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Electrolyte selection toward efficient photoelectrochemical glycerol oxidation on BiVO_4 [†]

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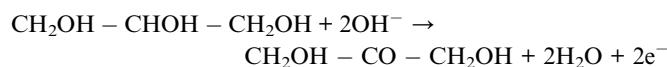
Glycerol, a primary by-product of biodiesel production, can be oxidized into various value-added chemicals, significantly enhancing the techno-economic value of photoelectrochemical (PEC) cells. Several studies have explored various photoelectrode materials and co-catalysts, but the influence of electrolytes on PEC glycerol oxidation has remained relatively unexplored despite its significance. Here, we explore the impact of various acidic (pH = 2) electrolytes, namely NaNO_3 , NaClO_4 , Na_2SO_4 , K_2SO_4 , and KP_i , on PEC glycerol oxidation using nanoporous thin film BiVO_4 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_4 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_3 is identified as the optimal electrolyte for PEC glycerol oxidation with BiVO_4 when considering various factors such as stability and production rates for glycerol oxidation reaction (GOR) products, surpassing the previously favored Na_2SO_4 . Glycolaldehyde emerges as the most dominant product with ~50% selectivity in NaNO_3 . 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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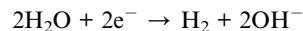
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Introduction

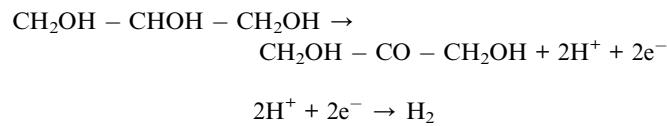
Glycerol, a major by-product of biodiesel production, holds significant potential as a feedstock to produce value-added chemicals.¹ A broad palette of high-value products from the glycerol oxidation reaction (GOR), including dihydroxyacetone (DHA), formic acid (FA), glyceraldehyde (GLAD), and glycolaldehyde (GCAD), can be obtained in one or more reaction steps.² 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



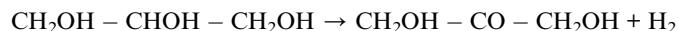
and the corresponding reduction reaction as



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 € kg⁻¹, depending on the degree of purity.³ 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 2020.⁴ 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.⁵ For example, Ding *et al.* showed that the choice of cations in alkaline electrolytes affects the water oxidation performance of TiO₂ photoanodes. This was attributed to different back-reaction rates (*i.e.*, oxygen reduction reaction) induced by the various cations.⁶ Similarly, the choice of anions has been shown to influence the performance of WO₃ photoanodes, as these anions can be parasitically oxidized alongside water at the electrode surface.^{5a,7} 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 BiVO₄ photoanodes exhibited the highest efficiency in acidic solutions (pH = 2) based on sodium sulfate (Na₂SO₄),⁸ subsequent studies mainly used Na₂SO₄-based electrolytes and predominantly focused on modifying the photoanode material and/or the deposited co-catalyst to optimize the performance.⁹ 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 (BiVO₄). We investigate acidic electrolytes (pH = 2) with different cations and anions: sodium nitrate (NaNO₃), sodium perchlorate

(NaClO₄), sodium sulfate (Na₂SO₄), potassium sulfate (K₂SO₄), and potassium phosphate (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, BiVO₄ photoanodes exhibit the highest glycerol oxidation performance in NaNO₃, surpassing the commonly employed Na₂SO₄. To the best of our knowledge, NaNO₃ 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 BiVO₄ 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 NaNO₃ as a favorable electrolyte for glycerol oxidation.

Results and discussion

BiVO₄ photoanodes were prepared using a previously reported electrodeposition method,¹⁰ 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 BiVO₄.¹¹

We first compare the PEC performance of BiVO₄ 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 mW cm⁻²) in KP_i, K₂SO₄, Na₂SO₄, NaClO₄, and NaNO₃ (see Fig. S3a† for the corresponding dark LSV curves). The concentration of all

