Energy revamping of solar panels through titania nanocomposite coatings; influence of aqueous silica precursor

V. S. Smitha, K. Vidya, M. Jayasankar, A. Peer Mohamed, U. S. Hareesh* and K. G. K. Warrier*

An all-inorganic nanocomposite coating of titania has been found to revamp the reduction in efficiency of solar panels arising due to atmospheric pollution. A multifunctional, photoactive and hydrophobic titania–silica–lanthanum phosphate (TSL) nanocomposite having excellent anatase thermal stability is reported for the first time as alternative coatings on solar panel covers for maintaining the energy efficiency of panels over a period of time under outdoor conditions. The precursor source of silica has been found to significantly influence the photoactivity of titania in the nanocomposite under investigation. Polymeric silica is derived from the tetraethylorthosilicate precursor while particulate silica is aqueous colloidal silica. The enhanced photoactivity of the particulate titania–silica composition is attributed to the presence of phase pure anatase having an optimum crystallite size and surface area, achieved in the presence of silica. Lanthanum phosphate which has low water wettability is further influenced by particulate silica in providing better non-wetting behavior to the TSL nanocomposite. The presence of particulate silica in the TSL composite is superior to that containing polymeric silica in terms of crystallinity, photoactivity and low wettability. Thus, functional titania coatings possessing synergistic properties of the constituents can be designed from a less expensive and effective silica precursor. The all-inorganic system investigated in the present work is environmentally friendly and is stable over a wide range of temperatures. The feasibility of large-scale preparation and application of the particulate TSL nanocomposite coatings on solar panels under outdoor exposure has been demonstrated. The present novel approach for the development of aqueous-derived, self-cleaning, energy conserving coatings will lead to the energy revamping of solar panels and may have large-scale industrial applications.

Introduction

Globally, there exists a huge challenge for the development of cleaner solar panel surfaces in energy conservation. In order to address the problem, energy-conserving, self-cleaning coatings on solar panels are being looked into which have become increasingly important in terms of tackling the efficiency reduction of solar panels and saving natural resources. Self-cleaning coatings over a range of surfaces have evolved recently1–4 and usually, the photoactive property of anatase titanium oxide is utilized for the development of such coatings. Associated modifications like doping with metal oxides or non-metals5 and use of surface modifiers and additives6,7 are reported to increase the photoactivity of titania through structural and textural changes. A photoactive and hydrophobic silica–titania composition that preserves the esthetic qualities of stone was reported by Kapridaki et al. in which an organic silica oligomer is added to reduce the surface energy that gives hydrophobic properties to the material.8 Improvement in the functional features such as hydrophobicity is usually achieved by the addition of organosilanes,9 but such coatings are less durable with respect to environment and temperature10 which often contain noxious and ecologically harmful solvents, not suitable for large scale applications.11,12 Titanium dioxide is widely used for environmental remediation but usually prepared from alkoxide precursors.13 Fully inorganic, self-cleaning coatings are characterized by a significant reduction in maintenance cost and environmental durability14,15. Hence a composition which is solely inorganic in nature synthesized from aqueous precursors can be considered as an alternative.16

Recently, compositions of titania with silica17 and lanthanum phosphate18 synthesized from aqueous precursors are reported to exhibit self-cleaning property.19,20 Silica provides better adhesion to the substrate and enables the formation of a large amount of surface active sites facilitating easy reaction with oxygen, which increases the photocatalytic activity21 while lanthanum phosphate imparts increased anatase phase stability and hydrophobicity.18 However, no detailed
investigation exists on the effect of particulate silica precursor on photoactivity of titanium dioxide.

In the present work, a novel nanocomposite containing titania, silica and lanthanum phosphate (TSL) exhibiting enhanced photoactivity is prepared. The photoactivity and hydrophobicity of the TSL nanocomposites containing particulate and polymeric silica are then compared. The results indicate that the TSL composition containing particulate silica is far more efficient than the one containing polymeric silica because of the presence of defect free, phase pure, highly crystalline anatase crystals. The feasibility of large-scale preparation and application of particulate TSL nanocomposite coatings on solar panels under outdoor exposure is demonstrated. This novel synthesis route for photoactive and hydrophobic titania–silica–lanthanum phosphate nanocomposites present promising applications on solar panels in order to increase their effectiveness and durability.

