

# Hierarchical Branched $\text{TiO}_2$ Nanowires, Reduced Graphene Oxide and $\text{Sb}_2\text{Se}_3$ for Dye-Sensitized Solar Cell Photoanodes: A Systematic Review and Meta-Analysis of Charge-Transport and Photovoltaic Gains Informing $\text{TiO}_2/\text{rGO}/\text{Sb}_2\text{Se}_3$ Ternary Nanocomposite Design

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**Abstract:** A ternary photoanode combining hierarchical branched  $\text{TiO}_2$  nanowires, reduced graphene oxide (rGO), and  $\text{Sb}_2\text{Se}_3$  has been proposed for dye-sensitized solar cells (DSSCs), yet no such device exists in the literature. To quantify the evidence for its individual building blocks, we followed PRISMA 2020 guidelines to search PubMed, Crossref, and web-indexed platforms through October 2026 across three streams: graphene-family additives in  $\text{TiO}_2$  photoanodes ( $n = 20$ ), hierarchical/branched  $\text{TiO}_2$  1D photoanodes ( $n = 9$ ), and  $\text{Sb}_2\text{Se}_3/\text{Sb}_2\text{S}_3$ -sensitized and ternary photoanodes ( $n = 15$  synthesised narratively). Studies reporting power conversion efficiency (PCE) alongside a same- paper reference control were pooled using the log response ratio ( $\ln \text{RR}$ ), with  $t$ -based confidence intervals (CIs) and prediction intervals (PIs); secondary parameters ( $J_{sc}$ ,  $V_{oc}$ , and FF) were analyzed similarly. Our results show that graphene incorporation raised PCE by a ratio of 1.64 (95% CI 1.28–2.10; PI 0.53–5.11), though this gain was inversely related to control efficiency (meta-regression slope  $-0.44$ ,  $R^2 = 0.50$ ,  $p < 0.001$ ), with studies having baseline PCE  $\geq 5\%$  showing a more modest ratio of 1.27 (1.16–1.38). This improvement stemmed primarily from  $J_{sc}$  (ratio 1.21, 1.14–1.29; accounting for 91% of the gain), with negligible changes to  $V_{oc}$  or FF. Hierarchical branching of  $\text{TiO}_2$  arrays increased PCE by a ratio of 2.21 (1.68–2.92) via a 2–3-fold higher dye loading, though accompanied by shorter electron lifetimes. No  $\text{TiO}_2/\text{rGO}/\text{Sb}_2\text{Se}_3$  devices were identified; while  $\text{Sb}_2\text{Se}_3$ -sensitized  $\text{TiO}_2$  achieved high  $J_{sc}$  (up to  $22.3 \text{ mA cm}^{-2}$ ), its maximum PCE stalled at 3.21% due to severe  $V_{oc}$  penalties ( $\approx 0.26\text{--}0.30 \text{ V}$ ). Ultimately, because branching increases light harvesting and dye loading while rGO improves charge collection, adding rGO to an optimized branched- $\text{TiO}_2$  photoanode yields a realistic 20–30% relative gain, rather than the multi-fold improvements often reported against weak baselines. Furthermore, because  $\text{Sb}_2\text{Se}_3$  introduces a severe  $V_{oc}$  penalty despite strong near-infrared absorption, future development should deploy it as a sparsely integrated co-sensitiser coupled with interface passivation..



**Keywords:** Dye-sensitized solar cell; Branched TiO<sub>2</sub> nanowire; Reduced graphene oxide; Sb<sub>2</sub>Se<sub>3</sub>; Ternary nanocomposite photoanode; Charge transport; Meta-analysis.

## I. INTRODUCTION

Dye-sensitized solar cells (DSSCs) convert light through a dye monolayer adsorbed on a mesoporous TiO<sub>2</sub> photoanode, from which injected electrons must diffuse to the transparent conducting oxide while competing with recombination to the oxidised electrolyte [1,2]. Molecular engineering of sensitizers has pushed laboratory efficiencies above 13% [3], but in most laboratory devices the photoanode still limits performance. It must offer a large internal surface for dye uptake and, at the same time, a fast, low-loss pathway for electron transport. In random nanoparticle networks these two needs conflict, because electrons hop across many grain boundaries and trap states [2].

Three materials strategies address this conflict. First, one-dimensional (1D) TiO<sub>2</sub> nanowires and nanorods provide direct conduction paths [4], and growing secondary branches on the 1D trunks (hierarchical or branched architectures) restores the surface area that bare arrays lack [5,6]. Second, graphene-family materials—graphene, reduced graphene oxide (rGO) and graphene oxide (GO)—have been embedded in TiO<sub>2</sub> films as two-dimensional electron "bridges" that speed up transport and suppress recombination [7]. Third, narrow-band-gap metal chalcogenides can extend light harvesting into the near-infrared. Sb<sub>2</sub>Se<sub>3</sub> is attractive because its band gap of about 1.1–1.3 eV is close to the Shockley–Queisser optimum [8], it is earth-abundant, and it forms quasi-1D ribbons with benign grain boundaries [9]; Sb<sub>2</sub>Se<sub>3</sub> nanorod-array thin-film cells have exceeded 9% efficiency [10].

These observations have motivated proposals for a ternary photoanode in which hierarchical branched TiO<sub>2</sub> nanowires are combined with rGO and Sb<sub>2</sub>Se<sub>3</sub> (TiO<sub>2</sub>/rGO/Sb<sub>2</sub>Se<sub>3</sub>). The expected benefits are attractive: branches for dye loading and light scattering, rGO for charge transport, and Sb<sub>2</sub>Se<sub>3</sub> for near-infrared absorption. However, the size of each contribution, and whether the contributions are compatible, has not been established quantitatively. Individual papers usually report a single champion device against a single in-house control, and the reported improvements range from negligible to almost ten-fold. Before experimental effort is invested in the ternary system, it is therefore useful to ask what the published evidence supports.

This study had four objectives: (i) to quantify, by meta-analysis, the effect of graphene-family incorporation on the PCE of TiO<sub>2</sub> photoanodes and to determine which photovoltaic parameter drives it; (ii) to quantify the effect of hierarchical branching of TiO<sub>2</sub> 1D arrays and summarise the reported transport metrics; (iii) to systematically map the evidence on Sb<sub>2</sub>Se<sub>3</sub> (and the related Sb<sub>2</sub>S<sub>3</sub>) as a sensitizer on TiO<sub>2</sub> and on TiO<sub>2</sub>/graphene/chalcogenide ternary photoanodes; and (iv) to translate these findings into an evidence-based design and testing framework for a hierarchical branched TiO<sub>2</sub>/rGO/Sb<sub>2</sub>Se<sub>3</sub> photoanode.

## II. METHODS

### A. Reporting standard and protocol

The review was conducted and reported in accordance with the PRISMA 2020 statement [11]. No protocol was registered in advance, because PROSPERO does not accept materials-science reviews; the eligibility criteria, effect measure and sensitivity analyses described below were fixed before data pooling.

### B. Eligibility criteria

Stream A included peer-reviewed experimental DSSC studies in which graphene, rGO or GO was incorporated into the TiO<sub>2</sub> photoanode (as a composite, nanocomposite or interlayer) and which reported PCE for both a bare-TiO<sub>2</sub> control and the best graphene-modified cell prepared in the same study. Studies were excluded if graphene was present only in the counter electrode, if the modified photoanode contained another major additive without a TiO<sub>2</sub>/graphene-only arm, if only a percentage improvement (without the control PCE) was given, or if the work was a simulation, thesis or conference abstract. Stream B included DSSC studies of hierarchical, branched, tree-like or nanoforest TiO<sub>2</sub> 1D arrays that reported PCE for the branched photoanode and an unbranched (or plain 1D) reference; where the paper stated an exact or approximate ratio (for example, "103.1% higher" or "nearly three times"), the reported ratio was used. Stream



C included any sensitised solar cell (dye-, semiconductor- or quantum-dot-sensitised, or extremely-thin-absorber) using Sb<sub>2</sub>Se<sub>3</sub> or Sb<sub>2</sub>S<sub>3</sub> on a metal-oxide photoanode, and any TiO<sub>2</sub>/graphene/metal-chalcogenide ternary photoanode.