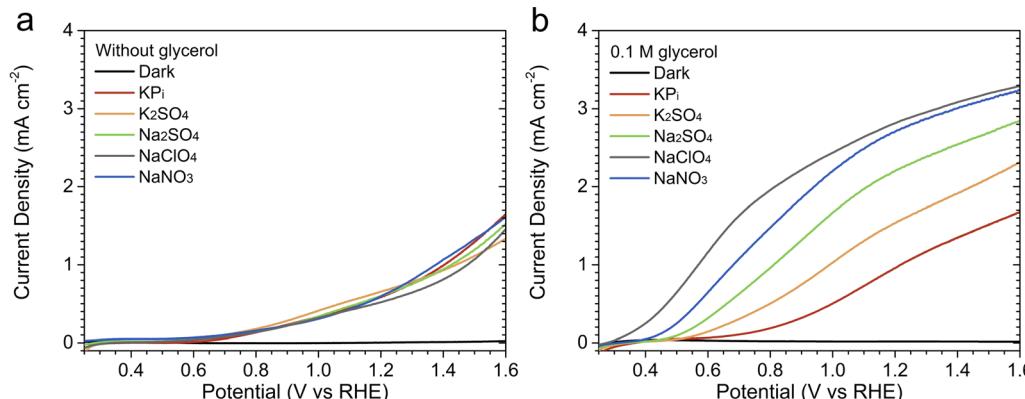


Fig. 1 Linear sweep voltammetry (LSV) curves recorded in different acidic solutions (pH = 2), all having a concentration of 0.5 M: (a) in the absence of glycerol and (b) with 0.1 M glycerol. Measurements were performed at a scan rate of 20 mV s⁻¹, sweeping from negative to positive potentials relative to the reversible hydrogen electrode (RHE), under AM 1.5G simulated sunlight illumination. LSV curves recorded in NaNO₃ 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 NaNO_3 , the pH was lowered using HNO_3 , whereas H_2SO_4 was used for K_2SO_4). Our electrodeposited BiVO_4 photoanodes showed similar photocurrent ($0.5\text{--}0.7 \text{ mA cm}^{-2}$) at $1.23 \text{ V}_{\text{RHE}}$ 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 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 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 KP_i solution, followed by the K_2SO_4 , Na_2SO_4 , NaNO_3 , and NaClO_4 solutions. The photocurrent improvement was rather significant, with 180% increase by changing the electrolyte from KP_i to NaClO_4 ($1.07 \pm 0.08 \text{ vs. } 2.97 \pm 0.11 \text{ mA cm}^{-2}$ 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 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 KP_i solution and the highest in the NaClO_4 solution. However, the photocurrents in the NaNO_3 and 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 NaNO_3 and NaClO_4 solutions, the photocurrent already reached 1.0 mA cm^{-2} at approximately $0.5 \text{ V}_{\text{RHE}}$, whereas in the 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 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 K_2SO_4 , Na_2SO_4 , NaClO_4 , and NaNO_3 . The corresponding LSV curves obtained before and after the CA are shown in Fig. 2b–f. After the CA measurement in KP_i , no photoactivity remained (see Fig. 2b), consistent with the complete photocurrent loss during the CA experiment. The samples tested in K_2SO_4 and NaClO_4 also showed a consistent photocurrent decrease after the CA (see Fig. 2c and e). Interestingly, the samples tested in Na_2SO_4 and 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 BiVO_4 to be unstable even in the 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 KP_i , the exposed area became white and transparent. This is not the case for samples tested in K_2SO_4 , Na_2SO_4 , NaClO_4 , and 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 NaNO_3 closely matched that of the pristine sample across the entire wavelength range. The samples tested in K_2SO_4 , Na_2SO_4 , and NaClO_4 exhibited a notable increase in transmittance, albeit with varying amount, suggesting the possible loss of BiVO_4 material due to photocorrosion and consequent dissolution. The sample tested in 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 BiVO_4 samples before and after the 12 hours CA measurements. Fig. 2h displays the X-ray diffractogram for the sample tested in KP_i . Diffraction peaks corresponding to BiPO_4 (as well as the FTO substrate) were detected, while peaks characteristic of monoclinic BiVO_4 were absent. This suggests that during the CA measurement, vanadium atoms in BiVO_4 leached into the electrolyte and were substituted by phosphorus atoms from the KP_i solution, leading to a crystal structure transformation and eventually a complete conversion to BiPO_4 . Indeed, BiPO_4 has a wide bandgap ($\sim 3.85 \text{ eV}$),¹² which explains the white and transparent appearance of the film after CA. Such a conversion could also account for the low photocurrent observed with KP_i (Fig. 1b). Note that the formation of a BiPO_4 thin film on the surface of BiVO_4 upon exposure to KP_i buffer solution at pH 7 has been previously reported.¹³ A full conversion to BiPO_4 has not been reported, which we attribute to the use of lower pH.

Fig. 2i shows the X-ray diffractograms of the BiVO_4 samples measured after the 12 hours CA measurements in K_2SO_4 , Na_2SO_4 , NaClO_4 , and NaNO_3 . Unlike the sample measured in KP_i , diffraction peaks characteristic of monoclinic BiVO_4 can be detected in these samples. For samples measured in K_2SO_4 , Na_2SO_4 , and NaClO_4 , the intensities of the (121) diffraction peak, which is the most prominent reflection for electrodeposited monoclinic BiVO_4 ,¹⁰ decreased, while the intensities of the FTO peak at $2\theta = 37.6^\circ$ increased. In the case of the sample measured in 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 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 NaClO_4 , Na_2SO_4 , and K_2SO_4 were considerably lower; 2.8 for NaClO_4 , 1.8 for Na_2SO_4 , and 1.4 for K_2SO_4 , respectively.



