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# Electrolyte selection toward efficient photoelectrochemical glycerol oxidation on BiVO<sub>4</sub>†

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Glycerol, a primary by-product of biodiesel production, can be oxidized into various value-added chemicals, significantly enhancing the techno-economic value of photoelectrochemical (PEC) cells. Several studies have explored various photoelectrode materials and co-catalysts, but the influence of electrolytes on PEC glycerol oxidation has remained relatively unexplored despite its significance. Here, we explore the impact of various acidic (pH = 2) electrolytes, namely NaNO<sub>3</sub>, NaClO<sub>4</sub>, Na<sub>2</sub>SO<sub>4</sub>, K<sub>2</sub>SO<sub>4</sub>, and KPi, on PEC glycerol oxidation using nanoporous thin film BiVO<sub>4</sub> as a model photoanode. Our experimental findings reveal that the choice of electrolyte anion and cation significantly affects the PEC performance (*i.e.*, photocurrent, onset potential, stability, and selectivity towards value-added products) of BiVO<sub>4</sub> for glycerol oxidation. To explain this interesting phenomenon, we correlate the observed performance trend with the ion specificity in the Hofmeister series as well as the buffering capacity of the electrolytes. Notably, NaNO<sub>3</sub> is identified as the optimal electrolyte for PEC glycerol oxidation with BiVO<sub>4</sub> when considering various factors such as stability and production rates for glycerol oxidation reaction (GOR) products, surpassing the previously favored Na<sub>2</sub>SO<sub>4</sub>. Glycolaldehyde emerges as the most dominant product with ~50% selectivity in NaNO<sub>3</sub>. The general applicability of our findings is confirmed by similar observation in electrochemical (EC) GOR with a polycrystalline platinum anode. Overall, these results emphasize the critical role of electrolyte selection in enhancing the efficiency of EC/PEC glycerol oxidation.

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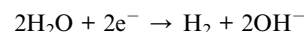
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## Introduction

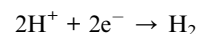
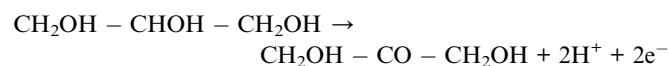
Glycerol, a major by-product of biodiesel production, holds significant potential as a feedstock to produce value-added chemicals.<sup>1</sup> A broad palette of high-value products from the glycerol oxidation reaction (GOR), including dihydroxyacetone (DHA), formic acid (FA), glyceraldehyde (GLAD), and glycolaldehyde (GCAD), can be obtained in one or more reaction steps.<sup>2</sup> Glycerol can also be oxidized electrochemically, which means it can serve as an anodic reactant in electrochemical (EC) or photoelectrochemical (PEC) devices. The oxidation of glycerol to *e.g.*, DHA in an aqueous environment can be written as



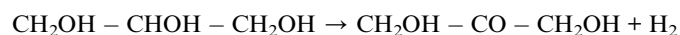
and the corresponding reduction reaction as



For acidic environments, the reactions are written as



The overall reaction is given as



The oxidation of glycerol ( $\Delta G = 3.9 \text{ kJ mol}^{-1}$ , when coupled with the hydrogen evolution reaction, HER) requires

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significantly less energy and can be driven at much lower overpotentials compared to hydrogen production *via* the direct water splitting reaction ( $\Delta G = 237.2 \text{ kJ mol}^{-1}$ , requiring an additional overpotential of at least 0.3 V for the oxygen evolution reaction, OER). Moreover, GOR products possess significantly higher economic value than glycerol. For instance, the market price of DHA ranges from approximately 2 to 150 €  $\text{kg}^{-1}$ , depending on the degree of purity.<sup>3</sup> In contrast, refined glycerol ( $\geq 99\%$ ) is available for  $\sim 0.75 \text{ € kg}^{-1}$ , while the worldwide wholesale price for crude glycerol ( $\sim 80\%$  purity) was  $\sim 0.1 \text{ € kg}^{-1}$  in 2020.<sup>4</sup> Therefore, the techno-economic case for this PEC Power-to-X process is much more attractive than that for PEC water splitting.

In many (photo)electrochemical reactions, the composition of the electrolyte is known to be crucial.<sup>5</sup> For example, Ding *et al.* showed that the choice of cations in alkaline electrolytes affects the water oxidation performance of  $\text{TiO}_2$  photoanodes. This was attributed to different back-reaction rates (*i.e.*, oxygen reduction reaction) induced by the various cations.<sup>6</sup> Similarly, the choice of anions has been shown to influence the performance of  $\text{WO}_3$  photoanodes, as these anions can be parasitically oxidized alongside water at the electrode surface.<sup>5a,7</sup> In the case of PEC glycerol oxidation, too few studies are available to determine the optimal supporting electrolyte for achieving high efficiency and stability. Since Liu *et al.* demonstrated that glycerol oxidation using  $\text{BiVO}_4$  photoanodes exhibited the highest efficiency in acidic solutions ( $\text{pH} = 2$ ) based on sodium sulfate ( $\text{Na}_2\text{SO}_4$ ),<sup>8</sup> subsequent studies mainly used  $\text{Na}_2\text{SO}_4$ -based electrolytes and predominantly focused on modifying the photoanode material and/or the deposited co-catalyst to optimize the performance.<sup>9</sup> It is still unclear whether altering the electrolyte composition could also optimize the PEC glycerol oxidation performance.

In this paper, we demonstrate that the electrolyte composition substantially impacts the glycerol oxidation performance of our model photoanode material, bismuth vanadate ( $\text{BiVO}_4$ ). We investigate acidic electrolytes ( $\text{pH} = 2$ ) with different cations and anions: sodium nitrate ( $\text{NaNO}_3$ ), sodium perchlorate

( $\text{NaClO}_4$ ), sodium sulfate ( $\text{Na}_2\text{SO}_4$ ), potassium sulfate ( $\text{K}_2\text{SO}_4$ ), and potassium phosphate ( $\text{KP}_i$ ), the latter being a pH buffer solution. Our systematic study reveals that, when performance factors such as photocurrent, stability, and production rates towards high-value GOR products are comprehensively considered,  $\text{BiVO}_4$  photoanodes exhibit the highest glycerol oxidation performance in  $\text{NaNO}_3$ , surpassing the commonly employed  $\text{Na}_2\text{SO}_4$ . To the best of our knowledge,  $\text{NaNO}_3$  has not been previously reported as an electrolyte for PEC GOR. The underlying reason behind this observed performance difference is discussed, particularly in relation to the classification of the ions in the Hofmeister series and the pH buffering capacities of the employed solutions. Furthermore, the same GOR performance trend with the electrolyte choice is also observed when the  $\text{BiVO}_4$  photoanode is replaced with a polycrystalline platinum (Pt) anode, suggesting that our explanations may be broadly applicable, irrespective of the anode material or whether the process is EC- or PEC-driven. Overall, these findings emphasize the critical role of electrolyte selection for achieving high performance and stability in glycerol oxidation and underscore the potential of  $\text{NaNO}_3$  as a favorable electrolyte for glycerol oxidation.