### **C. Information sources and search**

Searches were performed in October 2026 using web search engines and the platforms of the main publishers (Royal Society of Chemistry, Springer Nature, Elsevier, American Chemical Society, Wiley, MDPI, Institute of Physics), supplemented by PubMed and Crossref records. The search strings combined the terms ("dye-sensitized" OR DSSC OR "sensitized solar cell") with (graphene OR "reduced graphene oxide" OR rGO OR "graphene oxide") AND (TiO<sub>2</sub> OR titania) AND photoanode for stream A; with (branched OR hierarchical OR "tree-like" OR nanoforest OR hyperbranched) AND (nanowire OR nanorod) AND TiO<sub>2</sub> for stream B; and with (Sb<sub>2</sub>Se<sub>3</sub> OR "antimony selenide" OR Sb<sub>2</sub>S<sub>3</sub> OR stibnite) and (TiO<sub>2</sub>/rGO/X combinations) for stream C. Reference lists of eligible studies were screened for further records.

### **D. Study selection and data extraction**

Titles and abstracts were screened, and the full text or abstract of each potentially eligible record was assessed against the criteria. From each included study we extracted the bibliographic details, TiO<sub>2</sub> morphology, type and loading of the carbon additive or branch structure, dye and electrolyte, and the PCE, J<sub>sc</sub>, Voc and FF of the control and best modified cells. Every extracted number was required to be supported by a verbatim sentence or table row in the source; values that could not be confirmed in this way were not used. Where studies reported mean  $\pm$  standard deviation across devices, the mean was used. Transport-related metrics (electron lifetime, charge-transfer or recombination resistance, dye loading) were extracted for stream B when reported.

### **E. Effect measure and synthesis**

The effect measure was the log response ratio,  $\ln RR = \ln(PCE_{\text{modified}}/PCE_{\text{control}})$ , a scale-free measure suited to outcomes that differ widely in baseline between laboratories [12]. Because almost all studies reported champion-device values without a measure of variance, study-level sampling variances could not be computed. Studies were therefore pooled with equal weights, and the 95% CI of the mean  $\ln RR$  was obtained from the  $t$  distribution with  $k - 1$  degrees of freedom; results were back-transformed to ratios. Between-study dispersion was summarised by the standard deviation of  $\ln RR$  ( $\tau$ ) and by a 95% PI, which estimates the range of effects expected in a new study [13]. For comparison with conventional practice, I<sup>2</sup> was also calculated after imputing a within-study coefficient of variation of 5% per arm ( $n = 3$  devices) [14]; this imputation was varied from 2% to 10% in sensitivity analysis. A Wilcoxon signed-rank test of  $\ln RR$  against zero was used as a distribution-free check. J<sub>sc</sub>, Voc and FF ratios were pooled in the same way. Because  $PCE = J_{sc} \times Voc \times FF / Pin$ , the  $\ln RR$  of PCE equals the sum of the  $\ln RRs$  of the three parameters, which allowed the share of the efficiency gain contributed by each parameter to be calculated.

### **F. Heterogeneity, sensitivity analyses and meta-regression**

Pre-specified quality flags in stream A were: control PCE < 1% (implausibly weak baseline), use of non-reduced GO, and a reversed architecture in which TiO<sub>2</sub> was deposited onto an rGO film. Sensitivity analyses excluded each flag in turn and together ("strict" set), retained only one study from a research group that contributed four studies, and split studies by carbon type and by control PCE ( $\geq 5\%$  vs < 5%). Leave-one-out analysis was also performed. Meta-regression of  $\ln RR$  on  $\ln(\text{control PCE})$  and on publication year was carried out by ordinary least squares. In stream B, sensitivity analyses were restricted to studies with exact PCE pairs, and to studies whose structure was unambiguously branched 1D arrays. Analyses were performed in Python (NumPy/SciPy).

### **G. Risk of bias and certainty of evidence**

No validated risk-of-bias tool exists for device-engineering studies. Each study was therefore appraised for five domains: comparability of the control (same paper and processing), reporting of replicate devices, plausibility of the baseline, confounding of the architecture (for example, simultaneous change of film thickness), and selective reporting of champion cells. Certainty was judged qualitatively, considering risk of bias, inconsistency, indirectness and imprecision.



### III. RESULTS

#### A. Study selection and characteristics

The selection process is shown in Figure 1. In stream A, 85 records were sought and 60 could be assessed; 25 could not be retrieved because of paywalls or access blocks. Of the 60 assessed records, 39 were excluded (16 gave no bare-TiO<sub>2</sub> PCE, 10 had a co-additive without a TiO<sub>2</sub>/graphene-only arm, 6 had graphene outside the photoanode or no control, and 7 were off-topic) and one conference paper was excluded by the criteria, leaving 20 studies for meta-analysis [15–34]. In stream B, 39 of 49 records were assessed; 9 studies were pooled [5,6,35–41], five with exact PCE pairs and four with a reported ratio. Stream C yielded 15 studies with verifiable data for narrative synthesis.

The characteristics of the stream A studies are summarised in Table 1. Seventeen used nanoparticulate TiO<sub>2</sub> (most often P25 or commercial anatase pastes), one used electrospun nanofibres, and two deposited TiO<sub>2</sub> onto rGO films. Nine studies used rGO, nine graphene (exfoliated, few-layer or sputtered) and two GO. N719 was the dominant sensitizer. Control PCE ranged from 0.49% to 7.13%, and four studies had controls below 1%. Only two studies reported variability across replicate devices [20,21]; the remainder reported champion cells.

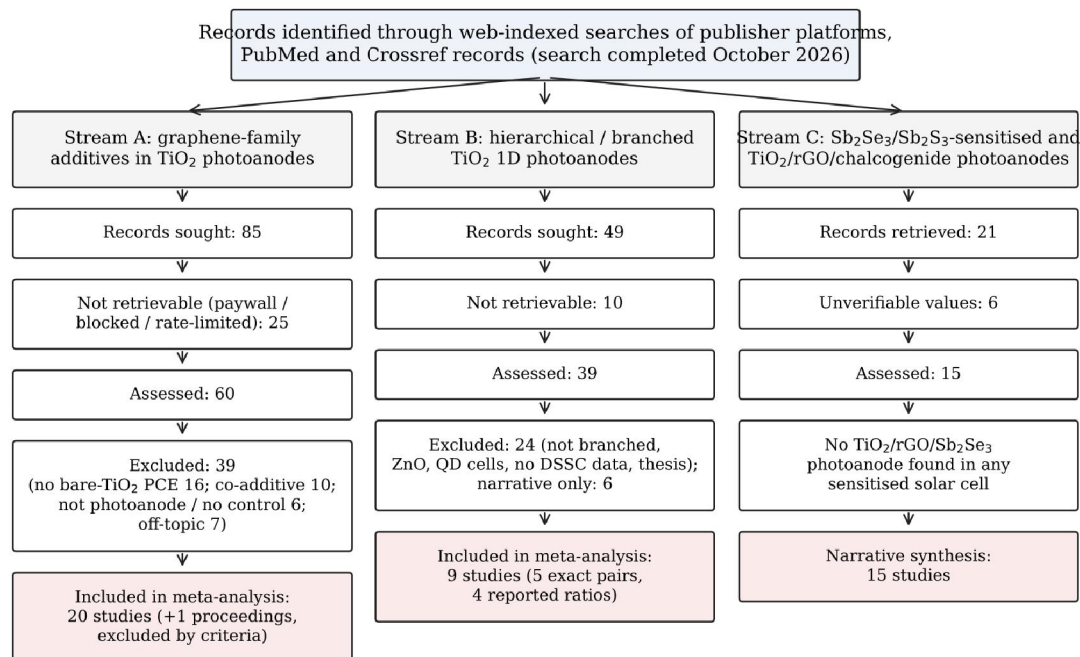


Figure 1. PRISMA-style flow of records through the three evidence streams.

