig. 10).¹⁴¹ Solution-processing techniques possess high exfoliation yield and a superior control over the final thickness, which is crucial in determining the

electronic properties and the related electrical properties and performances of TMD-based devices (see Section 2).¹⁴²

In particular, during the last few years many works have been published about the possible applications of LPE and *ce*-TMDs in (opto-)electronics, with intriguing results coming from the fabrication of devices such as transistors,¹⁴³ saturable absorbers for lasers,^{144,145} photodetectors¹⁴⁶ and Mg/Li-ion batteries.¹⁴⁷ However, solution-processed TMDs can undergo subsequent functionalization steps *via* molecular strategies in order to meticulously tailor and/or further enhance their physicochemical properties. More specifically, many scientific endeavors have been devoted to the production of light-sensitive hybrid structures, whose performances could boost the evolution of the current technologies.

In this regard, Yin *et al.* functionalized *ce*-MoS₂ nanosheets with AuNPs, increasing the device photocurrent with a maximum located at the wavelength corresponding to the AuNPs plasmon resonance.¹⁴⁸ From a mechanistic point of view, the localized surface plasmon resonance enhances the local optical field and thus the light absorption of the MoS₂ layer underneath the AuNPs. Moreover, the collective electron oscillation of neighboring AuNPs can increase the photocurrent due to coupling events, leading to better device electrical performances. Additionally, Au-MoS₂ hybrid systems have been tested as photoanode for water splitting application, exhibiting higher photocatalytic activity than pristine MoS₂, due to the presence of AuNPs which promote the photo-generated charges separation.

An additional example is provided by the work published by Zaumseil and co-workers, who exploited liquid-phase exfoliated TMD nanosheets to fabricate promising IR-photodetectors.¹⁴⁹ Indeed, combining MoS₂ and WS₂ nanosheets with PbSe QDs, the authors reported the fabrication of photodetectors with near-IR photosensitivity and long-term air stability. Moreover, the epitaxial growth of PbSe QDs on TMDs allows a defined and direct interface between the two systems without the use of any molecular linker. Such a condition guarantees an optimal charge transfer process and remarkable performances in hybrid systems characterized by excellent mechanical stability and therefore great potential in low-cost flexible optoelectronics.

5.2 (Photo-)catalysis

Solution-processed TMDs have also attracted the attention of the worldwide scientific community because of their great aptitude to fabricate hybrid systems characterized by superior (photo)catalytic activity, with consequent many interesting possible applications (Fig. 10). More specifically, TMDs have been widely used to catalyze reactions involving organic molecular systems^{150,151,152} or the production of molecular hydrogen during electrocatalytic¹⁵³ or photocatalytic¹⁵⁴ water splitting processes. In fact, hydrogen is one of the most important clean and renewable energy vectors for future sustainability. Nowadays, the most efficient manners to convert sustainable energy to clean energy carriers envisage photocatalytic and electrocatalytic approaches, such as HERs.¹⁵⁵ In this regard, catalysts based on TMDs represent promising

substitutes for noble metal-based systems, commonly adopted so far. Furthermore, the device performances might be further improved by combining TMDs with other nanomaterials, such as oxides,¹⁵⁶ QDs and carbon-based materials.¹⁵⁷ From this perspective, Chen *et al.* reported the production of high performance hybrid systems in HERs, consisting of CdS nanocrystals grown on the surface of solution-processed MoS₂/graphene hybrids.¹⁵⁷ Indeed, graphene could match with MoS₂ and enhances its conductivity, promoting fast charge transfer and boosting the catalytic performances. In particular, under visible light, the photogenerated excited electrons of CdS are transferred to the surface, where some of them, reaching the edges of MoS₂ systems, directly react with H⁺ in H₂O to form H₂, under the cocatalytic activity of unsaturated active S atoms. Other electrons, in the MoS₂/graphene basal plane, can be transferred to the MoS₂ edges *via* graphene sheets and then react with H⁺ following the aforementioned mechanism. Also, the nanosized MoS₂/graphene hybrid systems possess an abundant number of active edges, which shorten the path for the electron transfer. Finally, the overall CdS/MoS₂/graphene hybrid system shows enhanced electron transfer ability and retards the recombination of electron-hole pairs, improving the photocatalytic activity in HERs.

Ultimately, the synergetic effects among the components in a hybrid system allow an increase in performances, overcoming the individual weaknesses and raising the technological level of the final materials.