## Results and discussion

$\text{BiVO}_4$  photoanodes were prepared using a previously reported electrodeposition method,<sup>10</sup> and the detailed synthesis method is described in the ESI.† The samples exhibit a nanoporous morphology (Fig. S1†), while the X-ray diffractogram shows a monoclinic crystalline phase without any impurities (Fig. S2a†). Tauc analysis of the samples revealed an indirect bandgap of 2.48 eV (Fig. S2b†), which is within the range of typical bandgap values reported for monoclinic  $\text{BiVO}_4$ .<sup>11</sup>

We first compare the PEC performance of  $\text{BiVO}_4$  toward water oxidation in various acidic electrolytes, in the absence of glycerol. Fig. 1a shows the linear sweep voltammetry (LSV) curves measured under AM 1.5G simulated sunlight (100  $\text{mW cm}^{-2}$ ) in  $\text{KP}_i$ ,  $\text{K}_2\text{SO}_4$ ,  $\text{Na}_2\text{SO}_4$ ,  $\text{NaClO}_4$ , and  $\text{NaNO}_3$  (see Fig. S3a† for the corresponding dark LSV curves). The concentration of all



Fig. 1 Linear sweep voltammetry (LSV) curves recorded in different acidic solutions ( $\text{pH} = 2$ ), all having a concentration of 0.5 M: (a) in the absence of glycerol and (b) with 0.1 M glycerol. Measurements were performed at a scan rate of  $20 \text{ mV s}^{-1}$ , sweeping from negative to positive potentials relative to the reversible hydrogen electrode (RHE), under AM 1.5G simulated sunlight illumination. LSV curves recorded in  $\text{NaNO}_3$  without illumination are also shown as the representative dark curves; dark LSV curves recorded in other electrolytes are shown in Fig. S3.†



electrolytes was kept constant at 0.5 M, and the pH value was adjusted to 2. To avoid altering the ionicity of the solutions, the pH of each investigated electrolyte was lowered using mineral acids with the same anion of the electrolyte itself (e.g., in the case of  $\text{NaNO}_3$ , the pH was lowered using  $\text{HNO}_3$ , whereas  $\text{H}_2\text{SO}_4$  was used for  $\text{K}_2\text{SO}_4$ ). Our electrodeposited  $\text{BiVO}_4$  photoanodes showed similar photocurrent ( $0.5\text{--}0.7\text{ mA cm}^{-2}$ ) at  $1.23\text{ V}$  vs. the reversible hydrogen electrode ( $V_{\text{RHE}}$ ) and onset potential ( $\sim 0.6\text{ V}_{\text{RHE}}$ ) in all electrolytes (see Fig. S4 and Table S1† for the measurements' reproducibility), indicating that the difference in the electrolyte composition does not affect their performance toward water oxidation.

To investigate the effect of electrolyte composition on the performance of PEC glycerol oxidation using  $\text{BiVO}_4$ , 0.1 M glycerol was added to each of the five electrolyte solutions. Fig. 1b displays the LSV curves measured under illumination (also see Fig. S5 and Table S2† for reproducibility), while the LSV curves obtained in the absence of illumination are presented in Fig. S3b.† In the presence of 0.1 M glycerol, our  $\text{BiVO}_4$  photoanodes showed increased photocurrent in all electrolytes. This is attributed to the lower overpotential needed for the GOR as compared to the OER. Interestingly, the photocurrents varied significantly depending on the electrolyte composition. The lowest photocurrent was obtained in the  $\text{KP}_i$  solution, followed by the  $\text{K}_2\text{SO}_4$ ,  $\text{Na}_2\text{SO}_4$ ,  $\text{NaNO}_3$ , and  $\text{NaClO}_4$  solutions. The photocurrent improvement was rather significant, with 180% increase by changing the electrolyte from  $\text{KP}_i$  to  $\text{NaClO}_4$  ( $1.07 \pm 0.08$  vs.  $2.97 \pm 0.11\text{ mA cm}^{-2}$  at  $1.23\text{ V}_{\text{RHE}}$ ).

The same photocurrent trend was also observed when the glycerol concentration was increased. Fig. S6† shows the LSV curves of  $\text{BiVO}_4$  photoanodes measured with 0.5 M glycerol. As in the case of 0.1 M glycerol, our photoanodes showed the lowest photocurrent in the  $\text{KP}_i$  solution and the highest in the  $\text{NaClO}_4$  solution. However, the photocurrents in the  $\text{NaNO}_3$  and  $\text{NaClO}_4$  solutions were similar, especially at higher potentials ( $>1.0\text{ V}_{\text{RHE}}$ ). The photocurrent difference was more pronounced at relatively low potentials. For example, in the  $\text{NaNO}_3$  and  $\text{NaClO}_4$  solutions, the photocurrent already reached  $1.0\text{ mA cm}^{-2}$  at approximately  $0.5\text{ V}_{\text{RHE}}$ , whereas in the  $\text{KP}_i$  solution, a potential of  $0.9\text{ V}_{\text{RHE}}$  was needed.

Chronoamperometry (CA) was performed at  $1.23\text{ V}_{\text{RHE}}$  for a duration of 12 hours to assess the stability of our photoanodes in the five acidic electrolytes containing 0.5 M glycerol, as reported in Fig. 2a. In the  $\text{KP}_i$  solution, the photocurrent decreased rapidly to  $1/e$  (36.7%) of its initial value within only 1.8 hours, ultimately resulting in a complete loss of photocurrent within 8 hours. In contrast, the photoanodes exhibited photocurrent retention of approximately 70–80% over the 12 hours period in  $\text{K}_2\text{SO}_4$ ,  $\text{Na}_2\text{SO}_4$ ,  $\text{NaClO}_4$ , and  $\text{NaNO}_3$ . The corresponding LSV curves obtained before and after the CA are shown in Fig. 2b–f. After the CA measurement in  $\text{KP}_i$ , no photoactivity remained (see Fig. 2b), consistent with the complete photocurrent loss during the CA experiment. The samples tested in  $\text{K}_2\text{SO}_4$  and  $\text{NaClO}_4$  also showed a consistent photocurrent decrease after the CA (see Fig. 2c and e). Interestingly, the samples tested in  $\text{Na}_2\text{SO}_4$  and  $\text{NaNO}_3$  maintained similar photocurrent levels in their LSV measurements compared to