Table 1. Characteristics and PCE of the 20 studies of graphene-family additives in TiO<sub>2</sub> photoanodes (stream A).

| Study              | TiO <sub>2</sub> morphology | Carbon additive (best cell)   | Contr ol PCE (%) | Modified PCE (%) | Ratio | Flag |
|--------------------|-----------------------------|-------------------------------|------------------|------------------|-------|------|
| Madhavan 2012 [17] | Electrospun nanofibres      | Graphene, 0.7 wt%             | 6.30             | 7.60             | 1.21  | –    |
| Chen 2014 [24]     | Nanoparticles               | Sputtered graphene interlayer | 2.46             | 3.93             | 1.60  | –    |
| Liu 2014 [30]      | Nanoparticles               | Few-layer graphene, 0.75 wt%  | 5.01             | 8.25             | 1.65  | –    |
| Dembele 2015 [26]  | Nanoparticles               | Graphene, 0.01 wt%            | 6.30             | 8.80             | 1.40  | –    |
| Eshaghi 2015 [15]  | Nanoparticles               | Graphene, 1.5 wt%             | 0.49             | 0.70             | 1.43  | L    |



| Study              | TiO <sub>2</sub> morphology | Carbon additive (best cell)                              | Contr ol PCE (%) | Modified PCE (%) | Ratio | Flag |
|--------------------|-----------------------------|----------------------------------------------------------|------------------|------------------|-------|------|
| Zhang 2015 [34]    | Nanoparticles               | TiO <sub>2</sub> grown on graphene                       | 0.89             | 2.30             | 2.58  | L    |
| Ding 2016 [19]     | Nanoparticles               | Exfoliated graphene, 0.60 wt%                            | 5.77             | 8.24             | 1.43  | –    |
| Khannam 2016 [32]  | Nanoparticles               | GO@TiO <sub>2</sub> , 2.5 wt% (quasi-solid)              | 0.99             | 3.97             | 4.01  | L,G  |
| Low 2016 [33]      | TiO <sub>2</sub> on rGO     | TiO <sub>2</sub> on rGO film (0.3 wt% TiO <sub>2</sub> ) | 2.75             | 7.20             | 2.62  | R    |
| Wei 2016 [27]      | Nanoparticles               | rGO (optimum loading)                                    | 5.97             | 6.69             | 1.12  | –    |
| Wei 2017 [25]      | Nanoparticles               | Graphene, gradient content                               | 5.45             | 7.71             | 1.41  | –    |
| Wei 2018a [18]     | Nanoparticles               | GO in paste (annealed)                                   | 5.67             | 7.83             | 1.38  | G    |
| Wei 2018b [28]     | Nanoparticles               | Graphene/TiO <sub>2</sub> top layer                      | 5.94             | 7.08             | 1.19  | –    |
| Guo 2020 [29]      | Nanoparticles               | TiO <sub>2</sub> @rGO, 0.8 wt% rGO                       | 4.36             | 7.05             | 1.62  | –    |
| Low 2020 [22]      | TiO <sub>2</sub> on rGO     | TiO <sub>2</sub> sputtered onto rGO (120 °C)             | 0.79             | 7.27             | 9.20  | L,R  |
| Bhand 2022 [20]    | Nanoparticles               | rGO spin-coated on TiO <sub>2</sub>                      | 6.08             | 8.08             | 1.33  | –    |
| Rouhani 2022 [31]  | Nanoparticles               | rGO/TiO <sub>2</sub> (indoline dye)                      | 5.87             | 6.06             | 1.03  | –    |
| Singh 2022 [21]    | Nanoparticles               | rGO, 5 wt% in paste                                      | 7.13             | 8.80             | 1.23  | –    |
| AlSultan 2025 [23] | Nanoparticles               | Graphene, 0.1 wt% (middle layer; bifacial, front)        | 6.71             | 6.73             | 1.00  | –    |
| Bandara 2025 [16]  | Nanoparticles               | Graphene layer in multilayer film (quasi-solid)          | 5.50             | 6.80             | 1.24  | –    |

PCE, power conversion efficiency. Flags: L, control PCE < 1%; G, non-reduced graphene oxide; R, reversed architecture (TiO<sub>2</sub> deposited onto an rGO film). Values are champion devices except Bhand 2022 and Singh 2022, which reported means of replicate devices.

#### B. Effect of graphene-family incorporation on PCE

All 20 studies reported a higher PCE for the graphene-modified photoanode than for the bare-TiO<sub>2</sub> control (ratio range 1.00–9.20; Figure 2). The pooled ratio was 1.64 (95% CI 1.28–2.10;  $p < 0.001$ ; Wilcoxon  $p < 0.001$ ), corresponding to a 64% relative increase. Dispersion was large ( $\tau = 0.53$ ; PI 0.53–5.11), and imputed I<sup>2</sup> exceeded 97% for any assumed within-study coefficient of variation between 2% and 10%. Leave-one-out estimates ranged from 1.50 to 1.68, so no single study determined the result.

Table 2. Pooled ratios of photovoltaic parameters, with sensitivity and subgroup analyses.

| Analysis                          | k  | Pooled ratio (95% CI) | 95% PI     | $\tau$ |
|-----------------------------------|----|-----------------------|------------|--------|
| All studies                       | 20 | 1.64 (1.28–2.10)      | 0.53–5.11  | 0.53   |
| Excluding control PCE < 1%        | 16 | 1.37 (1.21–1.54)      | 0.83–2.25  | 0.22   |
| Excluding non-reduced GO          | 18 | 1.58 (1.22–2.03)      | 0.52–4.79  | 0.51   |
| Excluding reversed architecture   | 18 | 1.45 (1.23–1.71)      | 0.71–2.97  | 0.33   |
| Strict set (no flags)             | 14 | 1.30 (1.19–1.43)      | 0.92–1.84  | 0.15   |
| One study per research group      | 17 | 1.73 (1.30–2.30)      | 0.51–5.87  | 0.56   |
| rGO only                          | 9  | 1.71 (1.01–2.90)      | 0.31–9.47  | 0.69   |
| Graphene only                     | 9  | 1.45 (1.19–1.78)      | 0.76–2.79  | 0.26   |
| Control PCE $\geq$ 5%             | 13 | 1.27 (1.16–1.38)      | 0.93–1.72  | 0.13   |
| Control PCE < 5%                  | 7  | 2.65 (1.44–4.88)      | 0.44–16.16 | 0.66   |
| J <sub>sc</sub> ratio, strict set | 12 | 1.21 (1.14–1.29)      | 0.98–1.50  | 0.09   |
| V <sub>oc</sub> ratio, strict set | 11 | 1.01 (0.98–1.04)      | 0.98–1.05  | 0.01   |
| FF ratio, strict set              | 12 | 1.03 (0.98–1.08)      | 0.88–1.20  | 0.07   |
| Branched vs. unbranched: all      | 9  | 2.21 (1.68–2.92)      | 0.90–5.42  | 0.36   |



| Analysis                        | k | Pooled ratio (95% CI) | 95% PI    | $\tau$ |
|---------------------------------|---|-----------------------|-----------|--------|
| Branched: exact PCE pairs       | 5 | 2.16 (1.28–3.62)      | 0.51–9.18 | 0.42   |
| Branched: unambiguous 1D arrays | 5 | 2.41 (1.80–3.21)      | 1.08–5.35 | 0.23   |

Ratio, modified  $\div$  reference. CI, confidence interval (t-based); PI, prediction interval;  $\tau$ , between-study standard deviation of the log response ratio. Rows 1–13 refer to graphene-family additives (stream A); rows 14–16 to hierarchical branching (stream B).

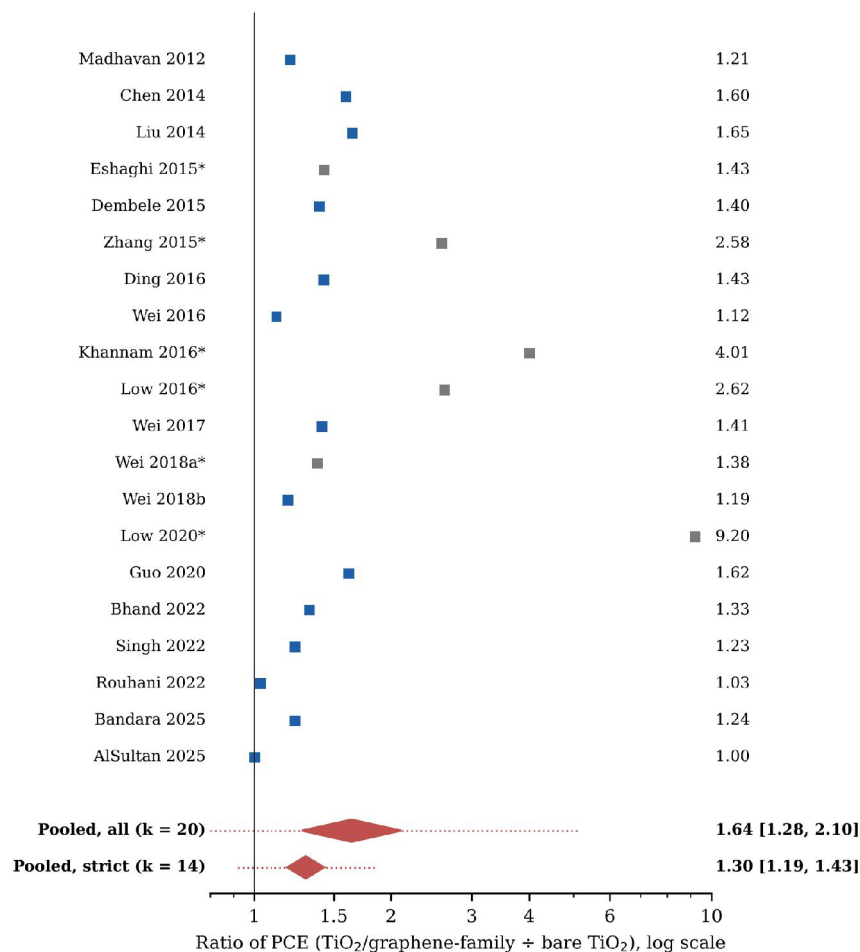


Figure 2. Forest plot of the PCE ratio for graphene-family additives in TiO<sub>2</sub> photoanodes (k = 20). Squares are individual studies (grey and asterisk, quality flag); diamonds show pooled ratios with 95% CIs, and dotted lines show 95% prediction intervals.