**Experimental**

Fully aqueous titania sol was prepared from the precursor titanium(iv)oxysulphate (99.99%, Sigma-Aldrich Chemicals). In a typical experiment, 16 g of titanyl sulphate was dissolved in 500 mL of distilled water to make a 0.2 M solution and was hydrolyzed by slow addition of ammonium hydroxide (25%, s.d. FINE-CHEM Ltd., India) solution under constant stirring at room temperature (32 °C), and was maintained at a stable pH of 7.5. The precipitate obtained was separated by filtration, washed free of sulfate ions with distilled water, as was confirmed by the BaCl₂ test. The precipitate was then redispersed in 500 mL of distilled water and was peptized by dropwise addition of 2 M HNO₃ (Merck, India) solution, till pH is brought down to 1.8–2 to get a stable titania sol. The stable sol was then aged for 24 h at room temperature. Ludox® TM-50 colloidal silica (Sigma-Aldrich Chemicals, 50 wt% suspension of silica in water), was used as the aqueous silica source which consists of dense, amorphous particles of SiO₂ and the building blocks of these particles are randomly-distributed [SiO₄]⁻tetrahedra. Since the dispersed phase consists of non-polymeric solid particles, colloidal silica is also termed as particulate silica sol. Polymeric silica sol refers to the silica suspension containing branched macromolecules generally obtained from hydrolysis of non-precursorous precursors. In the present work, polymeric silica sol was prepared from tetraethoxysilane by controlled hydrolysis using 0.001 M HCl in isopropanol medium. Tetraethoxysilane, isopropanol and HCl were mixed at a molar ratio of 1 : 4 : 16 and stirred for 2 h to prepare the polymeric silica sol. Lanthanum phosphate sol was separately prepared through sol–gel method by reacting lanthanum nitrate and orthophosphoric acid through precipitation–peptization using nitric acid. The prepared LaPO₄ sol was added to the particulate and polymeric titania–silica sols to get multicomponent TSL nanocomposite sols. The concentration of both particulate and polymeric silica was varied (30, 44 and 57 mol%) and the concentration of LaPO₄ was kept constant at 0.5 mol% while preparing TSL sols. The nanocomposite sols were then coated on commercially available glazed ceramic surfaces (5 × 5 cm²) by dip coating method in a KSV dip coating unit at a speed of 20 mm per minute. The coatings were dried (60 °C) and annealed at 700 °C and characterized further. An annealing temperature of 700 °C was already optimized for titania–silica coatings on glased surfaces.

The nanocomposite sols were also dried, powdered, calcined at 700 °C and characterized. Particle size of the nanocomposite sol was measured using Malvern Zetasizer 3000 HSA Instrument. X-ray diffraction (XRD) patterns of the calcined composite powders were obtained using a Philips Xpert Pro Diffractometer. The crystallite size was calculated using Scherrer equation.

\[ D_{\text{XRD}} = 0.9 \lambda / \beta \cos \theta \]  
(1)

where \( D_{\text{XRD}} \) is the average crystal diameter (nm), 0.9 is the shape factor, \( \lambda \) the X-ray wavelength (Cu Kα, 1.542 Å), \( \beta \) is the full width at half maximum intensity (in radian), and \( \theta \) is the Bragg angle. The amount of anatase and rutile in the sample was estimated using Spurr equation.

\[ F(R) = 1 / \left[ 0.8 \times I_{\text{A}(101)} / I_{\text{R}(110)} \right] \]  
(2)

where \( F(R) \) is the mass fraction of rutile in the sample and \( I_{\text{A}(101)} \) and \( I_{\text{R}(110)} \) are the integrated main peak intensities of anatase and rutile, respectively.