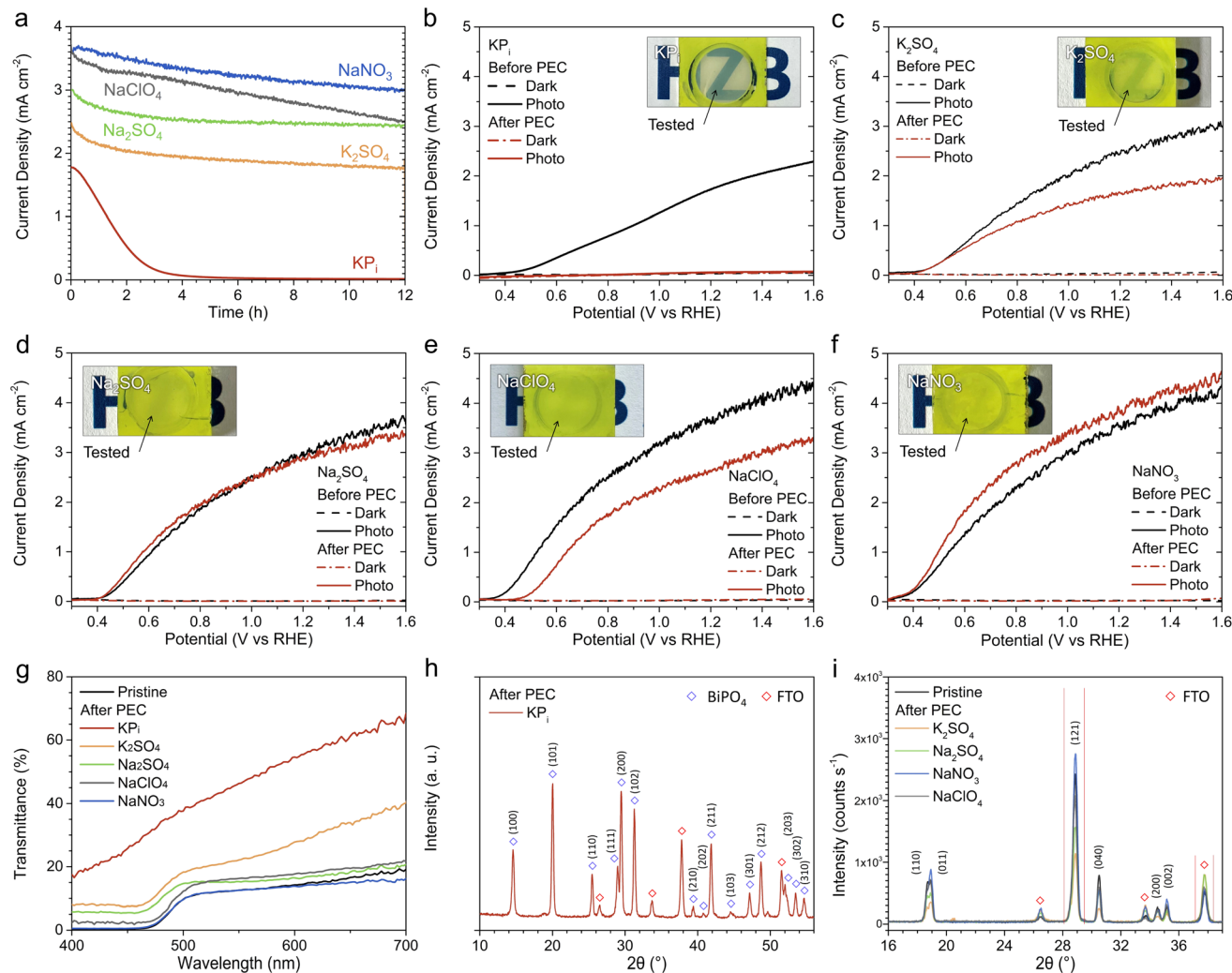
those observed before the 12 hours CA, indicating some degree of recovery (see Fig. 2d and f). Note that we limit our study to pH 2 electrolyte solutions, as the use of more acidic pH (e.g., pH 1) renders the  $\text{BiVO}_4$  to be unstable even in the  $\text{NaNO}_3$  solution (Fig. S7†).

The photographs of the sample taken after the 12 hours CA in each electrolyte solution are presented in the insets of Fig. 2b–f. In the case of the samples tested in  $\text{KP}_i$ , the exposed area became white and transparent. This is not the case for samples tested in  $\text{K}_2\text{SO}_4$ ,  $\text{Na}_2\text{SO}_4$ ,  $\text{NaClO}_4$ , and  $\text{NaNO}_3$ ; no significant difference was observed between the appearance of the tested and untested regions. We quantified our observation by measuring the UV-vis transmittance of these regions, as shown in Fig. 2g. Notably, the transmittance of the sample tested in  $\text{NaNO}_3$  closely matched that of the pristine sample across the entire wavelength range. The samples tested in  $\text{K}_2\text{SO}_4$ ,  $\text{Na}_2\text{SO}_4$ , and  $\text{NaClO}_4$  exhibited a notable increase in transmittance, albeit with varying amount, suggesting the possible loss of  $\text{BiVO}_4$  material due to photocorrosion and consequent dissolution. The sample tested in  $\text{KP}_i$  displayed significantly higher transmittance across the entire wavelength range, consistent with the appearance of the sample after electrolysis (see inset of Fig. 2b).

We then compared the crystallinity of the  $\text{BiVO}_4$  samples before and after the 12 hours CA measurements. Fig. 2h displays the X-ray diffractogram for the sample tested in  $\text{KP}_i$ . Diffraction peaks corresponding to  $\text{BiPO}_4$  (as well as the FTO substrate) were detected, while peaks characteristic of monoclinic  $\text{BiVO}_4$  were absent. This suggests that during the CA measurement, vanadium atoms in  $\text{BiVO}_4$  leached into the electrolyte and were substituted by phosphorus atoms from the  $\text{KP}_i$  solution, leading to a crystal structure transformation and eventually a complete conversion to  $\text{BiPO}_4$ . Indeed,  $\text{BiPO}_4$  has a wide bandgap ( $\sim 3.85\text{ eV}$ ),<sup>12</sup> which explains the white and transparent appearance of the film after CA. Such a conversion could also account for the low photocurrent observed with  $\text{KP}_i$  (Fig. 1b). Note that the formation of a  $\text{BiPO}_4$  thin film on the surface of  $\text{BiVO}_4$  upon exposure to  $\text{KP}_i$  buffer solution at pH 7 has been previously reported.<sup>13</sup> A full conversion to  $\text{BiPO}_4$  has not been reported, which we attribute to the use of lower pH.

Fig. 2i shows the X-ray diffractograms of the  $\text{BiVO}_4$  samples measured after the 12 hours CA measurements in  $\text{K}_2\text{SO}_4$ ,  $\text{Na}_2\text{SO}_4$ ,  $\text{NaClO}_4$ , and  $\text{NaNO}_3$ . Unlike the sample measured in  $\text{KP}_i$ , diffraction peaks characteristic of monoclinic  $\text{BiVO}_4$  can be detected in these samples. For samples measured in  $\text{K}_2\text{SO}_4$ ,  $\text{Na}_2\text{SO}_4$ , and  $\text{NaClO}_4$ , the intensities of the (121) diffraction peak, which is the most prominent reflection for electrodeposited monoclinic  $\text{BiVO}_4$ ,<sup>10</sup> decreased, while the intensities of the FTO peak at  $2\theta = 37.6^\circ$  increased. In the case of the sample measured in  $\text{NaNO}_3$ , the X-ray diffraction (XRD) pattern closely resembled that of the pristine sample. We quantified the area under the (121) peak and the FTO peak at  $2\theta = 37.6^\circ$  and then calculated their ratio. For the sample tested in  $\text{NaNO}_3$ , this ratio was 4.8, which was higher than that of the pristine sample (3.9). In contrast, the ratios for the samples tested in  $\text{NaClO}_4$ ,  $\text{Na}_2\text{SO}_4$ , and  $\text{K}_2\text{SO}_4$  were considerably lower; 2.8 for  $\text{NaClO}_4$ , 1.8 for  $\text{Na}_2\text{SO}_4$ , and 1.4 for  $\text{K}_2\text{SO}_4$ , respectively.