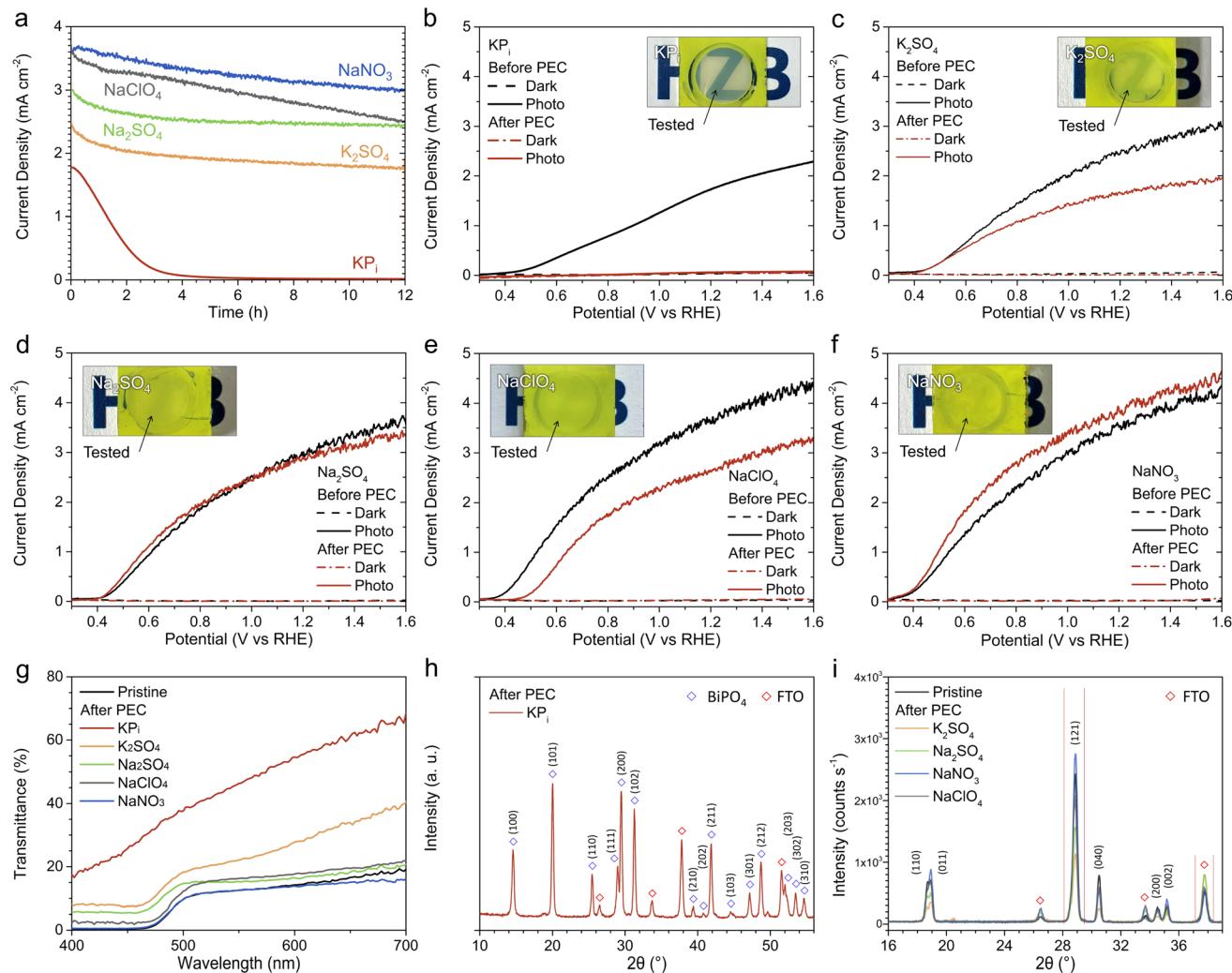


Fig. 2 (a) Chronoamperometry (CA) curves measured at $1.23\text{ V}_{\text{RHE}}$ under AM 1.5G illumination in different acidic electrolyte solutions ($\text{pH} = 2$) containing 0.5 M glycerol. Linear sweep voltammetry (LSV) curves measured under AM 1.5G illumination before (black curves) and after (red curves) the 12 hours CA measurements in (b) KP_i , (c) K_2SO_4 , (d) Na_2SO_4 , (e) NaClO_4 , and (f) 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 BiVO_4 and BiVO_4 samples following the 12 hours CA measurements shown in (a). X-ray diffractogram of the BiVO_4 samples after the CA tests (h) in KP_i solution and (i) in K_2SO_4 , Na_2SO_4 , NaClO_4 , and NaNO_3 solutions.