The sensitivity analyses (Table 2) showed that the pooled effect depended heavily on study quality. Excluding the four studies with controls below 1% reduced the ratio to 1.37 (1.21–1.54), and the strict set of 14 studies without any quality flag gave 1.30 (1.19 – 1.43) with a much narrower PI (0.92 – 1.84). Studies with control PCE  $\geq$  5% (k = 13) gave 1.27 (1.16 – 1.38), whereas those with weaker controls (k = 7) gave 2.65 (1.44 – 4.88). Restricting to rGO (k = 9) or to graphene (k = 9) gave ratios of 1.71 (1.01 – 2.90) and 1.45 (1.19–1.78), respectively; the difference reflected the concentration of weak controls in the rGO subgroup rather than an intrinsic superiority of rGO. Retaining one study from the group that contributed four studies did not change the conclusion (1.73, 1.30–2.30).



### C. Which photovoltaic parameter improves?

Fifteen studies reported  $J_{sc}$ ,  $V_{oc}$  and FF for both arms. In the strict set,  $J_{sc}$  increased by a ratio of 1.21 (1.14–1.29;  $k = 12$ ), whereas  $V_{oc}$  (1.01, 0.98–1.04;  $k = 11$ ) and FF (1.03, 0.98–1.08;  $k = 12$ ) did not change consistently (Figure 3). Across the 15 complete studies, the mean lnRR of PCE (0.386) was made up of 0.352 from  $J_{sc}$ , 0.018 from  $V_{oc}$  and 0.018 from FF;  $J_{sc}$  therefore accounted for about 91% of the efficiency gain. This pattern indicates that graphene-family additives act predominantly by improving charge collection and, in some reports, dye uptake, rather than by shifting the  $TiO_2$  quasi-Fermi level or reducing series resistance.

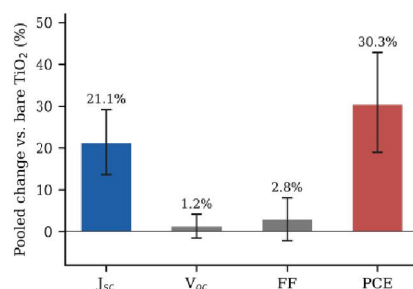


Figure 3. Pooled relative change in  $J_{sc}$ ,  $V_{oc}$ , FF and PCE for graphene-family additives (strict set). Error bars are 95% CIs.

### D. Moderators of the graphene effect

Meta-regression showed a strong inverse relationship between the efficiency of the control and the relative gain (slope  $-0.44$  on the log-log scale,  $R^2 = 0.50$ ,  $p < 0.001$ ; Figure 4); halving the control PCE was associated with a PCE ratio about 1.36 times larger. Publication year was not associated with the effect size ( $p = 0.51$ ). In practical terms, very large improvements (for example, 0.79% to 7.27% [22], or 0.99% to 3.97% [32]) are characteristic of under-optimised controls; against well-optimised controls ( $\geq 5\%$  PCE), the expected gain is about 20–30%.

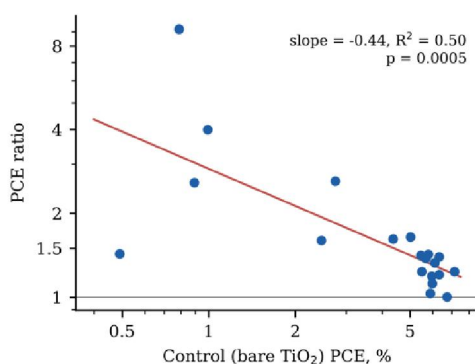


Figure 4. Meta-regression of the PCE ratio on the PCE of the bare- $TiO_2$  control (log-log scale,  $k = 20$ ).

### E. Effect of hierarchical branching of $TiO_2$ 1D arrays

Table 3 summarizes the nine stream B studies. All reported higher PCE for the branched architecture (ratio range 1.30–4.00). The pooled ratio was 2.21 (1.68–2.92;  $p < 0.001$ ; PI 0.90–5.42; Figure 5). Restricting to the five studies with exact PCE pairs gave 2.16 (1.28–3.62), and restricting to the five unambiguously branched 1D arrays gave 2.41 (1.80–3.21). The best absolute efficiency was 9.09% for a  $TiO_2$  nanowire–nanosheet–nanorod hyperbranched array, compared with 5.15% for the bare nanowire scaffold [5].



Table 3. Characteristics and PCE of the nine studies of hierarchical/branched TiO<sub>2</sub> 1D photoanodes (stream B).

| Study           | Branched architecture                                                          | Reference           | Ref. PCE (%) | Branched PCE (%) | Ratio | Basis                  | Flag |
|-----------------|--------------------------------------------------------------------------------|---------------------|--------------|------------------|-------|------------------------|------|
| Wang 2011 [40]  | Rutile nano-branched NR arrays on FTO                                          | Bare NR             | NR           | 3.75             | 3.00  | Stated ratio (approx.) | —    |
| Qiu 2012 [36]   | Branched double-shelled TiO <sub>2</sub> nanotube networks                     | Unbranched          | 4.42         | 5.74             | 1.30  | Exact pair             | B    |
| Chu 2014 [35]   | Tree-like anatase NW arrays on Ti wire (fibre cell)                            | Unbranched NW (3 h) | 2.58         | 6.32             | 2.45  | Exact pair             | C    |
| Sabba 2014 [38] | Rutile NR branches on electrospun nanofibres (solid-state)                     | Plain nanofibres    | NR           | 2.14             | 1.50  | Stated ratio           | B    |
| Tan 2014 [39]   | Three-level nanourchin/NW/nanoparticle hierarchy                               | Pure NW             | NR           | 3.25             | 2.03  | Stated ratio           | B    |
| Wu 2014 [5]     | TiO <sub>2</sub> NW trunks + nanosheet + nanorod branches (hyperbranched), FTO | Bare NW             | 5.15         | 9.09             | 1.77  | Exact pair             | —    |
| Chai 2015 [6]   | Anatase NW + nanorod branches on Ti foil (flexible)                            | Bare NW             | 0.85         | 1.76             | 2.07  | Exact pair             | —    |
| Chen 2016 [37]  | TiO <sub>2</sub> -B/anatase core/shell NW arrays                               | Bare NW             | 1.22         | 4.88             | 4.00  | Exact pair             | B    |
| Hu 2017 [41]    | Branched hierarchical rutile NR arrays on FTO                                  | Pure NR             | NR           | 2.01             | 3.00  | Stated ratio (approx.) | —    |

NW, nanowire; NR, nanorod; NR in PCE column, not reported (ratio stated in the paper). Flags: B, borderline architecture (not a branched 1D array or not a liquid DSSC); C, confounded (film thickness changed with branching time).

The reported transport metrics (Table 4) show why branching and graphene addition are complementary rather than redundant. Branching consistently increased dye loading—by about 2.8-fold (53.57 to 151.3 nmol cm<sup>-2</sup>) in the hyperbranched array [5], 2.0-fold (56.7 to 112.9 nmol cm<sup>-2</sup>) on flexible Ti foil [6] and 1.8-fold in core/shell nanowires [37]—and the resulting J<sub>sc</sub> rose from 3.36 to 7.24 mA cm<sup>-2</sup> [6] and from 2.28 to 8.98 mA cm<sup>-2</sup> [37]. However, the added interfacial area also increased recombination: the hyperbranched array had the shortest electron lifetime (38.2 ms) of the series [5], the electron lifetime of core/shell nanowires fell from 0.63 s to 0.10 s and the recombination resistance from 569.3 Ω to 111.8 Ω [37], and FF fell from 0.47 to 0.34 [6] or from 63% to 55% [36] in branched devices. Branching therefore improves light harvesting at the cost of a larger recombination surface—precisely the loss channel that graphene-family additives are reported to mitigate.