**Fig. 2** (a) Chronoamperometry (CA) curves measured at 1.23  $V_{\text{RHE}}$  under AM 1.5G illumination in different acidic electrolyte solutions (pH = 2) containing 0.5 M glycerol. Linear sweep voltammetry (LSV) curves measured under AM 1.5G illumination before (black curves) and after (red curves) the 12 hours CA measurements in (b)  $\text{KP}_1$ , (c)  $\text{K}_2\text{SO}_4$ , (d)  $\text{Na}_2\text{SO}_4$ , (e)  $\text{NaClO}_4$ , and (f)  $\text{NaNO}_3$  solutions containing 0.5 M glycerol. Insets in (b)–(f) show the digital photographs of the specimens after undergoing the 12 hours CA tests in the different acidic electrolytes in the presence of 0.5 M glycerol. The circular areas exposed to the electrolyte during the tests are indicated. (g) UV-vis transmittance of pristine  $\text{BiVO}_4$  and  $\text{BiVO}_4$  samples following the 12 hours CA measurements shown in (a). X-ray diffractogram of the  $\text{BiVO}_4$  samples after the CA tests (h) in  $\text{KP}_1$  solution and (i) in  $\text{K}_2\text{SO}_4$ ,  $\text{Na}_2\text{SO}_4$ ,  $\text{NaClO}_4$ , and  $\text{NaNO}_3$  solutions.

The XRD and UV-vis transmittance results above indicate that  $\text{BiVO}_4$  substantially degraded during GOR in acidic  $\text{NaClO}_4$ ,  $\text{Na}_2\text{SO}_4$  and  $\text{K}_2\text{SO}_4$ , likely due to photocorrosion, but not in  $\text{NaNO}_3$ . These findings are interesting because, according to the Pourbaix diagram,<sup>14</sup>  $\text{BiVO}_4$  is expected to decompose into  $\text{BiO}^+$  and  $\text{VO}_4^{3-}$  at pH 2 and 1.23  $V_{\text{RHE}}$ . This suggests that  $\text{NO}_3^-$  (either by itself or in conjunction with glycerol) plays a role in stabilizing  $\text{BiVO}_4$  under these conditions. The exact mechanism requires further investigation beyond the scope of this study.

The surface chemical characteristics of the pristine sample and samples subjected to 12 hours CA in glycerol-containing  $\text{K}_2\text{SO}_4$ ,  $\text{Na}_2\text{SO}_4$ ,  $\text{NaClO}_4$ , and  $\text{NaNO}_3$  electrolytes were investigated using X-ray photoelectron spectroscopy (XPS). The sample subjected to the same treatment in  $\text{KP}_1$  was not tested since XRD already showed a clear transformation to  $\text{BiPO}_4$ . The Bi 4f core-level spectra are displayed in Fig. S8,<sup>†</sup> and the O 1s and V 2p core-level spectra are presented in Fig. S9.<sup>†</sup> While the binding

energy difference ( $\Delta\text{BE}$ ) between the Bi 4f<sub>5/2</sub> and 4f<sub>7/2</sub> peaks remained constant, the tested samples exhibited a slight shift towards higher binding energies. The magnitude of this peak shift was 0.1 eV in the  $\text{NaNO}_3$  solution and increased to 0.2 eV in the  $\text{K}_2\text{SO}_4$ ,  $\text{Na}_2\text{SO}_4$ , and  $\text{NaClO}_4$  solutions. A notable difference among the samples was observed in the O 1s core-level spectra. The samples tested in the  $\text{K}_2\text{SO}_4$ ,  $\text{Na}_2\text{SO}_4$ , and  $\text{NaClO}_4$  solutions showed distinct peaks at higher binding energies of approximately 531–533 eV. These peaks could originate from adsorbed hydroxyl ions (at ~532 eV),<sup>15</sup> likely due to glycerol adsorption during GOR. Their significant emergence may imply a somewhat reduced surface chemical stability of  $\text{BiVO}_4$  during PEC oxidation of glycerol in the  $\text{K}_2\text{SO}_4$ ,  $\text{Na}_2\text{SO}_4$ , and  $\text{NaClO}_4$  solutions at pH 2. Indeed, if the  $\text{O}^{2-}$  ions in  $\text{BiVO}_4$  were substituted by hydroxyl ( $\text{OH}^-$ ) ions, the resulting decrease in the number of valence electrons could potentially lead to a shift to higher binding energies in the Bi 4f and V 2p peaks. In contrast, the



sample tested in  $\text{NaNO}_3$  solution exhibited only a slight increase in signal intensity near 532 eV, indicating the relatively superior chemical stability of  $\text{BiVO}_4$  in pH 2  $\text{NaNO}_3$  solution during PEC glycerol oxidation. Overall, these XPS findings are in agreement with the XRD and UV-vis results.

The selectivity and production rates towards value-added GOR products during the 12 hours CA tests in various acidic electrolyte solutions were analyzed using high-performance liquid chromatography (HPLC). Detailed experimental methods for the HPLC analyses are provided in the ESI† (also refer to Fig. S10–S12† for calibration information).  $\text{KPi}$  was excluded from our analysis due to the severe instability of  $\text{BiVO}_4$  during the GOR in the pH 2  $\text{KPi}$  solution (*vide supra*). Fig. 3a displays the selectivity of  $\text{BiVO}_4$  towards various GOR products and the total faradaic efficiency, calculated in terms of charges used for GOR, in  $\text{K}_2\text{SO}_4$ ,  $\text{Na}_2\text{SO}_4$ ,  $\text{NaClO}_4$ , and  $\text{NaNO}_3$  solutions (the corresponding chromatograms are shown in Fig. S13–S16†). In our study, GCAD ( $\text{C}_2\text{H}_4\text{O}_2$ ), GLAD ( $\text{C}_3\text{H}_6\text{O}_3$ ), DHA ( $\text{C}_3\text{H}_6\text{O}_3$ ), and FA ( $\text{CH}_2\text{O}_2$ ) were detected as the GOR products. Notably, GCAD emerged as the most dominant product in all electrolytes, which is consistent with a recent report.<sup>16</sup> However, the selectivity varied depending on the electrolyte. In  $\text{K}_2\text{SO}_4$ , the selectivity for GLAD (28%) a C3 molecule, was the highest among the electrolytes tested. Furthermore, the selectivity for FA, the only C1 product in our case, was as low as 10%. Interestingly, in the  $\text{Na}_2\text{SO}_4$ ,  $\text{NaClO}_4$ , and  $\text{NaNO}_3$  solutions, the selectivities for GCAD (C2) and FA (C1) increased, while the selectivity for GLAD (C3) decreased (the selectivity for DHA remained relatively constant at ~20% in all electrolytes). In  $\text{NaNO}_3$ , the selectivity for GCAD exceeded 50% and the selectivity for GLAD was as low as 14%. These results suggest that the rate of C–C cleavage in GLAD, which was proposed as a pathway to the formation of GCAD and FA,<sup>16</sup> might differ among various electrolyte solutions, consequently influencing the overall GOR performance. One possible explanation is that

GLAD adsorbs more favorably onto the  $\text{BiVO}_4$  surface in the  $\text{NaNO}_3$  solution compared to others. Further computational and/or experimental studies beyond the scope of our work are needed to reveal the actual mechanism. Fig. 3b presents the production rates of the four GOR products. In the  $\text{NaNO}_3$  solution, the production rate of GCAD was calculated to be  $318 \text{ mmol m}^{-2} \text{ h}^{-1}$ , which is, to the best of our knowledge, the highest reported value for undoped  $\text{BiVO}_4$  without any co-catalysts.