The XRD and UV-vis transmittance results above indicate that BiVO_4 substantially degraded during GOR in acidic NaClO_4 , Na_2SO_4 and K_2SO_4 , likely due to photocorrosion, but not in NaNO_3 . These findings are interesting because, according to the Pourbaix diagram,¹⁴ BiVO_4 is expected to decompose into BiO^+ and VO_4^{3-} at pH 2 and $1.23\text{ V}_{\text{RHE}}$. This suggests that NO_3^- (either by itself or in conjunction with glycerol) plays a role in stabilizing 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 K_2SO_4 , Na_2SO_4 , NaClO_4 , and NaNO_3 electrolytes were investigated using X-ray photoelectron spectroscopy (XPS). The sample subjected to the same treatment in KP_i was not tested since XRD already showed a clear transformation to BiPO_4 . The Bi 4f core-level spectra are displayed in Fig. S8,† and the O 1s and V 2p core-level spectra are presented in Fig. S9.† While the binding

energy difference (ΔBE) between the Bi $4f_{5/2}$ and $4f_{7/2}$ 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 NaNO_3 solution and increased to 0.2 eV in the K_2SO_4 , Na_2SO_4 , and NaClO_4 solutions. A notable difference among the samples was observed in the O 1s core-level spectra. The samples tested in the K_2SO_4 , Na_2SO_4 , and 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),¹⁵ likely due to glycerol adsorption during GOR. Their significant emergence may imply a somewhat reduced surface chemical stability of BiVO_4 during PEC oxidation of glycerol in the K_2SO_4 , Na_2SO_4 , and NaClO_4 solutions at pH 2. Indeed, if the O^{2-} ions in BiVO_4 were substituted by hydroxyl (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 NaNO_3 solution exhibited only a slight increase in signal intensity near 532 eV, indicating the relatively superior chemical stability of BiVO_4 in pH 2 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). KP_i was excluded from our analysis due to the severe instability of BiVO_4 during the GOR in the pH 2 KP_i solution (*vide supra*). Fig. 3a displays the selectivity of BiVO_4 towards various GOR products and the total faradaic efficiency, calculated in terms of charges used for GOR, in K_2SO_4 , Na_2SO_4 , NaClO_4 , and 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 (CH_2O_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.¹⁶ However, the selectivity varied depending on the electrolyte. In K_2SO_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 Na_2SO_4 , NaClO_4 , and 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 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,¹⁶ might differ among various electrolyte solutions, consequently influencing the overall GOR performance. One possible explanation is that

GLAD adsorbs more favorably onto the BiVO_4 surface in the 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 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 BiVO_4 without any co-catalysts.

The total faradaic efficiency was highest in the 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 NaNO_3 solution indicate that no O_2 was generated above our detection limit. This suggests that the OER was effectively suppressed in the NaNO_3 solution, likely owing to the relatively low energy requirement of the GOR. A slight increase in the mass signal corresponding to CO_2 was observed, suggesting the potential for complete oxidation of glycerol to CO_2 . We tentatively attribute the remaining photo-generated holes (~18%) to the generation of other glycerol oxidation products including CO_2 (undetected with HPLC and MS) or to photocorrosion. The lower faradaic efficiencies observed in Na_2SO_4 (74%), NaClO_4 (71%), and K_2SO_4 (72%) support the hypothesis of partial hole consumption due to photocorrosion, especially given the poorer photo-stability of BiVO_4 in these solutions. We also confirm that nitrate reduction reaction (NRR), which could potentially occur at the counter electrode when 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, NaNO_3 was identified as the most suitable electrolyte for PEC glycerol oxidation using BiVO_4 . To elucidate how the choice of electrolyte influences the GOR performance of BiVO_4 , it is first necessary to examine the electrical conductivities of the electrolyte solutions. The electrical conductivities of