Table 4. Light-harvesting and transport metrics reported for branched versus unbranched TiO<sub>2</sub> photoanodes.

| Study       | Light harvesting / current                                            | Transport and recombination                                                                                        | Net interpretation           |
|-------------|-----------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------|------------------------------|
| Wu 2014 [5] | Dye loading 53.57 → 151.3 nmol cm <sup>-2</sup> (TNW → hyperbranched) | Shortest electron lifetime (38.2 ms) for hyperbranched array; R <sub>2</sub> 158.1 → 65.08 Ω (TNW → hyperbranched) | More dye; more recombination |



| Study          | Light harvesting / current                                                                                      | Transport and recombination                                                         | Net interpretation              |
|----------------|-----------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|---------------------------------|
|                |                                                                                                                 | TNW-NS)                                                                             |                                 |
| Chai 2015 [6]  | Dye loading $56.7 \rightarrow 112.9 \text{ nmol cm}^{-2}$ ; $J_{sc} 3.36 \rightarrow 7.24 \text{ mA cm}^{-2}$   | FF $0.47 \rightarrow 0.34$                                                          | More dye; collection/FF loss    |
| Chu 2014 [35]  | PCE $2.58 \rightarrow 6.32\%$ with branch growth                                                                | $R_{ct} 356.1 \rightarrow 85.99 \Omega$ (3 h $\rightarrow$ 12 h)                    | Lower interfacial resistance    |
| Chen 2016 [37] | Dye loading $59.14 \rightarrow 104.46 \text{ nmol cm}^{-2}$ ; $J_{sc} 2.28 \rightarrow 8.98 \text{ mA cm}^{-2}$ | $\tau_n 0.63 \rightarrow 0.10 \text{ s}$ ; $R_{rec} 569.3 \rightarrow 111.8 \Omega$ | More dye; faster recombination  |
| Qiu 2012 [36]  | $J_{sc} 8.2 \rightarrow 13.7 \text{ mA cm}^{-2}$                                                                | $V_{oc} 0.84 \rightarrow 0.75 \text{ V}$ ; FF $63 \rightarrow 55\%$                 | More current; $V_{oc}$ /FF loss |

TNW, TiO<sub>2</sub> nanowire; NS, nanosheet;  $R_2$ ,  $R_{ct}$ ,  $R_{rec}$ , charge-transfer/recombination resistance at the TiO<sub>2</sub>/electrolyte interface from impedance spectroscopy;  $\tau_n$ , electron lifetime. All values as reported in the source papers.

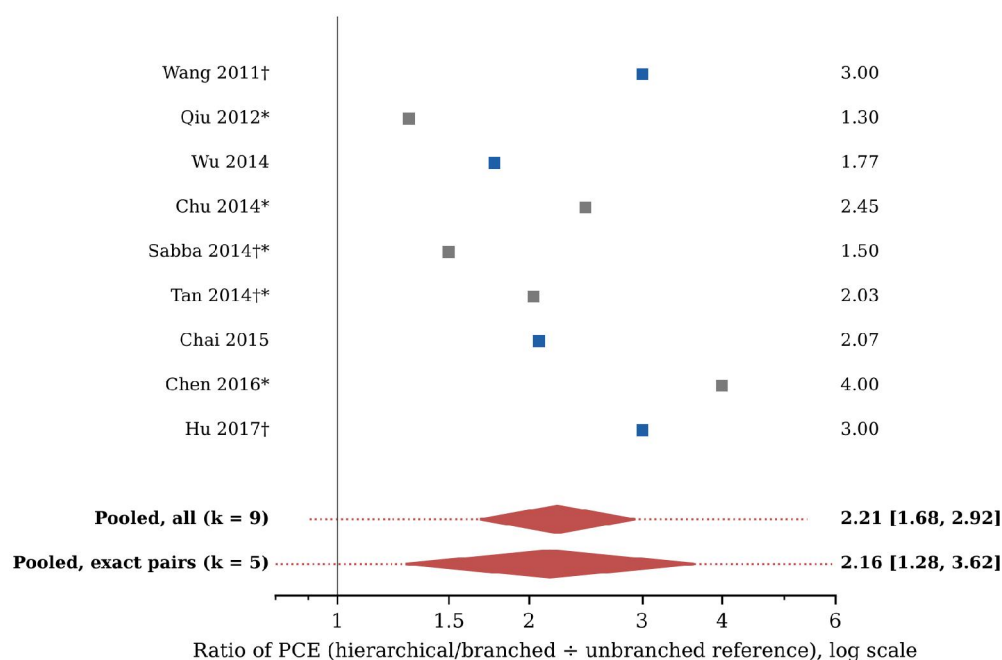


Figure 5. Forest plot of the PCE ratio for hierarchical/branched versus unbranched TiO<sub>2</sub> 1D photoanodes (k = 9). †, ratio stated in the source paper; \*, borderline or confounded architecture.

#### F. Sb<sub>2</sub>Se<sub>3</sub> and ternary graphene/chalcogenide photoanodes

No study reporting a TiO<sub>2</sub>/rGO/Sb<sub>2</sub>Se<sub>3</sub> photoanode in any type of sensitised solar cell was identified. The Sb<sub>2</sub>Se<sub>3</sub> and Sb<sub>2</sub>S<sub>3</sub> evidence is summarised in Table 5. Transient absorption showed electron injection from Sb<sub>2</sub>Se<sub>3</sub> into mesoporous TiO<sub>2</sub>, which improved three-fold after low-temperature annealing, with regeneration yields above 80% [42]. The best Sb<sub>2</sub>Se<sub>3</sub>-sensitised TiO<sub>2</sub> device, a solid-state cell with a polymer hole conductor, achieved 3.21% PCE with  $J_{sc} = 22.3 \text{ mA cm}^{-2}$  but  $V_{oc} = 304.5 \text{ mV}$  and FF = 47.2% [43]. Electrodeposited Sb<sub>2</sub>Se<sub>3</sub> on TiO<sub>2</sub> gave photocurrents up to  $18 \text{ mA cm}^{-2}$  with an external quantum efficiency onset near 1050 nm, and hole transport was identified as the main limitation [44]. Liquid-junction Sb<sub>2</sub>Se<sub>3</sub>-sensitised devices on SnO<sub>2</sub> or Sb-doped TiO<sub>2</sub> reached only 0.31% and 0.71%, with  $V_{oc}$  of 0.27 V and 0.26 V, respectively [8,45]. Sb<sub>2</sub>S<sub>3</sub>, the wider-gap analogue ( $E_g \approx 1.7 \text{ eV}$ ), has reached 5.1 – 7.3% in sensitised TiO<sub>2</sub> architectures [46 – 48].



Ternary TiO<sub>2</sub>/graphene/chalcogenide evidence was limited to CdS quantum-dot-sensitised cells. Adding 0.5 wt% rGO to TiO<sub>2</sub>/CdS raised PCE from 0.15% to 0.79%, with Voc increasing from 0.32 V to 0.55 V; at higher rGO loading (0.8–1.0 wt%) PCE fell to 0.44–0.52% [49]. In a GO–TiO<sub>2</sub>/CdS system, Jsc increased four-fold, from 0.481 to 2 mA cm<sup>-2</sup> [50]. A TiO<sub>2</sub>/MoS<sub>2</sub>–rGO DSSC photoanode has been reported [51], but its performance values could not be verified and it was not included in the synthesis.

Table 5. Evidence on Sb<sub>2</sub>Se<sub>3</sub>/Sb<sub>2</sub>S<sub>3</sub>-sensitised photoanodes and TiO<sub>2</sub>/graphene/chalcogenide ternary photoanodes (stream C).