The total faradaic efficiency was highest in the  $\text{NaNO}_3$  solution, as shown in Fig. 3a, where an estimated 82% of the photo-generated holes were used for oxidizing glycerol. Mass spectroscopy (MS) results (see Fig. S17†) obtained from the  $\text{NaNO}_3$  solution indicate that no  $\text{O}_2$  was generated above our detection limit. This suggests that the OER was effectively suppressed in the  $\text{NaNO}_3$  solution, likely owing to the relatively low energy requirement of the GOR. A slight increase in the mass signal corresponding to  $\text{CO}_2$  was observed, suggesting the potential for complete oxidation of glycerol to  $\text{CO}_2$ . We tentatively attribute the remaining photo-generated holes (~18%) to the generation of other glycerol oxidation products including  $\text{CO}_2$  (undetected with HPLC and MS) or to photocorrosion. The lower faradaic efficiencies observed in  $\text{Na}_2\text{SO}_4$  (74%),  $\text{NaClO}_4$  (71%), and  $\text{K}_2\text{SO}_4$  (70%) support the hypothesis of partial hole consumption due to photocorrosion, especially given the poorer photo-stability of  $\text{BiVO}_4$  in these solutions. We also confirm that nitrate reduction reaction (NRR), which could potentially occur at the counter electrode when  $\text{NaNO}_3$  is used as the electrolyte, was not detected in our experiments (see Fig. S18†).

In terms of photocurrent, stability, and selectivity to high-value GCAD,  $\text{NaNO}_3$  was identified as the most suitable electrolyte for PEC glycerol oxidation using  $\text{BiVO}_4$ . To elucidate how the choice of electrolyte influences the GOR performance of  $\text{BiVO}_4$ , it is first necessary to examine the electrical conductivities of the electrolyte solutions. The electrical conductivities of



Fig. 3 Product analysis using high-performance liquid chromatography (HPLC). (a) Selectivity and (b) production rate towards glycerol oxidation reaction (GOR) products in various acidic electrolytes (pH = 2). Total faradaic efficiency, calculated in terms of charges used for GOR, is presented on the right y-axis in (a). The methods for calculating selectivity, production rate, and faradaic efficiency are described in the ESI†. Liquid samples were collected after 12 hours photoelectrolysis at a constant potential of  $1.23 V_{\text{RHE}}$ , corresponding to the measurements shown in Fig. 2a. GCAD: glycolaldehyde, GLAD: glyceraldehyde, DHA: dihydroxyacetone, FA: formic acid.

0.5 M  $\text{NaNO}_3$ ,  $\text{NaClO}_4$ ,  $\text{Na}_2\text{SO}_4$ ,  $\text{K}_2\text{SO}_4$ , and  $\text{KPi}$  solutions (all at pH 2) were measured as  $75.5 \text{ mS cm}^{-1}$ ,  $98.2 \text{ mS cm}^{-1}$ ,  $102.6 \text{ mS cm}^{-1}$ ,  $141.2 \text{ mS cm}^{-1}$ , and  $100.0 \text{ mS cm}^{-1}$ , respectively, which do not correlate with the trends observed in GOR performance. Moreover, if the differing GOR performance observed in  $\text{BiVO}_4$  was due to differences in electrical conductivity among the electrolytes, then the water-splitting performance of  $\text{BiVO}_4$  should have varied accordingly.

Moreover, to determine whether the GOR performance trend in different acidic electrolytes is specific to  $\text{BiVO}_4$  and/or the PEC process, we examined the GOR performance of a polycrystalline Pt anode. Fig. 4a displays the LSV curves of the Pt anode measured without glycerol in various acidic electrolytes. Note that  $\text{NaClO}_4$  solution is excluded from this particular study, the formation of platinum oxide that degrades the activity has been reported when Pt is exposed to perchloric acid.<sup>17</sup> The Pt anode exhibited similar LSV curves across all electrolytes. For example, the onset potential for OER was observed at approximately  $1.6 V_{\text{RHE}}$ , and an overpotential of  $\sim 0.8 \text{ V}$  was required to achieve  $10 \text{ mA cm}^{-2}$  (at  $\sim 2.0 V_{\text{RHE}}$ ) in all solutions. Fig. 4b presents the LSV curves of the Pt anode measured in the presence of  $0.1 \text{ M}$  glycerol. The current density for the Pt anode began to increase earlier than in its absence, similar to the case with  $\text{BiVO}_4$ , reflecting the lower energy requirement of GOR compared to OER. Interestingly, the Pt anode exhibited the same GOR performance trend as  $\text{BiVO}_4$  in terms of current density. At  $1.4 V_{\text{RHE}}$ , a potential more negative than the onset for OER, the current densities at  $1.4 V_{\text{RHE}}$  ranked as follows:  $\text{NaNO}_3 > \text{Na}_2\text{SO}_4 > \text{K}_2\text{SO}_4 > \text{KPi}$  (see Fig. 4b). These results indicate that the influence of the electrolyte on GOR performance, particularly in terms of current density, is not unique to  $\text{BiVO}_4$  and may be generally applicable to other anode materials and whether the reaction is EC- or PEC-driven.

These findings lead us to investigate the impact of specific ions in the electrolytes on PEC glycerol oxidation performance, extending beyond mere electrolyte conductivity or anode material. Specifically, the photocurrent trend in the different electrolytes (for  $\text{BiVO}_4$ :  $\text{NaClO}_4 > \text{NaNO}_3 > \text{Na}_2\text{SO}_4 > \text{K}_2\text{SO}_4 > \text{KPi}$ )

suggests that the presence of specific ions in the electrolyte is beneficial/detrimental to the PEC glycerol oxidation performance. First, the trend indicates that  $\text{Na}^+$  is more favorable than  $\text{K}^+$  for GOR on  $\text{BiVO}_4$ . We attribute this observation to the prominent difference between the cation size. As illustrated in Fig. 5a,  $\text{K}^+$  has an approximately 30% larger effective ionic radius of  $138 \text{ pm}$  compared to  $\text{Na}^+$  ( $102 \text{ pm}$ ),<sup>18</sup> resulting in a larger effective nuclear charge than  $\text{Na}^+$ .<sup>19</sup> According to density functional theory (DFT) calculations performed by Liu *et al.*, the hydroxyl groups of glycerol spontaneously adsorb at the exposed  $\text{Bi}^{3+}$  sites of  $\text{BiVO}_4$  through electrostatic interactions between  $\text{Bi}^{3+}$  and oxygen in the hydroxyl groups, as depicted in Fig. 5b.<sup>8</sup> Similarly, previous DFT calculations on glycerol adsorption to Pt surfaces also showed that the hydroxyl groups of glycerol adsorb to the surface Pt atoms. Furthermore, previous liquid chromatography-mass spectrometry results showed that glycerol molecules in  $\text{Na}_2\text{SO}_4$  solutions (pH 2) were found in the form of  $\text{C}_3\text{H}_8\text{O}_3\text{Na}$  (glycerol =  $\text{C}_3\text{H}_8\text{O}_3$ ).<sup>8</sup> This observation indicates a strong interaction between the hydroxyl groups of glycerol, with their negative partial charge  $\delta^-$ , and the cations in the electrolytes. Given that  $\text{K}^+$  has a larger effective nuclear charge (defined as  $Z_{\text{eff}} = Z - S$ , where  $Z$  is the number of protons (atomic number) and  $S$  is the shielding constant),<sup>20</sup> the glycerol hydroxyl groups are expected to interact more strongly with  $\text{K}^+$  than with  $\text{Na}^+$ . Consequently, this can lead to stronger electrical neutralization of the hydroxyls of glycerol, which may weaken the electrostatically induced adsorption of glycerol molecules to the  $\text{Bi}^{3+}$  sites. As a result, GOR at  $\text{BiVO}_4$  in  $\text{K}^+$ -containing electrolytes would be hindered.