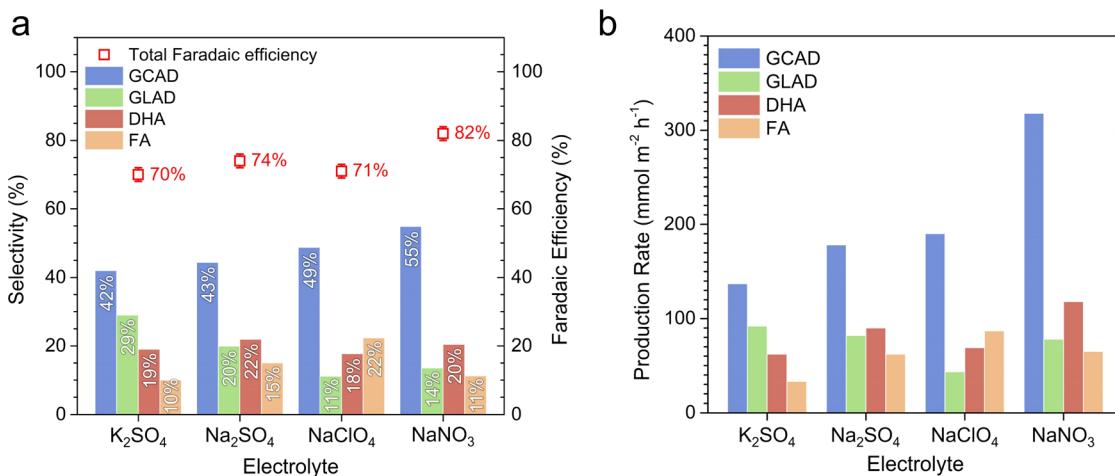


Fig. 3 Product analysis using high-performance liquid chromatography (HPLC). (a) Selectivity and (b) production rate towards glycerol oxidation reaction (GOR) products in various acidic electrolytes (pH = 2). Total faradaic efficiency, calculated in terms of charges used for GOR, is presented on the 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 $1.23 \text{ V}_{\text{RHE}}$, corresponding to the measurements shown in Fig. 2a. GCAD: glycolaldehyde, GLAD: glyceraldehyde, DHA: dihydroxyacetone, FA: formic acid.



0.5 M NaNO_3 , NaClO_4 , Na_2SO_4 , K_2SO_4 , and KP_i solutions (all at pH 2) were measured as 75.5 mS cm^{-1} , 98.2 mS cm^{-1} , 102.6 mS cm^{-1} , 141.2 mS cm^{-1} , and 100.0 mS cm^{-1} , respectively, which do not correlate with the trends observed in GOR performance. Moreover, if the differing GOR performance observed in BiVO_4 was due to differences in electrical conductivity among the electrolytes, then the water-splitting performance of BiVO_4 should have varied accordingly.

Moreover, to determine whether the GOR performance trend in different acidic electrolytes is specific to 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 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.¹⁷ The Pt anode exhibited similar LSV curves across all electrolytes. For example, the onset potential for OER was observed at approximately $1.6 \text{ V}_{\text{RHE}}$, and an overpotential of $\sim 0.8 \text{ V}$ was required to achieve 10 mA cm^{-2} (at $\sim 2.0 \text{ V}_{\text{RHE}}$) in all solutions. Fig. 4b presents the LSV curves of the Pt anode measured in the presence of 0.1 M glycerol. The current density for the Pt anode began to increase earlier than in its absence, similar to the case with BiVO_4 , reflecting the lower energy requirement of GOR compared to OER. Interestingly, the Pt anode exhibited the same GOR performance trend as BiVO_4 in terms of current density. At $1.4 \text{ V}_{\text{RHE}}$, a potential more negative than the onset for OER, the current densities at $1.4 \text{ V}_{\text{RHE}}$ ranked as follows: $\text{NaNO}_3 > \text{Na}_2\text{SO}_4 > \text{K}_2\text{SO}_4 > \text{KP}_i$ (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 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 BiVO_4 : $\text{NaClO}_4 > \text{NaNO}_3 > \text{Na}_2\text{SO}_4 > \text{K}_2\text{SO}_4 > \text{KP}_i$)

suggests that the presence of specific ions in the electrolyte is beneficial/detrimental to the PEC glycerol oxidation performance. First, the trend indicates that Na^+ is more favorable than K^+ for GOR on BiVO_4 . We attribute this observation to the prominent difference between the cation size. As illustrated in Fig. 5a, K^+ has an approximately 30% larger effective ionic radius of 138 pm compared to Na^+ (102 pm),¹⁸ resulting in a larger effective nuclear charge than Na^+ .¹⁹ According to density functional theory (DFT) calculations performed by Liu *et al.*, the hydroxyl groups of glycerol spontaneously adsorb at the exposed Bi^{3+} sites of BiVO_4 through electrostatic interactions between Bi^{3+} and oxygen in the hydroxyl groups, as depicted in Fig. 5b.⁸ 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 Na_2SO_4 solutions (pH 2) were found in the form of $\text{C}_3\text{H}_8\text{O}_3\text{Na}$ (glycerol = $\text{C}_3\text{H}_8\text{O}_3$).⁸ This observation indicates a strong interaction between the hydroxyl groups of glycerol, with their negative partial charge δ^- , and the cations in the electrolytes. Given that 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),²⁰ the glycerol hydroxyl groups are expected to interact more strongly with K^+ than with 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 Bi^{3+} sites. As a result, GOR at BiVO_4 in K^+ -containing electrolytes would be hindered.