| Study                   | Device / photoanode                                                             | PCE (%)      | Key reported values                                                                                    |
|-------------------------|---------------------------------------------------------------------------------|--------------|--------------------------------------------------------------------------------------------------------|
| Choi 2014 [43]          | FTO/mp-TiO <sub>2</sub> /Sb <sub>2</sub> Se <sub>3</sub> /PCPDTBT (solid-state) | 3.21         | J <sub>sc</sub> 22.3 mA cm <sup>-2</sup> ; V <sub>oc</sub> 304.5 mV; FF 47.2%                          |
| Ngo 2014 [44]           | TiO <sub>2</sub> /electrodeposited Sb <sub>2</sub> Se <sub>3</sub> /CuSCN       | NR           | J <sub>sc</sub> up to 18 mA cm <sup>-2</sup> ; EQE onset ≈ 1050 nm; hole transport limiting            |
| Guijarro 2012 [42]      | mp-TiO <sub>2</sub> /Sb <sub>2</sub> Se <sub>3</sub> /spiro-OMeTAD              | –            | Electron injection into TiO <sub>2</sub> shown; 3-fold gain after annealing; regeneration > 80%        |
| Kulkarni 2015 [8]       | SnO <sub>2</sub> /Sb <sub>2</sub> Se <sub>3</sub> , polysulphide electrolyte    | 0.31         | V <sub>oc</sub> 0.272 V; J <sub>sc</sub> 0.715 mA cm <sup>-2</sup> ; FF 49%; E <sub>g</sub> 1.1–1.3 eV |
| Ayala-Sánchez 2020 [45] | mp-TiO <sub>2</sub> :Sb/Sb <sub>2</sub> Se <sub>3</sub>                         | 0.71         | V <sub>oc</sub> 261 mV; J <sub>sc</sub> 3.92 mA cm <sup>-2</sup>                                       |
| Li 2013 [52]            | Nanostructured TiO <sub>2</sub> /Sb <sub>2</sub> S <sub>3</sub> (annealing)     | 0.46 → 1.47  | E <sub>g</sub> 2.25 → 1.73 eV after annealing                                                          |
| Gödel 2015 [46]         | mp-TiO <sub>2</sub> /Sb <sub>2</sub> S <sub>3</sub> /PCPDTBT:PCBM               | 5.1          | E <sub>g</sub> ≈ 1.7 eV; room-temperature aqueous deposition                                           |
| Choi 2018 [48]          | Sb <sub>2</sub> S <sub>3</sub> -sensitised mp-TiO <sub>2</sub>                  | > 6          | SbCl <sub>3</sub> –thiourea solution processing                                                        |
| Olasoji 2025 [47]       | TiO <sub>2</sub> inverse opal/Sb <sub>2</sub> S <sub>3</sub>                    | 7.30         | 8.56% at 0.5 sun                                                                                       |
| Ahmad 2023 [49]         | TiO <sub>2</sub> + rGO (0–1.0 wt%)/CdS QDSSC                                    | 0.15 → 0.79  | Optimum 0.5 wt% rGO; V <sub>oc</sub> 0.32 → 0.55 V; decline at 0.8–1.0 wt%                             |
| Yahyaoui 2025 [50]      | GO–TiO <sub>2</sub> /CdS QDSSC                                                  | NR           | J <sub>sc</sub> 0.481 → 2 mA cm <sup>-2</sup>                                                          |
| Ali 2025 [51]           | TiO <sub>2</sub> /MoS <sub>2</sub> –rGO DSSC                                    | Not verified | Full text not accessible                                                                               |

## IV DISCUSSION

### A. Principal findings

This is, to our knowledge, the first quantitative synthesis of the building blocks of a hierarchical branched TiO<sub>2</sub>/rGO/Sb<sub>2</sub>Se<sub>3</sub> photoanode. Three findings are central. First, graphene-family incorporation reliably improves DSSC efficiency, but the realistic magnitude against an optimised control is about 1.2–1.3-fold, not the several-fold improvements that dominate abstracts; the larger gains are largely an artefact of weak baselines. Second, the improvement is carried almost entirely by Jsc, consistent with the long-proposed role of graphene as a 2D electron collector that reduces transport losses [7], and not by Voc or FF. Third, hierarchical branching roughly doubles efficiency relative to bare 1D arrays, mainly by multiplying dye loading, but it frequently increases recombination.

### B. Complementarity of branching and rGO

The two established components act on different loss channels. Branching raises the light-harvesting efficiency (more dye per unit projected area and better scattering) while degrading the collection efficiency through a larger recombining interface. Graphene-family additives act mainly on collection, with smaller effects on light harvesting, and raise Jsc



through improved collection. Because  $J_{sc}$  is proportional to the product of light-harvesting, injection and collection efficiencies, the effects would be expected to combine approximately multiplicatively if they are independent. Under this assumption, the pooled estimates suggest that an rGO-modified branched TiO<sub>2</sub> photoanode could reach about 1.2–1.3 times the efficiency of an optimised branched TiO<sub>2</sub> photoanode. This expectation is a hypothesis to be tested; it should not be presented as a predicted device efficiency, because no study has measured the interaction directly. Two caveats apply. The optimum graphene loadings in the included studies were small (0.01–5 wt%, typically below 1 wt%), and the CdS quantum-dot study showed a clear optimum followed by decline at higher loading [49], consistent with light absorption by graphene and loss of dye-anchoring sites. In a branched array, rGO must also be distributed along the trunk–branch junctions rather than lying on top of the film, which calls for in situ hydrothermal co-growth or electrophoretic deposition rather than simple paste blending.

### C. The role and risks of Sb<sub>2</sub>Se<sub>3</sub>

Sb<sub>2</sub>Se<sub>3</sub> offers absorption to about 1050 nm [44] and high photocurrents [43], which would complement the visible-range absorption of N719-type dyes. However, the evidence identifies a consistent  $V_{oc}$  penalty: every Sb<sub>2</sub>Se<sub>3</sub>-sensitised TiO<sub>2</sub> or SnO<sub>2</sub> device in this review had  $V_{oc}$  of about 0.26–0.30 V [8,43,45], compared with typical  $V_{oc}$  values of 0.6–0.77 V in the stream A DSSCs. If Sb<sub>2</sub>Se<sub>3</sub> forms a continuous absorber on the photoanode, the device  $V_{oc}$  is likely to be pinned near the lower value, offsetting any  $J_{sc}$  gain. Compatibility with the iodide/triiodide electrolyte is a further risk, as the liquid-junction Sb<sub>2</sub>Se<sub>3</sub> devices in this review used polysulphide electrolytes and achieved below 1% PCE [8,45]. Sb<sub>2</sub>Se<sub>3</sub> should therefore be introduced as sparse nanocrystals (a co-sensitiser) rather than a continuous layer, with an ultrathin passivating shell and electrolyte selection treated as experimental variables. The rGO–CdS study [49], in which rGO raised  $V_{oc}$  by 0.23 V, suggests that rGO may partly offset chalcogenide-related recombination, but this has not been shown for Sb<sub>2</sub>Se<sub>3</sub>.

### D. Evidence-based design and testing framework

Figure 6 shows the proposed architecture and the qualitative energy-level relationships that must be verified. Table 6 sets out a factorial testing matrix that would isolate the main effect of each component and their interactions, with expected outcomes derived from the present meta-analysis. We recommend that any experimental study of the ternary photoanode (i) include all intermediate configurations prepared in the same batch; (ii) report the mean  $\pm$  standard deviation of at least five devices per configuration together with the champion cell; (iii) quantify dye loading and the graphene and Sb<sub>2</sub>Se<sub>3</sub> contents; (iv) measure electron lifetime, transport time and recombination resistance by intensity-modulated photocurrent and photovoltage spectroscopy (IMPS/IMVS) and electrochemical impedance spectroscopy (EIS); (v) determine band positions by ultraviolet photoelectron spectroscopy and Mott–Schottky analysis; and (vi) report external quantum efficiency spectra to confirm near-infrared contribution from Sb<sub>2</sub>Se<sub>3</sub>.

Table 6. Proposed factorial testing matrix for a hierarchical branched TiO<sub>2</sub>/rGO/Sb<sub>2</sub>Se<sub>3</sub> photoanode, with evidence-based expectations.

| Config. | Photoanode                                               | Purpose                                           | Expected outcome from this review                                                       |
|---------|----------------------------------------------------------|---------------------------------------------------|-----------------------------------------------------------------------------------------|
| C0      | Mesoporous TiO <sub>2</sub> nanoparticle film            | Laboratory benchmark                              | Reference PCE; dye loading                                                              |
| C1      | Bare TiO <sub>2</sub> NW array                           | 1D baseline                                       | Lower dye loading than C2                                                               |
| C2      | Branched TiO <sub>2</sub> NW (BNW)                       | Effect of branching (C2/C1)                       | $\approx 2.2\times$ PCE (95% CI 1.7–2.9); higher dye loading; possible shorter $\tau_n$ |
| C3      | BNW + rGO (0.1–1.0 wt% series)                           | Effect of rGO (C3/C2); optimum loading            | $\approx 1.2\text{--}1.3\times$ PCE at optimum, $J_{sc}$ -driven; decline above optimum |
| C4      | BNW + Sb <sub>2</sub> Se <sub>3</sub> (deposition-cycle) | Effect of Sb <sub>2</sub> Se <sub>3</sub> (C4/C2) | NIR EQE gain; risk of $V_{oc}$ loss if                                                  |



| Config. | Photoanode                                  | Purpose                   | Expected outcome from this review           |
|---------|---------------------------------------------|---------------------------|---------------------------------------------|
|         | series)                                     |                           | coverage is continuous                      |
| C5      | BNW + rGO + Sb <sub>2</sub> Se <sub>3</sub> | Ternary; interaction test | Synergy if $C5/C2 > (C3/C2) \times (C4/C2)$ |
| C6      | C5 + ultrathin passivating shell            | Recombination control     | Recovery of $V_{oc}$ and FF                 |

Branched TiO<sub>2</sub> NW trunk + branches; rGO sheets (dashed); Sb<sub>2</sub>Se<sub>3</sub> nanocrystals (dots); dye on remaining surface