Photocatalytic activity of the nanocomposites was studied by monitoring the degradation of Methylene Blue (MB) (AR Grade, Qualigens Fine Chemicals, India) dye in an aqueous suspension under UV-A exposure and continuous stirring using a magnetic stirrer. The intensity of the UV light was 0.4 mW cm⁻². 0.03 g of the prepared nanocomposite was dispersed in 75 mL of 10⁻⁴ M aqueous solution of MB. The suspension was stirred in the dark for half an hour before irradiating with UV light for equilibration. The concentration of the dye was measured at different time intervals using a UV-visible spectrometer (Shimadzu, Japan, UV-2401PC). A blank dye solution was also irradiated, for about 2 hours to confirm that the dye was not photobleached by UV exposure. The dye concentration remained unchanged even after irradiation for 2 h. The maximum intensity absorbance peak at 663.2 nm of MB solution was taken for measuring the degradation. The absorbance of MB solution after keeping in dark for half an hour under stirring was taken as initial absorbance (\( A_0 \)) and absorbance after UV-A exposure in the presence of nanocomposites was taken as \( A \) (in time intervals of 20 minutes). The degradation of MB was calculated using the equation given below.

\[ C / C_0 = A_{\text{time} \rightarrow t} / A_{\text{time} \rightarrow 0} \]  
(3)

where \( A_{\text{time} \rightarrow 0} \) is the initial absorbance of MB solution, i.e., \( A_0 \) and \( A_{\text{time} \rightarrow t} \) is the absorbance after time intervals, i.e., \( A \). Converting the \( C / C_0 \) values into percentage gives the dye degradation efficiency.

The morphology of the coatings was studied using JEOL JSM-5600LV scanning electron microscope (SEM) and that of nanocrystallites through a high-resolution transmission electron
microscope (HRTEM), FEI Tecnai 30G2S-TWIN. The static contact angle measurements of the coated ceramic substrates were performed by the sessile drop method with a Data Physics OCA 40 micro automatic contact angle meter.

On field studies of particulate TSL coating on solar panel covers were also carried out. Particulate TSL sol was synthesized on a large scale (15 L) and was further used for preparing coatings on glass covers (30 cm × 60 cm) by dip coating technique. Withdrawal speed of 50 mm min⁻¹ was used. The coatings were dried at room temperature and annealed at 400 °C in a chamber furnace (the annealing temperature was fixed as 400 °C here since the substrate is glass). Both single and double coats of TSL were prepared by following the similar experimental conditions. Ten solar panels were installed on an open terrace where maximum solar light is ensured. The solar panels were equipped with an instrumental set up to collect the output voltage and current generated. The photographs of the installed solar panels are shown below in Fig. 1. The first four modules (modules 1-4) were covered with uncoated glass. The last four modules (modules 6-9) were covered using TSL coated glass. Thus, the coatings after installation over solar cells were sealed.

The variation in the output volts of the solar panels are continuously monitored by means of a 24 channel data acquisition system connected to a computer and the data were collected with the help of software Vijeo Citect Runtime. In order to nullify the day to day intensity variation of sunlight, a ratio between the average output volts recorded for the uncoated module and coated module were calculated from the collected data from a peak exposure time (11:30 a.m.–12:30 p.m.), using the equation given below.

\[ R(V) = \frac{V_{\text{uncoated}}}{V_{\text{coated}}} \]  

where \( R(V) \) is the ratio of the average output voltage, \( V_{\text{uncoated}} \) and \( V_{\text{coated}} \) are the average output voltages of the uncoated module and coated module. An increase in the ratio of the output voltages over a period of time indicates the efficiency of the coated modules in providing enhanced output voltage by virtue of its self-cleanability. The percentage increment in the output voltage of a coated module after prolonged outdoor exposure, when normalized with the output voltage of an uncoated module, can be better expressed in terms of the equation provided below.

\[ \% \text{ Increase in voltage} = (R(V)_n - R(V)_{\text{i}})/R(V)_{\text{i}} \times 100 \]  

where \( R(V)_0 \) is the ratio of the initial output voltage (1st day, after installation) and \( R(V)_n \) is the ratio of the final output voltage (n-th day, after installation) for respective modules.