In addition, the superior performance of BiVO_4 in NaNO_3 and NaClO_4 than in Na_2SO_4 may be explained considering the different types of anions, NO_3^- , ClO_4^- , and SO_4^{2-} . The Pt anode also exhibited a higher GOR current in NaNO_3 than in Na_2SO_4 . Interestingly, we note that SO_4^{2-} stands out as one of the anions exhibiting potent specific ion effects, positioned towards the left end of the Hofmeister series,²¹ as shown in Fig. 5c. This indicates a strong salting-out effect of SO_4^{2-} . In contrast, NO_3^- and ClO_4^- are positioned closer to the right end of the Hofmeister

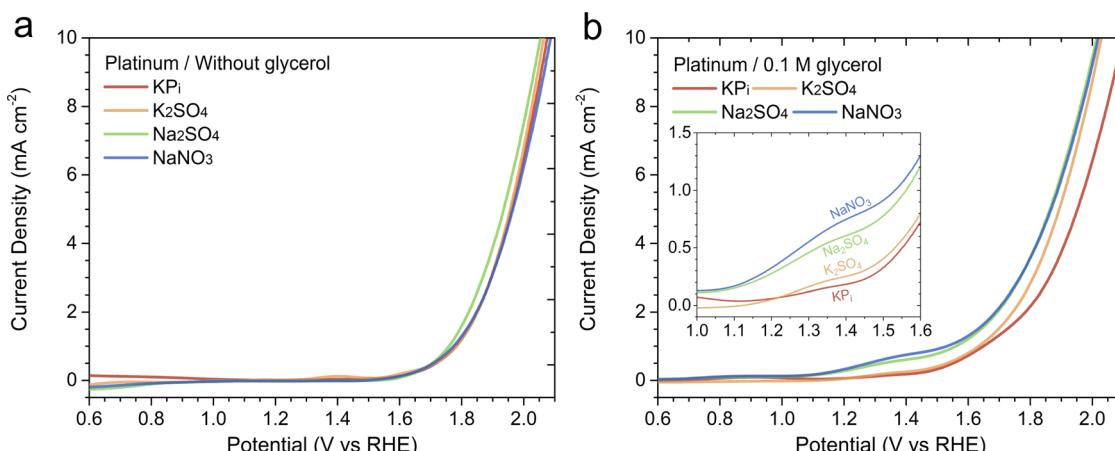


Fig. 4 Linear sweep voltammetry (LSV) curves of a polycrystalline platinum (Pt) anode measured (a) without glycerol and (b) in the presence of 0.1 M glycerol in various acidic electrolytes at pH 2, with an electrolyte concentration of 0.5 M. Measurements were performed at a scan rate of 20 mV s^{-1}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