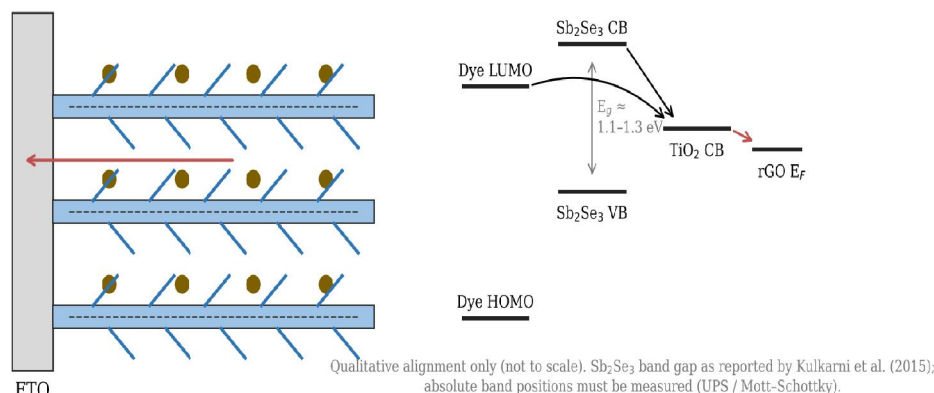


Figure 6. Proposed hierarchical branched TiO<sub>2</sub>/rGO/Sb<sub>2</sub>Se<sub>3</sub> photoanode (left) and qualitative energy-level relationships to be verified experimentally (right). Electrons are expected to be collected along the TiO<sub>2</sub> trunks and rGO sheets towards the FTO.

### E Limitations

Several limitations should be considered. The search relied on web-indexed publisher platforms, PubMed and Crossref rather than a subscription database, and 35 potentially relevant records in streams A and B could not be retrieved; the pooled estimates may therefore not represent the full literature. Data were extracted by a single reviewer, although every value was verified against a verbatim source statement. Because studies reported champion devices without variance, conventional inverse-variance weighting, formal heterogeneity statistics and funnel-plot tests of publication bias could not be applied; the uniformly positive effects (all 20 stream A studies and all 9 stream B studies favoured the modification) strongly suggest selective publication of successful modifications. Four stream A studies came from one research group. Four stream B ratios were approximate statements in the source papers, and some branched architectures changed film thickness simultaneously. Finally, the evidence on Sb<sub>2</sub>Se<sub>3</sub> is sparse, heterogeneous in device type and does not include any ternary device, so conclusions about the full TiO<sub>2</sub>/rGO/Sb<sub>2</sub>Se<sub>3</sub> system are inferential. Overall certainty is moderate for the direction of the graphene and branching effects, low for their magnitude, and very low for the Sb<sub>2</sub>Se<sub>3</sub> contribution.

### V. CONCLUSION

Graphene-family additives increase the efficiency of TiO<sub>2</sub> DSSC photoanodes by about 30% against well-optimised controls, almost entirely through higher J<sub>sc</sub>, and hierarchical branching of TiO<sub>2</sub> 1D arrays roughly doubles efficiency relative to bare arrays by multiplying dye loading, at the cost of more recombination. These mechanisms are complementary, which provides a sound rationale for rGO-modified branched TiO<sub>2</sub> photoanodes. In contrast, no



TiO<sub>2</sub>/rGO/Sb<sub>2</sub>Se<sub>3</sub> photoanode has yet been reported, and the existing Sb<sub>2</sub>Se<sub>3</sub>-sensitized devices show a large Voc penalty. The proposed ternary photoanode is therefore a credible but untested hypothesis. It should be evaluated with the factorial design, replicate-based reporting and transport diagnostics outlined here, with realistic expectations of a 20–30% gain from rGO and with Sb<sub>2</sub>Se<sub>3</sub> loading optimised to avoid Voc loss.

## REFERENCES

- [1]. O'Regan B, Grätzel M. A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO<sub>2</sub> films. *Nature*. 1991;353:737–740.
- [2]. Hagfeldt A, Boschloo G, Sun L, Kloo L, Pettersson H. Dye-sensitized solar cells. *Chem Rev*. 2010;110:6595–6663.
- [3]. Mathew S, Yella A, Gao P, Humphry-Baker R, Curchod BFE, Ashari-Astani N, et al. Dye-sensitized solar cells with 13% efficiency achieved through the molecular engineering of porphyrin sensitizers. *Nat Chem*. 2014;6:242–247.
- [4]. Law M, Greene LE, Johnson JC, Saykally R, Yang P. Nanowire dye-sensitized solar cells. *Nat Mater*. 2005;4:455–459.
- [5]. Wu WQ, Feng HL, Rao HS, Xu YF, Kuang DB, Su CY. Maximizing omnidirectional light harvesting in metal oxide hyperbranched array architectures. *Nat Commun*. 2014;5:3968. doi:10.1038/ncomms4968
- [6]. Chai Z, et al. High-performance flexible dye-sensitized solar cells by using hierarchical anatase TiO<sub>2</sub> nanowire arrays. *RSC Adv*. 2015;5(107):88052. doi:10.1039/C5RA17294B
- [7]. Yang N, Zhai J, Wang D, Chen Y, Jiang L. Two-dimensional graphene bridges enhanced photoinduced charge transport in dye-sensitized solar cells. *ACS Nano*. 2010;4:887–894.
- [8]. Kulkarni AN, et al. Sb<sub>2</sub>Se<sub>3</sub> sensitized heterojunction solar cells. *Mater Renew Sustain Energy*. 2015;4:15. doi:10.1007/s40243-015-0058-5
- [9]. Zhou Y, Wang L, Chen S, Qin S, Liu X, Chen J, et al. Thin-film Sb<sub>2</sub>Se<sub>3</sub> photovoltaics with oriented one-dimensional ribbons and benign grain boundaries. *Nat Photonics*. 2015;9:409–415.
- [10]. Li Z, Liang X, Li G, Liu H, Zhang H, Guo J, et al. 9.2%-efficient core-shell structured antimony selenide nanorod array solar cells. *Nat Commun*. 2019;10:125.
- [11]. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*. 2021;372:n71.
- [12]. Hedges LV, Gurevitch J, Curtis PS. The meta-analysis of response ratios in experimental ecology. *Ecology*. 1999;80:1150–1156.
- [13]. Int'Hout J, Ioannidis JPA, Rovers MM, Goeman JJ. Plea for routinely presenting prediction intervals in meta-analysis. *BMJ Open*. 2016;6:e010247.
- [14]. Higgins JPT, Thompson SG. Quantifying heterogeneity in a meta-analysis. *Stat Med*. 2002;21:1539–1558.
- [15]. Eshaghi A, et al. Effect of TiO<sub>2</sub>–graphene nanocomposite photoanode on dye-sensitized solar cell performance. *Bull Mater Sci*. 2015;38(5):1177–1182. doi:10.1007/s12034-015-0998-5
- [16]. Bandara TMWJ, et al. Strategic graphene integration in multilayer photoanodes for enhanced quasi-solid-state dye-sensitized solar cells and performance under variable irradiance. *J Appl Electrochem*. 2025;55:691–707. doi:10.1007/s10800-024-02204-x
- [17]. Madhavan AA, et al. Electrical and optical properties of electrospun TiO<sub>2</sub>–graphene composite nanofibers and its application as DSSC photo-anodes. *RSC Adv*. 2012;2. doi:10.1039/C2RA22091A
- [18]. Wei L, Wang P, Yang Y, Zhan Z, Dong Y, Song W, et al. Enhanced performance of the dye-sensitized solar cells by the introduction of graphene oxide into the TiO<sub>2</sub> photoanode. *Inorg Chem Front*. 2018;5(1):54–62. doi:10.1039/C7QI00503B
- [19]. Ding H, Zhang S, Juan PC, Liu TY, Du ZF, Zhao DL. Enhancing the photovoltaic performance of dye-sensitized solar cells by modifying TiO<sub>2</sub> photoanodes with exfoliated graphene sheets. *RSC Adv*. 2016;6(47):41092–41102. doi:10.1039/C6RA05639C