In addition, the superior performance of  $\text{BiVO}_4$  in  $\text{NaNO}_3$  and  $\text{NaClO}_4$  than in  $\text{Na}_2\text{SO}_4$  may be explained considering the different types of anions,  $\text{NO}_3^-$ ,  $\text{ClO}_4^-$ , and  $\text{SO}_4^{2-}$ . The Pt anode also exhibited a higher GOR current in  $\text{NaNO}_3$  than in  $\text{Na}_2\text{SO}_4$ . Interestingly, we note that  $\text{SO}_4^{2-}$  stands out as one of the anions exhibiting potent specific ion effects, positioned towards the left end of the Hofmeister series,<sup>21</sup> as shown in Fig. 5c. This indicates a strong salting-out effect of  $\text{SO}_4^{2-}$ . In contrast,  $\text{NO}_3^-$  and  $\text{ClO}_4^-$  are positioned closer to the right end of the Hofmeister



Fig. 4 Linear sweep voltammetry (LSV) curves of a polycrystalline platinum (Pt) anode measured (a) without glycerol and (b) in the presence of  $0.1 \text{ M}$  glycerol in various acidic electrolytes at pH 2, with an electrolyte concentration of  $0.5 \text{ M}$ . Measurements were performed at a scan rate of  $20 \text{ mV s}^{-1}$ .



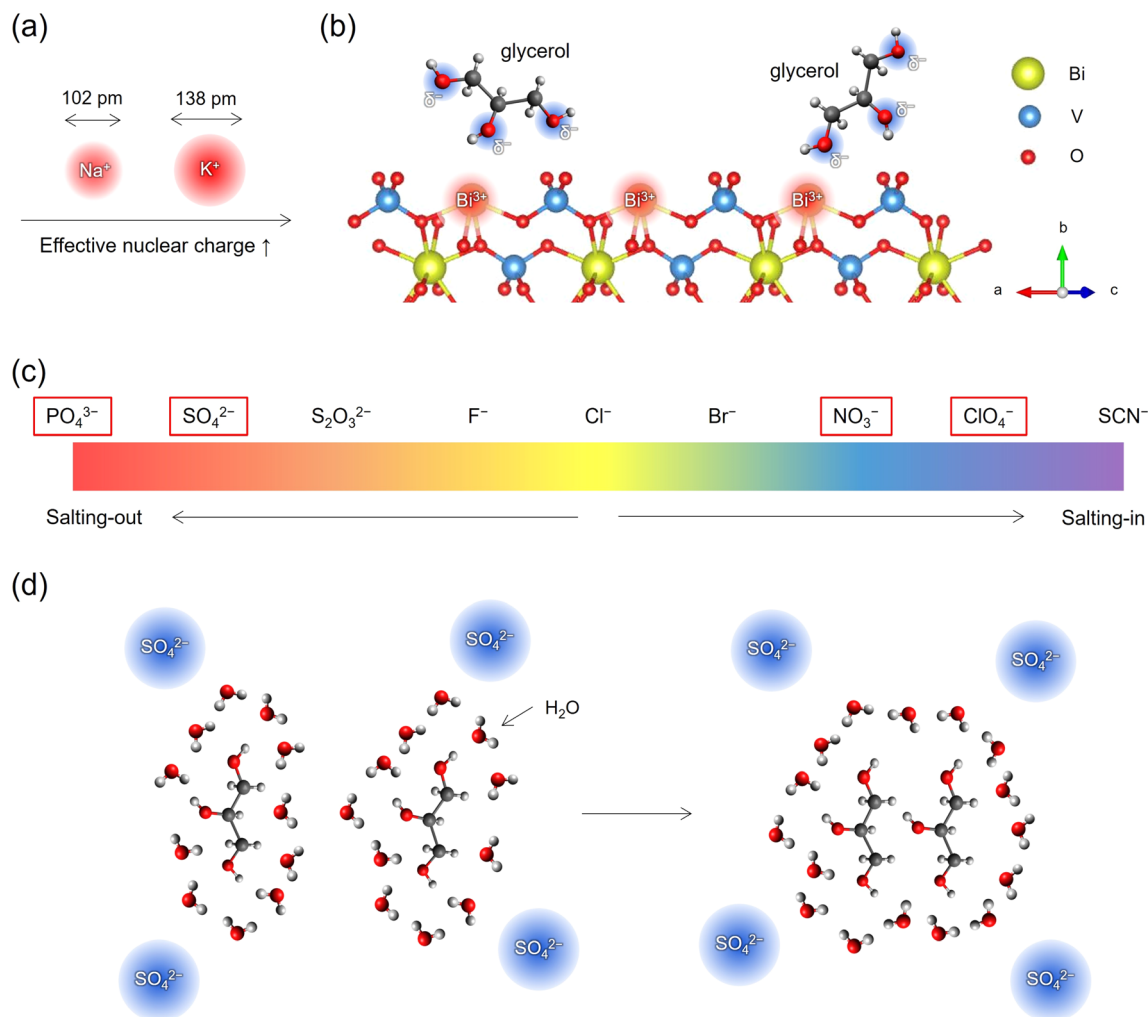


Fig. 5 Schematic illustrations of (a)  $\text{Na}^+$  and  $\text{K}^+$  ions with distinct effective ionic radii, leading to varying effective nuclear charges, and (b) the  $\text{BiVO}_4$  surface interaction with glycerol: hydroxyls of glycerol, carrying a partial negative charge ( $\delta^-$ ), are electrostatically drawn to the  $\text{Bi}^{3+}$  ions on the  $\text{BiVO}_4$  surface. (c) The Hofmeister series. (d) Schematic illustration of the aggregation of glycerol molecules induced by the presence of  $\text{SO}_4^{2-}$  anions.

series, indicating that these anions exhibit comparatively weak specific ion effects and limited salting-out effects. Anions with relatively small sizes and high charge densities, such as  $\text{SO}_4^{2-}$  and  $\text{PO}_4^{3-}$ , trigger the salting-out phenomenon in aqueous solutions by inducing electronic repulsion and enhancing the hydrophobic nature of the molecules involved.<sup>22</sup> The stronger hydrophobicity prompts the molecules to aggregate, thereby minimizing the entropic cost related to a highly ordered structure at the interface between the solute and water, as illustrated in Fig. 5d. This aggregation of glycerol molecules could reduce the probability of glycerol adsorbing onto  $\text{Bi}^{3+}$  sites, thereby hindering GOR on  $\text{BiVO}_4$ . It is noted that a similar anion effect following the trend of the Hofmeister series has also been recently discussed to explain different  $\text{H}_2$  microbubble coalescence efficiencies.<sup>23</sup>