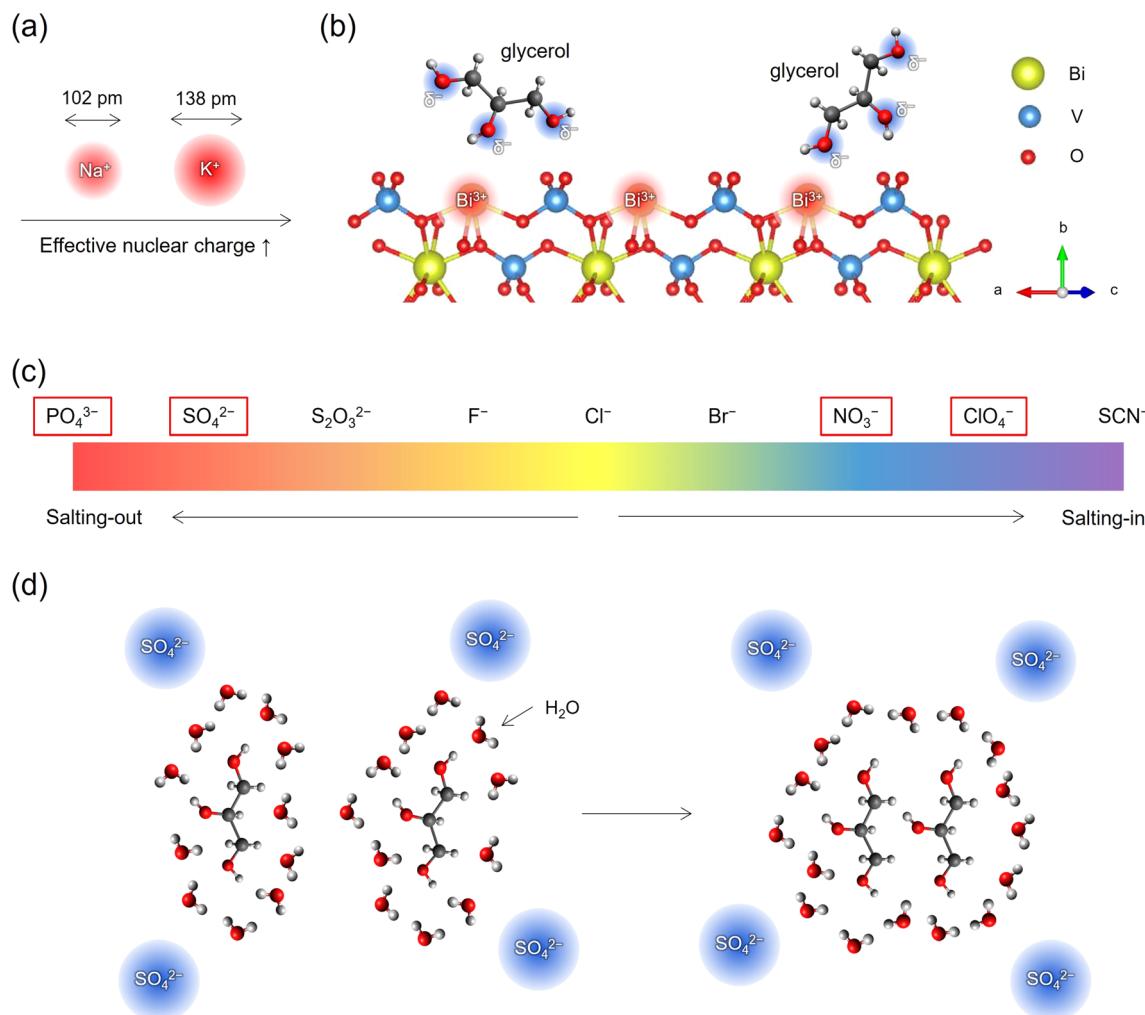


Fig. 5 Schematic illustrations of (a) Na^+ and K^+ ions with distinct effective ionic radii, leading to varying effective nuclear charges, and (b) the $BiVO_4$ surface interaction with glycerol: hydroxyls of glycerol, carrying a partial negative charge (δ^-), are electrostatically drawn to the Bi^{3+} ions on the $BiVO_4$ surface. (c) The Hofmeister series. (d) Schematic illustration of the aggregation of glycerol molecules induced by the presence of 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 SO_4^{2-} and PO_4^{3-} , trigger the salting-out phenomenon in aqueous solutions by inducing electronic repulsion and enhancing the hydrophobic nature of the molecules involved.²² 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 Bi^{3+} sites, thereby hindering GOR on $BiVO_4$. It is noted that a similar anion effect following the trend of the Hofmeister series has also been recently discussed to explain different H_2 microbubble coalescence efficiencies.²³

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 cm^{-1} , as indicated by the grey area in the full range spectra reported in Fig. S19.†²⁴ The band was scanned between 950 cm^{-1} and 1200 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 $NaNO_3$. 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 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 Na_2SO_4 and $NaNO_3$ 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