Results and discussion

Characterization of titania–silica–lanthanum phosphate (TSL) nanocomposites and coatings

The role of particulate and polymeric silica in tuning the photocatalytic properties of TSL nanocomposite was investigated. The photocatalytic activities of particulate and polymeric TSL nanocomposites containing varying silica concentration were further measured and the results are provided in Fig. 2.

For both particulate and polymeric TSL compositions, 44 mol% silica was found to provide better photocatalytic properties. Hence, TSL nanocomposites containing particulate and polymeric silica (44 mol%) were characterized further.

Particle size analysis of the TSL nanocomposite sols containing particulate and polymeric silica (44 mol%) are presented in Fig. 3. A monomodal distribution was obtained for particulate-TSL sol whereas a bimodal distribution was shown.

Fig. 1 Photographs of (a) installed solar panels and (b) the data acquisition system.

Fig. 2 Degradation of methylene blue by (i) particulate and (ii) polymeric TSL nanocomposites containing (a) 30 (b) 44 and (c) 57 mol% silica, calcined at 700 °C and subjected to UV-A exposure.

Fig. 3 Particle size distribution of (a) particulate-TSL and (b) polymeric-TSL sols.
by polymeric-TSL sol. LaPO₄ addition to particulate titania–silica sol resulted in an excellent homogeneity of distribution of the third phase in the nanocomposite sol as revealed by the monomodal distribution. The bimodal distribution in the case of polymeric-TSL sol can be attributed to the increased crosslinking behavior originated mainly due to the difference in the hydrolysis conditions of silica. The increased particle size of the polymeric TSL composition is ascribed to the increased crosslinking behavior of the branched macromolecules in the polymeric silica sol. In addition, the chemical structure and nature of the solvent used for the formation and growth of the silica particles also have a strong influence on the average particle size in a non-aqueous route. The solvent effect on a non-aqueous synthesis is rather complex and apart from regulating the miscibility of the system, it acts as a reactant through an alkoxy exchange reaction which is promoted in an acidic environment and hence the reaction rate as well as the resulting particle size of the polymeric silica is increased.

Thus the fast hydrolysis of silica precursor, TEOS, under high acidic conditions in the present study has lead to fast polymerization reaction leading to gelation which correspond to a crosslinking process taking place between macromolecular species of polysiloxanes containing free Si–OH bonds which is clearly evidenced by an increased population of particles in the size range of ~250 nm in addition to the small population of particles having size 45 nm (Fig. 2). This observation is consistent with the reported work on silica in which the size of SiO₂ particles was varied from 8–41 nm by changing the acid catalyzed hydrolysis conditions. Further, particulate TSL sol was visibly more transparent than that of the polymeric-TSL sol and was stable for more than 6 months, while the latter started gelation within one month at room temperature as can be seen from Fig. 4.

X-ray diffraction patterns of the particulate-TSL and polymeric-TSL nanocomposite powders, calcined at 700 °C are provided in Fig. 5. There is no peak corresponding to silica in the pattern which may be attributed to the discrete amorphous nature of the sol–gel derived silica particles even after calcination at 700 °C. For particulate-TSL, peaks corresponding to the anatase phase of titania as well as the hexagonal phase of lanthanum phosphate were observed. The thermal stability of anatase in particulate-titania–silica composition is retained even after LaPO₄ addition. Phase transformation of lanthanum phosphate from hexagonal phase to monoclinic phase usually happens around 600 °C. If we can prevent the intergranular contact between lanthanum phosphate particles to some extent, the phase transformation can be further delayed. Homogeneous mixing of LaPO₄ occurs in the particulate titania–silica system and hence the hexagonal phase of LaPO₄ is retained even after calcination at 700 °C. This is due to decrease in the number of intergranular contacts between LaPO₄ grains as a result of the homogeneous distribution of LaPO₄ among titania and silica particles.