In order to experimentally investigate the aforementioned molecular aggregation, we performed Raman scattering spectroscopy on electrolyte solutions containing 0.5 M glycerol (the detailed method is described in the ESI†). We focused on the

C–O stretching band, centered at around  $1050\text{ cm}^{-1}$ , as indicated by the grey area in the full range spectra reported in Fig. S19.†<sup>24</sup> The band was scanned between  $950\text{ cm}^{-1}$  and  $1200\text{ cm}^{-1}$  and fitted with multiple symmetric Voigt functions after subtracting a linear background. Fig. S20a and S20b† report the fitting results for the spectral references, namely 0.5 M glycerol in water and 0.5 M of aqueous  $\text{NaNO}_3$ . The latter was taken since a spectral overlap exists between the C–O and the N–O stretching bands. The line shape of the Voigt functions retrieved by fitting the spectral references was then kept constant during the fitting of the pristine electrolytes, with their spectral position and full-width at half-maximum (FWHM) allowed to adjust in a range of  $5\text{ cm}^{-1}$  with respect to their values in the spectral references during the fitting procedure. Fig. 6a and b show the fitting procedure obtained on the 0.5 M  $\text{Na}_2\text{SO}_4$  and  $\text{NaNO}_3$  solutions (pH 2) containing 0.5 M glycerol, respectively. Table 1 summarizes the Raman shift values of the C–O stretching band retrieved during the fitting procedure of the samples above and the corresponding difference with



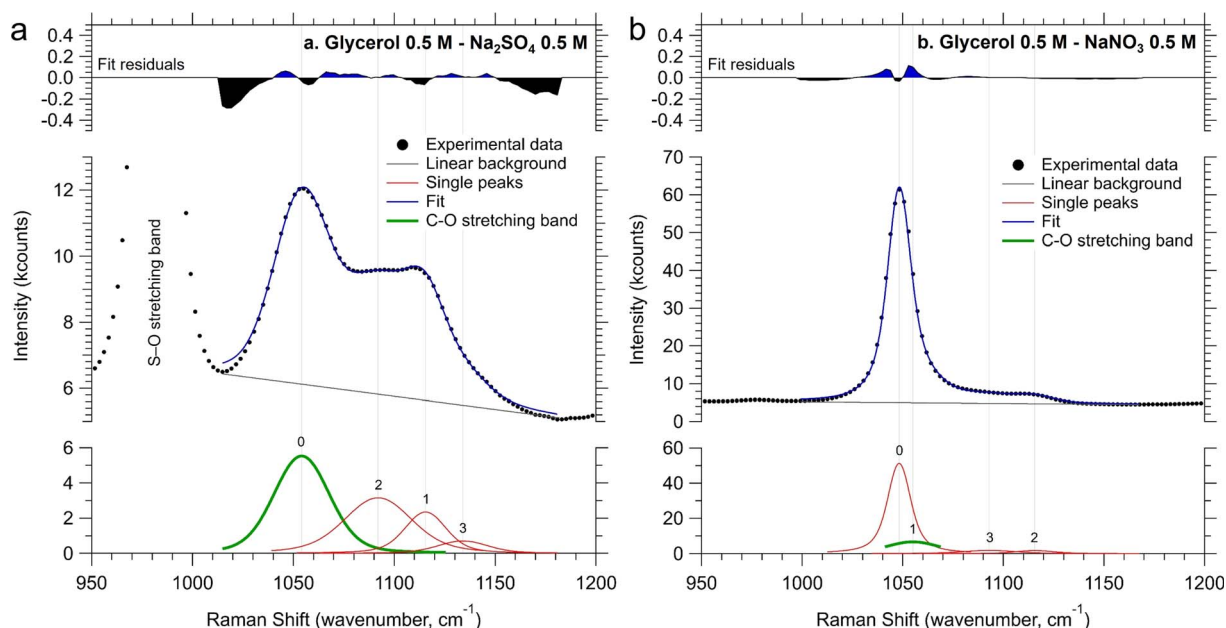


Fig. 6 C–O stretching band region for the two Na-based electrolytes at pH 2, (a)  $\text{Na}_2\text{SO}_4$  and (b)  $\text{NaNO}_3$ , both containing 0.5 M glycerol. The spectra were recorded at approximately 22 °C, using a 2 mL optical grade-quartz cuvette, at a laser wavelength of 785 nm, and a total spectral power of 450 mW.

**Table 1** Raman shift values of the C–O stretching band retrieved during the fitting procedure of the liquid samples, and the corresponding difference with respect to the glycerol in water without any supporting electrolyte

|                                                 | C–O stretching<br>Raman shift<br>( $\text{cm}^{-1}$ ) | C–O stretching<br>$\Delta$ Raman shift<br>( $\text{cm}^{-1}$ ) |
|-------------------------------------------------|-------------------------------------------------------|----------------------------------------------------------------|
| 0.5 M glycerol                                  | 1055.8                                                | —                                                              |
| 0.5 M glycerol + 0.5 M $\text{NaNO}_3$          | 1055.0                                                | 0.8                                                            |
| 0.5 M glycerol + 0.5 M $\text{Na}_2\text{SO}_4$ | 1054.1                                                | 1.7                                                            |

respect to the glycerol in water without any supporting electrolyte. It is evident that there is a red shift of the C–O stretching frequency, indicating that the reduced mass of the C–O stretching mode of glycerol increases upon the addition of salts. This phenomenon can be attributed to the formation of glycerol “aggregates” in the solution, driven by the coulombic interaction between the partial negative charge present on the oxygen of glycerol’s OH groups and the ions introduced into the solution. Notably, the observed downward shift of the C–O stretching frequency is more pronounced with  $\text{Na}_2\text{SO}_4$  than with  $\text{NaNO}_3$ . These observations support our hypothesis that sulfate groups prompt the formation of slightly more glycerol aggregates in the solution.<sup>25</sup>

We also note that the photocurrent trend may also be explained by the ability of the different electrolytes in suppressing (or allowing) pH changes. When glycerol undergoes oxidation at the anode, protons are generated. These protons subsequently migrate to the cathode and participate in the HER. Since acidic environment is preferred for the GOR,<sup>8</sup> the overall glycerol oxidation performance may be affected if