5.3 (Bio-)sensing

In the last few years, solution-processed TMDs have led to wide ranging and diversified technological applications because of their intriguing and versatile properties. More specifically, favorable branches involve (bio-)sensing and nanomedicine (Fig. 10) applications, taking advantage of the large surface area of 2D materials.^{158,159} Indeed, TMDs represent forefront sensing platforms on which suitable and versatile receptors might also be anchored, *via* covalent and non-covalent interactions, in order to detect environmental parameters (e.g., temperature, pressure, humidity) or specific (bio-)analytes, spanning from small molecules to complex molecular (bio-)structures.^{160,161,162}

In this regard, many different TMD-based sensors have been designed, taking advantage of different interactions, properties and techniques, in order to expand the sensing fields with the consequent discovery of a great potential. Electrochemical^{163,164} and colorimetric¹⁶⁵ sensors based on solution-processed TMD pristine or hybrid materials represent a typical example, proving how this class of 2D systems could be of paramount importance in supporting the future technological progress.

Furthermore, the optical properties of solution-processed TMDs contributed in supporting their application for imaging purposes, even though some crucial aspects must be tackled to encourage a massive use, such as the poor stability of colloidal dispersions, the lack of strategies to selectively functionalize ultrathin layered nanosheets and control the functionalization degree. From this perspective, many novel molecular strategies have been conceived in the last few years, aiming at overcoming

Fig. 10 Illustration of the main applications envisaged for solution-processed TMD nanosheets, both in the pristine and functionalized forms. In particular, (opto-) electronics, (bio-)sensing and (photo-)catalysis represent the most influential topics covered in literature so far. From this perspective, the areas of the different sectors reported in the graph take into account the amount of works published in the last few years. To facilitate the comprehension of the graph, a small legend is reported below: MOSFETs = Metal-Oxide-Semiconductor Field-Effect Transistors, TCEs = Transparent Conductive Electrodes, SCs = Solar Cells, LEDs = Light Emitting Diodes, HERs = Hydrogen Evolution Reactions, Biomol. = Biomolecules, Press. = Pressure, Temp. = Temperature.

the aforementioned limitations by means of the fabrication of hybrid materials. Notably, Liu and co-workers developed a new generation of promising theranostic and contrast agents based on TMD nanosheets functionalized with biocompatible polymer (polyethylene glycol, PEG)¹⁶⁶ and iron oxide nanoparticles along with the ⁶⁴Cu radioisotope.¹⁶⁷ Therefore, the functionalization of solution-processed TMD systems with molecular receptors is a promising and cutting-edge strategy to detect specific analytes with a high degree of selectivity and sensitivity, besides fast response.¹⁵⁹

6. Conclusions and outlook

The unique and versatile physicochemical properties of TMDs render them unique 2D functional scaffolds for developing new fundamental science with a great potential for technological applications. In this regard, achieving a full control over the various production methods represents the first crucial task since the final properties of TMDs depend on the presence and type of defects along with the flakes lateral size and thickness. Such characteristics need to be tuned in view of the application of interest. Hereof, solution-phase methods are promising for scalable, efficient and controlled production of TMDs, thus enabling a widespread exploration and application. Although TMDs possess an extraordinary versatility, their properties

could be further tuned *via* meticulous molecular strategies, by designing *ad hoc* functionalizing molecules to tailor *on demand* the properties of the resulting hybrid systems *via* covalent and non-covalent interactions. More specifically, the virtually-infinite number of functional molecular systems, made available by means of chemical synthesis, provides an appealing opportunity to develop new disrupting technologies. Therefore, such an approach allows the fabrication of TMD-based hybrid devices characterized by multiresponsive nature, where external stimuli, such as heat, light and/or magnetic fields, can be exploited to trigger changes in the physicochemical properties of the molecules interacting with the 2D structures. However, to succeed in this direction, a prior and challenging aspect to tackle concerns the choice of the proper functionalization strategy to adopt, along with the suitable operating conditions, in order to achieve an accurate control over the fabrication of the hybrid systems. In particular, the nature of the interacting species and the related forces involved in the process are of paramount importance, managing the functionalization yield as well.

Ultimately, the fine tuning of TMD properties could result in a smart and elegant alternative to develop new, disrupting and exotic hybrid technologies based on solution-processed TMDs. In particular, the forthcoming technological progress shall exploit the enormous potential of these emerging materials, flagship systems in 2DM science, with possible and engaging applications in flexible and wearable (opto-)electronics, (bio-)sensing and (photo-)catalysis.

Conflicts of interest

The authors declare no conflict of interest.

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