Thus the fast hydrolysis of silica precursor, TEOS, under high acidic conditions in the present study has lead to fast polymerization reaction leading to gelation which correspond to a crosslinking process taking place between macromolecular species of polysiloxanes containing free Si–OH bonds which is clearly evidenced by an increased population of particles in the size range of ~250 nm in addition to the small population of particles having size 45 nm (Fig. 2). This observation is consistent with the reported work on silica in which the size of SiO₂ particles was varied from 8–41 nm by changing the acid catalyzed hydrolysis conditions. Further, particulate TSL sol was visibly more transparent than that of the polymeric-TSL sol and was stable for more than 6 months, while the latter started gelation within one month at room temperature as can be seen from Fig. 4.

X-ray diffraction patterns of the particulate-TSL and polymeric-TSL nanocomposite powders, calcined at 700 °C are provided in Fig. 5. There is no peak corresponding to silica in the pattern which may be attributed to the discrete amorphous nature of the sol–gel derived silica particles even after calcination at 700 °C. For particulate-TSL, peaks corresponding to the anatase phase of titania as well as the hexagonal phase of lanthanum phosphate were observed. The thermal stability of anatase in particulate-titania–silica composition is retained even after LaPO₄ addition. Phase transformation of lanthanum phosphate from hexagonal phase to monoclinic phase usually happens around 600 °C. If we can prevent the intergranular contact between lanthanum phosphate particles to some extent, the phase transformation can be further delayed. Homogeneous mixing of LaPO₄ occurs in the particulate titania–silica system and hence the hexagonal phase of LaPO₄ is retained even after calcination at 700 °C. This is due to decrease in the number of intergranular contacts between LaPO₄ grains as a result of the homogeneous distribution of LaPO₄ among titania and silica particles.
In the case of polymeric-TSL, peaks of anatase, rutile phases of titania and monoclinic phase of lanthanum phosphate were observed. In addition to anatase, less than 5% of rutile was also present in the polymeric-TSL indicating that the third phase distribution is not uniform in polymeric-TSL nanocomposite resulting in phase separation. Thus, even small amount of LaPO₄ addition (0.5 mol%) in polymeric titania–silica sol can affect the anatase phase stability due to the distributional behavior of the third phase. Also, in polymeric TSL, mixing of LaPO₄ in the nonaqueous titania–silica sol is not homogeneous and hence, the phase transformation from hexagonal phase to monoclinic phase of LaPO₄ will occur after calcination at 700 °C. This happens as a result of increased intergranular contacts between LaPO₄ grains in the areas of island formation due to inhomogeneous distribution of LaPO₄ among titania and silica particles.

The anatase crystallite size in pure titania was 31.6 nm whereas for the particulate and polymeric TSL nanocomposites, the crystallite sizes were 14.5 and 11.3 nm respectively. The anatase crystallite size increased drastically from 4.2 to 11.3 nm when LaPO₄ is introduced to the polymeric titania–silica composite, and this crystal growth is an evidence for the nonuniform distribution of LaPO₄. In the case of particulate titania–silica composite, LaPO₄ addition has not resulted in such crystal growth. On the other hand, there was a slight decrease in the crystal size from 15.7 to 14.5 nm. The efficacy of the present composite approach in obtaining anatase titania composite with high crystallinity is clearly evident from the XRD data.