- [20]. Bhand S, Jha PK, Ballav N. Unusual enhancement in efficiency of DSSCs upon modifying photoanodes with reduced graphene oxide. *RSC Adv.* 2022;12(46):30041–30044. doi:10.1039/D2RA05375F
- [21]. Singh A, et al. Property modulation of graphene oxide incorporated with TiO<sub>2</sub> for dye-sensitized solar cells. *ACS Omega.* 2022;7(48):44170–44179. doi:10.1021/acsomega.2c05637
- [22]. Low FW, Hock GC, Kashif M, Samsudin NA, Chau CF, Utami ARI, et al. Influence of sputtering temperature of TiO<sub>2</sub> deposited onto reduced graphene oxide nanosheet as efficient photoanodes in dye-sensitized solar cells. *Molecules.* 2020;25(20):4852. doi:10.3390/molecules25204852
- [23]. AlSultan HA, et al. Optimising bifacial dye-sensitized solar cells with graphene-enhanced TPT configuration photoanode for operational stability. *Sci Rep.* 2025;15:38285. doi:10.1038/s41598-025-06097-4
- [24]. Chen LC, et al. Improving the performance of dye-sensitized solar cells with TiO<sub>2</sub>/graphene/TiO<sub>2</sub> sandwich structure. *Nanoscale Res Lett.* 2014;9:380. doi:10.1186/1556-276X-9-380
- [25]. Wei L, Wang P, Yang Y, Fan R, Yang Y, Qiu Y. Construction of efficient photoanodes for dye sensitized solar cells: TiO<sub>2</sub> films with a gradient content of graphene. *Sustain Energy Fuels.* 2017;1(5):1112–1122. doi:10.1039/C7SE00192D
- [26]. Dembele KT, Selopal GS, Milan R, Trudeau C, Benetti D, Soudi A, et al. Graphene below the percolation threshold in TiO<sub>2</sub> for dye-sensitized solar cells. *J Mater Chem A.* 2015;3(6):2580–2588. doi:10.1039/C4TA04395B
- [27]. Wei L, et al. Reduced graphene oxide modified TiO<sub>2</sub> semiconductor materials for dye-sensitized solar cells. *RSC Adv.* 2016;6(103). doi:10.1039/C6RA22112B
- [28]. Wei L, et al. Effect of graphene/TiO<sub>2</sub> composite layer on the performance of dye-sensitized solar cells. *J Nanosci Nanotechnol.* 2018;18(2):976–983. doi:10.1166/jnn.2018.14186
- [29]. Guo J, et al. Superior photoanode based on nanostructured TiO<sub>2</sub>@reduced graphene oxide composite with enhanced photo-to-electron conversion efficiency. *J Mater Sci Mater Electron.* 2020;31:8618–8626. doi:10.1007/s10854-020-03397-5
- [30]. Liu Y, et al. Formation and photovoltaic performance of few-layered graphene-decorated TiO<sub>2</sub> nanocrystals used in dye-sensitized solar cells. *Nanoscale.* 2014;6. doi:10.1039/C4NR00288A
- [31]. Rouhani S, et al. Investigation of the effect of rGO/TiO<sub>2</sub> on photovoltaic performance of DSSCs devices. *Prog Color Colorants Coat.* 2022;15:123–131.
- [32]. Khannam M, et al. A graphene oxide incorporated TiO<sub>2</sub> photoanode for high efficiency quasi solid state dye sensitized solar cells based on a poly-vinyl alcohol gel electrolyte. *RSC Adv.* 2016;6:55406–55414. doi:10.1039/C6RA07577K
- [33]. Low FW, et al. Study of reduced graphene oxide film incorporated of TiO<sub>2</sub> species for efficient visible light driven dye-sensitized solar cell. *J Mater Sci Mater Electron.* 2016. doi:10.1007/s10854-016-5993-0
- [34]. Zhang M, Sun Q, Zhao M, et al. Improved photoelectrical performance of graphene supported highly crystallized anatase TiO<sub>2</sub>. *Appl Phys A.* 2015;120:595–600. doi:10.1007/s00339-015-9221-1
- [35]. Chu L, et al. A general method for preparing anatase TiO<sub>2</sub> treelike-nanoarrays on various metal wires for fiber dye-sensitized solar cells. *Sci Rep.* 2014;4:4420. doi:10.1038/srep04420
- [36]. Qiu J, et al. Branched double-shelled TiO<sub>2</sub> nanotube networks for dye sensitized solar cells. *J Mater Chem.* 2012;22:23411–23417. doi:10.1039/C2JM34574A
- [37]. Chen HY, et al. Hierarchical TiO<sub>2</sub>–B/anatase core/shell nanowire arrays for efficient dye-sensitized solar cells. *RSC Adv.* 2016;6(2). doi:10.1039/C5RA21296K
- [38]. Sabba D, Agarwala S, Pramana SS, Mhaisalkar S. A maskless synthesis of TiO<sub>2</sub>-nanofiber-based hierarchical structures for solid-state dye-sensitized solar cells with improved performance. *Nanoscale Res Lett.* 2014;9:14. doi:10.1186/1556-276X-9-14
- [39]. Tan X, et al. Three-level hierarchical TiO<sub>2</sub> nanostructure based high efficiency dye-sensitized solar cells. *CrystEngComm.* 2014;16:1020–1025. doi:10.1039/C3CE41648H



- [40]. Wang H, et al. Rutile TiO<sub>2</sub> nano-branched arrays on FTO for dye-sensitized solar cells. *Phys Chem Chem Phys*. 2011;13(15):7008–7013. doi:10.1039/C1CP20351G
- [41]. Hu A, et al. Hydrothermal growth of branched hierarchical TiO<sub>2</sub> nanorod arrays for application in dye-sensitized solar cells. *J Mater Sci Mater Electron*. 2017;28:3415–3422. doi:10.1007/s10854-016-5938-7
- [42]. Guijarro N, et al. Toward antimony selenide sensitized solar cells: efficient charge photogeneration at spiro-OMeTAD/Sb<sub>2</sub>Se<sub>3</sub>/metal oxide heterojunctions. *J Phys Chem Lett*. 2012;3(10):1351–1356. doi:10.1021/jz3004365
- [43]. Choi YC, et al. Sb<sub>2</sub>Se<sub>3</sub>-sensitized inorganic–organic heterojunction solar cells fabricated using a single-source precursor. *Angew Chem Int Ed*. 2014;53(5):1329–1333. doi:10.1002/anie.201308331
- [44]. Ngo TT, et al. Electrodeposition of antimony selenide thin films and application in semiconductor sensitized solar cells. *ACS Appl Mater Interfaces*. 2014;6(4):2836–2841. doi:10.1021/am405416a
- [45]. Ayala-Sánchez, et al. Effect of Sb doping and polyvinylpyrrolidone on the mesoporous TiO<sub>2</sub> photoanodes for Sb<sub>2</sub>Se<sub>3</sub> sensitized solar cells. *MRS Adv*. 2020;5:2477–2486. doi:10.1557/adv.2020.333
- [46]. Gödel KC, et al. Efficient room temperature aqueous Sb<sub>2</sub>S<sub>3</sub> synthesis for inorganic–organic sensitized solar cells with 5.1% efficiencies. *Chem Commun*. 2015;51(41):8640–8643. doi:10.1039/C5CC01966D
- [47]. Olasoji AJ, et al. Facile fabrication of crack-free TiO<sub>2</sub> inverse opal thin-film and its application as electron transporting scaffold for efficient Sb<sub>2</sub>S<sub>3</sub>-sensitized solar cells. *J Colloid Interface Sci*. 2025;678(Pt B):842–853. doi:10.1016/j.jcis.2024.08.259
- [48]. Choi YC, et al. Key factors affecting the performance of Sb<sub>2</sub>S<sub>3</sub>-sensitized solar cells during an Sb<sub>2</sub>S<sub>3</sub> deposition via SbCl<sub>3</sub>–thiourea complex solution-processing. *J Vis Exp*. 2018;(137):58062. doi:10.3791/58062
- [49]. Ahmad H, et al. Synthesis, characterization and electrochemical impedance study of CdS quantum dot-sensitized solar cell with reduced graphene oxide/TiO<sub>2</sub> composite photoanode. *Bull Mater Sci*. 2023;46:44. doi:10.1007/s12034-022-02878-z
- [50]. Yahyaoui N, et al. Investigation of the GO effect on CdS quantum dot sensitized PV-cells based on the GO–TiO<sub>2</sub> nanocomposite photoanode: modeling using the Lambert function. *Phys Chem Chem Phys*. 2025;27(16):8077–8089. doi:10.1039/D5CP00181A
- [51]. Ali AA, et al. TiO<sub>2</sub>/MoS<sub>2</sub>-rGO composite photoanodes: a path to improved electron transport and photovoltaic efficiency in dye-sensitized solar cells. *Sol Energy*. 2025;291:113405. doi:10.1016/j.solener.2025.113405
- [52]. Li Y, et al. Annealing effect on Sb<sub>2</sub>S<sub>3</sub>–TiO<sub>2</sub> nanostructures for solar cell applications. *Nanoscale Res Lett*. 2013;8:89. doi:10.1186/1556-276X-8-89