protons produced near the  $\text{BiVO}_4$ /electrolyte interface are removed from the reaction environment through buffering. In other words, differently from what has been previously observed for PEC water oxidation,<sup>26</sup> a lower buffering capacity within the electrolyte solution might correlate with an improved GOR performance. We therefore evaluated the buffering capacity of the solutions by introducing equimolar amounts of protons to the glycerol-containing solutions. For instance, 25 mmol of  $\text{H}_2\text{SO}_4$  was added to 1 L of a pH 2 solution of either  $\text{K}_2\text{SO}_4$  or  $\text{Na}_2\text{SO}_4$  containing 0.1 M glycerol, each with an electrolyte concentration of 0.5 M. Subsequently, the pH of the resulting mixtures was measured. In a separate instance, 50 mmol of  $\text{HNO}_3$  or  $\text{HClO}_4$  was added to 1 L of a pH 2  $\text{NaNO}_3$  or  $\text{NaClO}_4$  solution containing 0.1 M glycerol (electrolyte concentration = 0.5 M). The resultant changes in pH ( $\Delta\text{pH}$ ) induced by the addition of 50 mM protons are presented in Table 2. Interestingly, the  $\text{NaNO}_3$  and  $\text{NaClO}_4$  solutions exhibited considerably higher  $\Delta\text{pH}$  (indicative of the lowest buffering capacity) compared to the other three solutions, whereas the  $\text{KPi}$  solution demonstrated the lowest  $\Delta\text{pH}$  (indicative of the highest buffering capacity). The estimated buffering capacities were ranked as follows:  $\text{NaNO}_3 < \text{NaClO}_4 < \text{Na}_2\text{SO}_4 < \text{K}_2\text{SO}_4 < \text{KPi}$ . This trend agrees well with the photocurrent trend, except for the ranking between  $\text{NaClO}_4$  and  $\text{NaNO}_3$ , thus implying a potential impact of buffering action in the electrolyte on the GOR process.

Despite the evidence provided above, the speculative nature of these explanations is acknowledged. Further experiments beyond the scope of this study would be needed to fully reveal the mechanism behind the clearly observed performance trend. Another factor that needs to be considered is the effect of anions on the reorganization energy of glycerol in the electrolyte. As outlined in the Marcus-Gerischer theory,<sup>27</sup> the charge



**Table 2** The impact of adding 50 mM protons to the pH of the various acidic electrolytes used in this study. All electrolytes had a concentration of 0.5 M and contained 0.1 M glycerol. The displayed values represent the averages ( $\pm$  standard deviation) obtained from three distinct measurements. The raw data can be found in the ESI (Table S3–S7)

|             | KP <sub>i</sub> | K <sub>2</sub> SO <sub>4</sub> | Na <sub>2</sub> SO <sub>4</sub> | NaClO <sub>4</sub> | NaNO <sub>3</sub> |
|-------------|-----------------|--------------------------------|---------------------------------|--------------------|-------------------|
| Initial pH  | 2.00 $\pm$ 0.01 | 1.99 $\pm$ 0.01                | 1.98 $\pm$ 0.01                 | 2.00 $\pm$ 0.01    | 1.99 $\pm$ 0.02   |
| Final pH    | 1.93 $\pm$ 0.01 | 1.80 $\pm$ 0.01                | 1.72 $\pm$ 0.02                 | 1.38 $\pm$ 0.03    | 1.19 $\pm$ 0.07   |
| $\Delta$ pH | 0.07 $\pm$ 0.01 | 0.19 $\pm$ 0.01                | 0.27 $\pm$ 0.01                 | 0.62 $\pm$ 0.05    | 0.80 $\pm$ 0.09   |

transfer rate at a semiconductor/liquid interface depends on the alignment between the energy levels in the semiconductor (*i.e.*, conduction and valence bands) and the donor/acceptor states of the redox species in the electrolyte (in our case, glycerol). Any change in the reorganization energy, possibly induced by the presence of different anions, would change the energy gap between the donor/acceptor states of the solute. Hence, this would change the relative energy alignment at the interface and consequently modify the electron transfer kinetics. The reorganization energy of glycerol in these acidic electrolytes, which is to the best of our knowledge not yet available, needs therefore to be evaluated.

## Conclusion

In summary, the influence of various acidic electrolytes (KP<sub>i</sub>, K<sub>2</sub>SO<sub>4</sub>, Na<sub>2</sub>SO<sub>4</sub>, NaClO<sub>4</sub>, and NaNO<sub>3</sub>; pH = 2) on the PEC glycerol oxidation over BiVO<sub>4</sub> was systematically investigated. Interestingly, we observed that BiVO<sub>4</sub> exhibited the following GOR performance trend: NaClO<sub>4</sub>, NaNO<sub>3</sub> > Na<sub>2</sub>SO<sub>4</sub> > K<sub>2</sub>SO<sub>4</sub> > KP<sub>i</sub>, with the photocurrent in NaClO<sub>4</sub>  $\sim$ 3-fold of that in KP<sub>i</sub>. Although our BiVO<sub>4</sub> photoanodes exhibited the highest photocurrent in NaClO<sub>4</sub>, the low production rate of GOR products, due to the poor stability of BiVO<sub>4</sub> in this electrolyte solution, made it less promising than NaNO<sub>3</sub>. NaNO<sub>3</sub> emerged as the preferred electrolyte for PEC glycerol oxidation on BiVO<sub>4</sub>, offering superior performance in terms of photocurrent, stability, and selectivity towards value-added GOR products. Glycolaldehyde (GCAD) was identified as the most dominant GOR product in our study, achieving a selectivity higher than 50% in NaNO<sub>3</sub>. We attributed the observed GOR performance trend among the employed electrolytes to the various effects induced by both cations and anions on the GOR performance of BiVO<sub>4</sub>. First, the larger effective nuclear charge of K<sup>+</sup> vs. Na<sup>+</sup> may result in reduced electrostatic adsorption of glycerol onto the BiVO<sub>4</sub> surface, consistent with the lower performance in K<sup>+</sup>-containing electrolytes. In addition, the specific ion effects were considered as they may impact the aggregation of glycerol in the electrolyte. Our Raman spectroscopy results suggest more extensive glycerol aggregation in the presence of SO<sub>4</sub><sup>2-</sup> compared to NO<sub>3</sub><sup>-</sup>, consistent with the weaker salting-out effect of NO<sub>3</sub><sup>-</sup> ions indicated by the Hofmeister series. Finally, we found an inverse relationship between the buffering capacity of the electrolyte and the GOR performance of BiVO<sub>4</sub>. The underlying mechanism is likely a combination of the factors above, and future studies should be directed towards understanding this complex process through *e.g.*, *operando* investigation of the

BiVO<sub>4</sub>/liquid electrolyte interface during PEC GOR and an assessment of the reorganization energy of glycerol in diverse electrolytes. The general applicability of our results to other anode materials and/or whether the reaction is EC- or PEC-driven was suggested as dark EC measurements with polycrystalline Pt anodes also showed a similar GOR current density trend. Overall, our findings suggest the critical role of electrolyte selection in optimizing EC/PEC glycerol oxidation, with potential implications for other (photo)electrocatalytic reactions.

## Data availability

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

## Author contributions

H. K.: investigation (sample preparation, EC, PEC, XRD, XPS, UV-vis, HPLC, solution conductivity measurements, buffering capacity measurements), data curation, visualisation, conceptualisation, writing – original draft; S. G.: investigation (HPLC), writing – review & editing; A. F. P.-T.: investigation (HPLC), writing – review & editing; C. H.: investigation (XPS), writing – review & editing; P. B.: investigation (MS), data curation, visualisation, writing – review & editing; M. T. M.: resources, writing – review & editing; R. v. d. K.: supervision, writing – review & editing; M. F.: supervision, investigation (Raman spectroscopy), data curation, visualisation, conceptualisation, writing – review & editing; F. F. A.: supervision, funding acquisition, conceptualisation, writing – review & editing.

## Conflicts of interest

There are no conflicts to declare.

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