The morphology of particulate-TSL powder heat treated at 700 °C is presented in Fig. 6. The silica particles and titania particles have an average size of ~21 nm and ~12 nm respectively. Nanorods of lanthanum phosphate having ~50 nm length and ~8 nm diameter with an interplanar spacing of 0.611 nm, corresponding to the (100) plane of the hexagonal LaPO₄ were observed. The corresponding FFT analysis also confirm the presence of (100) plane. The composite behavior is clearly revealed from the TEM images. The amorphous behavior of the silica can be attributed to the alkoxide hydrolysis of silica under high acidic conditions. Small rods of lanthanum phosphate were also identified in the titania matrix as seen from Fig. 7b. The polymeric-TSL composition has introduced certain dislocations in the anatase crystal lattice. An extrinsic stacking fault in which there is an intervening layer (marked using arrows) between two layers slightly shifted from each other is clearly visible in Fig. 7c. The lattice fringes in anatase titania crystals also showed the presence of crystallographic defects with wave-like line-dislocations (screw type) which are attributed to electric stress originated from silica addition. Similar kind of dislocation is already reported for titania–silica composite systems by Wang et al. in which the strong interaction between Ti⁴⁺ and Si⁴⁺ inducing the diffusion and redistribution of Ti⁴⁺ and Si⁴⁺ ions. Since the ionic radius of Si⁴⁺ is small (0.042 nm) enough to enter the TiO₂ (0.068 nm) lattice interstitially, the diffusion between Ti⁴⁺ and Si⁴⁺ leading to the formation of Ti–O–Si linkages may be the reason for the observed dislocations in the titania crystal. A decrease in the...
crystal size below an optimum level is reported to increase the defects and grain boundaries, which in turn increases the recombination rate of electron–hole pairs leading to a decrease in photoactivity.\textsuperscript{34,35}

Even though the surface area of polymeric-TSL (294.18 m\(^2\) g\(^{-1}\)) is much higher than that of particulate-TSL (64.64 m\(^2\) g\(^{-1}\)), the dye degradation efficiency was only 87.9\% compared to 93.1\% for particulate TSL composite (Fig. 2). The lower photoactivity of polymeric TSL composite despite its high surface area could be due to the absence of crystalline titania phases as separate domains\textsuperscript{8} considering the highly amorphous nature of polymeric silica. Further, the acid mediated hydrolysis of silica in the case of polymeric-TSL composition can result in strong interaction between Ti\(^{4+}\) and Si\(^{4+}\) thereby producing certain crystal defects which may reduce the photocatalytic activity.\textsuperscript{34,35} In the case of polymeric-TSL, the surface of a crystal can be assumed to be a defect site where the long range ordering of crystal lattice breaks and charge carrier recombination may occur at the defect site. Thus, the higher surface area and lower crystallinity of the polymeric-TSL composition leads to a lower rate of photocatalytic activity because of an increase in the electron–hole recombination rate.\textsuperscript{35}

SEM images of particulate-TSL and polymeric-TSL coatings on glazed ceramic substrates annealed at 700 °C are presented in Fig. 8 which reveals an increased surface roughness for the particulate-TSL coating arising from the increased crystallinity of the coating. On the other hand, polymeric-TSL coating appeared smooth and had smaller particles consistent with the lower crystallite size obtained from X-ray analysis. AFM images of particulate and polymeric TSL composite coatings presented in Fig. 9 also support the above observation of smaller particles for polymeric-TSL. Titania particles in particulate-TSL coating had a size of \(\sim 100\) nm while in a polymeric-TSL coating, the size was \(\sim 50\) nm. Polymeric-TSL coating appeared to be more porous than the particulate-TSL coating and some agglomerated titania particles are also visible in the surface images of both the coatings. Both the particulate and polymeric-TSL composite coatings appeared to be rough. Particulate-TSL coating has shown a more uniform surface roughness (Fig. 9c) when compared with that of polymeric-TSL composite coating (Fig. 9d). Since surface roughness can impart hydrophobicity to the composite coatings, the water contact angles were measured for particulate and polymeric-TSL composite coatings by sessile drop method and the results are provided as insets in Fig. 8. Both the particulate and polymeric TSL nanocomposite coatings were reasonably hydrophobic (WCA-97.5 and 89.1° respectively) which indicate the ability of LaPO\(_4\) in imparting surface hydrophobicity.\textsuperscript{16} Even though particulate and polymeric TSL compositions contain an identical quantity of LaPO\(_4\), the relatively lower hydrophobicity for polymeric-TSL (89°) is due to larger number of defect sites generated by diffusion between Ti and Si atoms, as a result of increased cross-linking behavior in the presence of non-aqueous polymeric silica.