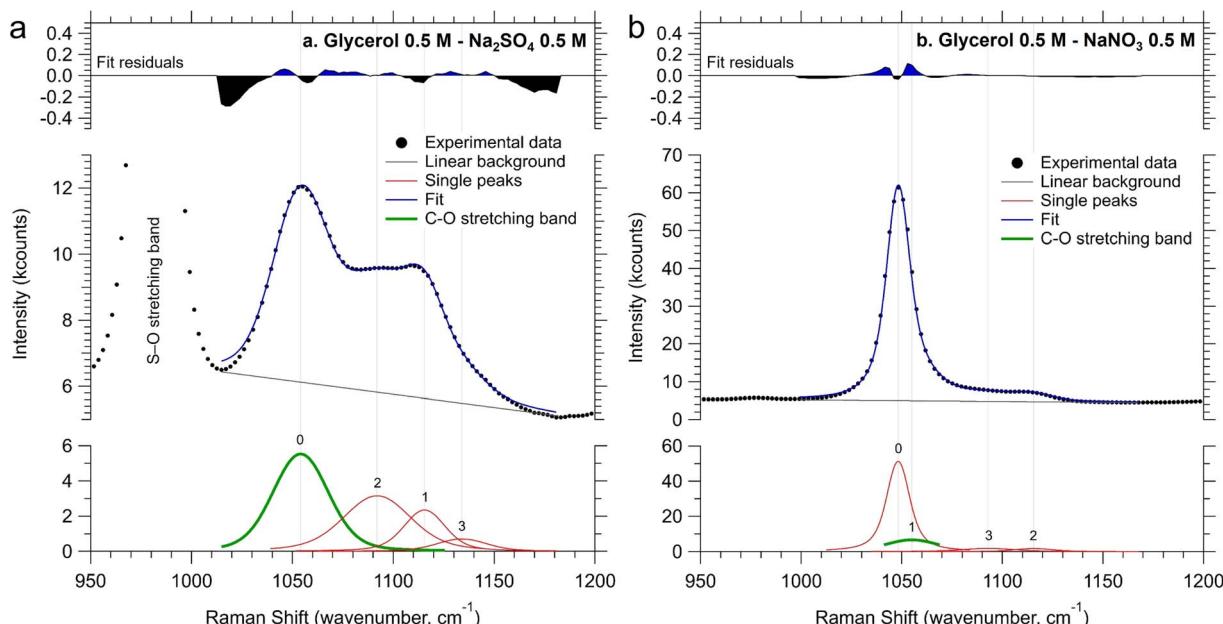


Fig. 6 C–O stretching band region for the two Na-based electrolytes at pH 2, (a) Na_2SO_4 and (b) NaNO_3 , both containing 0.5 M glycerol. The spectra were recorded at approximately 22 °C, using a 2 mL optical grade-quartz cuvette, at a laser wavelength of 785 nm, and a total spectral power of 450 mW.

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 Raman shift (cm^{-1})	C–O stretching $\Delta\text{Raman shift}$ (cm^{-1})
0.5 M glycerol	1055.8	—
0.5 M glycerol + 0.5 M NaNO_3	1055.0	0.8
0.5 M glycerol + 0.5 M Na_2SO_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 Na_2SO_4 than with NaNO_3 . These observations support our hypothesis that sulfate groups prompt the formation of slightly more glycerol aggregates in the solution.²⁵

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,⁸ the overall glycerol oxidation performance may be affected if

protons produced near the 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,²⁶ 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 H_2SO_4 was added to 1 L of a pH 2 solution of either K_2SO_4 or Na_2SO_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 HNO_3 or HClO_4 was added to 1 L of a pH 2 NaNO_3 or NaClO_4 solution containing 0.1 M glycerol (electrolyte concentration = 0.5 M). The resultant changes in pH (ΔpH) induced by the addition of 50 mM protons are presented in Table 2. Interestingly, the NaNO_3 and NaClO_4 solutions exhibited considerably higher ΔpH (indicative of the lowest buffering capacity) compared to the other three solutions, whereas the K_2SO_4 solution demonstrated the lowest ΔpH (indicative of the highest buffering capacity). The estimated buffering capacities were ranked as follows: $\text{NaNO}_3 < \text{NaClO}_4 < \text{Na}_2\text{SO}_4 < \text{K}_2\text{SO}_4 < \text{KP}_i$. This trend agrees well with the photocurrent trend, except for the ranking between NaClO_4 and 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,²⁷ 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 _i	K ₂ SO ₄	Na ₂ SO ₄	NaClO ₄	NaNO ₃
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
Δ 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_i, K₂SO₄, Na₂SO₄, NaClO₄, and NaNO₃; pH = 2) on the PEC glycerol oxidation over BiVO₄ was systematically investigated. Interestingly, we observed that BiVO₄ exhibited the following GOR performance trend: NaClO₄, NaNO₃ > Na₂SO₄ > K₂SO₄ > KP_i, with the photocurrent in NaClO₄ \sim 3-fold of that in KP_i. Although our BiVO₄ photoanodes exhibited the highest photocurrent in NaClO₄, the low production rate of GOR products, due to the poor stability of BiVO₄ in this electrolyte solution, made it less promising than NaNO₃. NaNO₃ emerged as the preferred electrolyte for PEC glycerol oxidation on BiVO₄, 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 NaNO₃. 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 BiVO₄. First, the larger effective nuclear charge of K⁺ *vs.* Na⁺ may result in reduced electrostatic adsorption of glycerol onto the BiVO₄ surface, consistent with the lower performance in K⁺-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 SO₄²⁻ compared to NO₃⁻, consistent with the weaker salting-out effect of NO₃⁻ ions indicated by the Hofmeister series. Finally, we found an inverse relationship between the buffering capacity of the electrolyte and the GOR performance of BiVO₄. 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

BiVO₄/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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