**On field studies of particulate TSL coating on solar panel covers**

The photograph of the prepared titanium dioxide sol and the nanocomposite coatings on large area glass substrates is shown\textsuperscript{8}.
below in Fig. 10. In order to find out the effect of TSL coating on the efficiency of solar cells, the output voltages of the solar panels covered with uncoated glasses and that of TSL single coat and double coat, after six months of outdoor exposure were compared with the data collected using the online acquisition system. The reduction in the output voltage of the installed solar panels with and without TSL coatings, over a period of six months is presented in Fig. 11. Initially, at the time of installation, the percent reduction in volts was much less and after a period of one month, there was a drastic reduction in the output volts which can be attributed to the severity of the climatic conditions (monsoon) in Kerala. An initial six-month analysis of the data indicates that TSL coated module has shown less reduction in efficiency when compared with that of an uncoated module. Thus, the TSL coating has considerably decreased the reduction in volts during the six months, compared to an uncoated module which can be attributed to the increased self-cleaning characteristic of the TSL coating in view of its increased photoactivity and low wettability. There was a difference of approximately 15% in the output voltages recorded for an uncoated module and a TSL coated module.

Fig. 12 shows the percentage increase in the output voltage of a TSL coated module when normalized with that of an uncoated module over a period of six months. The variation in sunlight intensity caused by different season is thus fully eliminated. TSL coating has considerably increased the output volts during the six months, compared to an uncoated module which can be attributed to the increased self-cleaning characteristic of the TSL coating. An increase in output voltage by ~15% by TSL double coat can increase the net efficiency of solar panels considerably since the net efficiency of solar cells is directly proportional to the output volts and current. The photographs of both the TSL coated glasses and uncoated glasses over solar panels after six months from the installation are presented in Fig. 13. TSL coated glass covers were much cleaner when compared with that of uncoated glass covers after six months exposure to the outdoor conditions.

In order to account for the durability of the TSL-double coat, SEM analysis was carried out further. SEM images of a TSL double coat before and after outdoor exposure for six months are presented in Fig. 14. TSL-double coat even after six months outdoor exposure has not shown any signs of peeling off indicated the long term stability of such heat treated coatings. Thus, the initial studies have shown that TSL coatings are highly promising in increasing the efficiency of solar panels by virtue of its enhanced self-cleaning capability.

Conclusions

A novel synthesis route to produce photoactive and hydrophobic titania–silica–lanthanum phosphate nanocomposites which have promising applications on solar panels in order to increase their effectiveness and durability is presented in the present work. An all-inorganic, aqueous sol–gel method based on a multi-component nanocomposite approach was used for the preparation of titania–silica–lanthanum phosphate (TSL) nanocomposite and the properties of the nanocomposite can be effectively tuned by choosing the right silica precursor. TSL nanocomposite containing particulate silica resulted in better self-cleanability because of the presence of defect free, phase pure, highly crystalline anatase crystals. On the other hand, polymeric silica containing titania nanocomposite was less photoactive despite its high specific surface area, because of lower crystallinity and strong interaction between the phase elements. The feasibility of large-scale preparation and application of particulate TSL nanocomposite coatings on solar panels under outdoor exposure has been demonstrated. Particulate TSL coated solar panel module has exhibited an increased output voltage (~15%) which is a direct measure of the self-cleanability of the TSL coat and can address the issue of efficiency reduction of solar panels under prolonged outdoor exposure. The present novel approach for the development of aqueous-derived self-cleaning coatings can, therefore, be considered for energy conservation and may lead to large-scale industrial applications.

Acknowledgements

The authors (V. S. Smitha) thanks, CSIR, India, K. Vidya acknowledge DST for providing financial support and K. G. K.
Warrier acknowledges the CSIR Emeritus Scheme. The authors acknowledge the members of Materials Science and Technology Division for providing general assistance. Mr M. Kiran and Mr M. R. Chandran are being acknowledged for the HRTEM and SEM images respectively.

Notes and references