










Stripped and enriched: the role of ram–pressure in shaping chemical enrichment of galaxies at intermediate redshift

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ABSTRACT

The chemical evolution of galaxies is shaped by their star formation histories and the exchange of gas with their environments. Metallicity provides key insights into these processes, reflecting the interplay between star formation and gas flows. A fundamental aspect of this evolution is the mass–metallicity relation, which captures the strong correlation between a galaxy stellar mass (M_*) and its gas-phase oxygen abundance. In this study, we use MUSE observations to analyse star-forming disc galaxies in 12 clusters within the redshift range $0.3 < z < 0.5$. Galaxies were classified into three groups: ram-pressure stripping (RPS), control cluster, and control field. For the first time, we investigate the impact of RPS on gas-phase metallicities across a wide mass range of galaxies at intermediate redshift, comparing RPS galaxies to counterparts in both cluster and field environments. By analysing the integrated flux within galactic discs, our result reveals that, on average, RPS induces a metallicity enhancement of 0.2 dex over non-stripped galaxies. Contrary to the prevailing view that cluster membership alone drives metallicity enrichment, we find that control cluster galaxies exhibit metallicities comparable to field galaxies at a given M_* , with only RPS galaxies displaying significantly higher metal content, highlighting the unique role of RPS in shaping the chemical properties of galaxies. These differences become more pronounced at lower M_* , indicating that environmental influences play a more critical role in shaping the chemical evolution of lower-mass galaxies. Our findings suggest that both enhanced star formation rates and suppressed gas inflows – consequences of ram pressure stripping – drive the elevated metallicity observed in RPS galaxies.

Key words: ISM: abundances – galaxies: clusters: intracluster medium – galaxies: evolution – galaxies: ISM.

1 INTRODUCTION

The chemical evolution of a galaxy is closely tied to its star formation history (SFH) and the exchange of gas with its surroundings through inflows and outflows (e.g. Mannucci et al. 2010; Petropoulou, Vílchez & Iglesias-Páramo 2012; Maiolino & Mannucci 2019; Peluso et al. 2023; Amiri et al. 2024; Vulcani et al. 2024). In this context, the metallicity of a galaxy serves as an observable indicator, offering insights into how environmental factors influence its SFH and gas content. Much focus has been placed on the mass–metallicity relation (MZR), which highlights the strong correlation between a galaxy’s stellar mass and gas-phase oxygen abundance. This relationship has been explored through studies of star-forming galaxies, spanning redshifts 0 to ~ 10 (e.g. Tremonti et al. 2004; Kewley & Ellison 2008; Maiolino et al. 2008; Zahid et al. 2014;

Sanders et al. 2015; Jones et al. 2020; Nakajima et al. 2023). The shape of the MZR could be influenced by various processes, including variations in the initial mass function (IMF), stellar and active galactic nucleus (AGN) feedback, and the infall of pristine gas (e.g. Maiolino & Mannucci 2019). The interplay of these factors can shape the MZR and its scatter while providing valuable insights into how environmental conditions impact galaxy properties.

Several potential mechanisms have been suggested for changes in galaxy properties as they migrate from lower density areas towards the core of galaxy clusters, including intracluster medium (ICM) and interstellar medium (ISM) interactions, the cluster gravitational potential, and minor to major galaxy merging (e.g. Treu et al. 2003; Boselli & Gavazzi 2006; Poggianti et al. 2006; Thomas et al. 2010; Marasco et al. 2023). Many previous studies at different redshifts have demonstrated that, for a given mass range, galaxies within clusters exhibit similar or marginally higher metallicities compared to field galaxies (e.g. Ellison et al. 2009; Maier et al. 2019; Ciocan et al. 2020; Chartab et al. 2021; Sotillo-Ramos et al.

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2021, Maier et al. 2022). In a study of 259 cluster galaxies and 169 field galaxies at redshifts between 0.15 and 0.26, Maier et al. (2019) discovered that cluster galaxies with $\log(M_*/M_\odot) < 10.5$ within $R < R_{200}^1$ exhibited metallicities approximately 0.06 dex higher than the median metallicity of field galaxies. Subsequently, Ciocan et al. (2020) reported an increase in gas-phase metallicity in cluster galaxies (with $9.2 < \log(M_*/M_\odot) < 10.2$) by 0.065 dex. Similarly, Sotillo-Ramos et al. (2021) found metallicity differences of approximately 0.08 dex when comparing galaxies in low- and high-density environments. At higher redshifts, studies like Chartab et al. (2021) also observed similar trends, showing consistent patterns in metallicity differences between these environments.

However, several studies have shown that factors other than cluster membership contribute to metallicity enhancements in galaxies. For example, Ellison et al. (2009) found that the slight metallicity increase is primarily influenced by the presence of nearby companion galaxies rather than the cluster environment itself. Similarly, Andrade et al. (2024) speculates that at $z = 0.3$, galaxies in clusters not undergoing ram-pressure stripping (RPS) or strangulation exhibit metallicities comparable to or lower than those of field galaxies. In contrast, only galaxies affected by RPS or strangulation are speculated to display elevated metallicities above the MZR of both field and cluster galaxies. As part of the Gas Stripping Phenomena in galaxies with MUSE (GASP; Poggianti et al. 2017) project, Franchetto et al. (2020) demonstrated that cluster galaxies (both stripped and non-stripped) in the local Universe tend to be slightly more metal-rich than field galaxies at masses below $10^{10.25}M_\odot$, while exhibiting a similar metallicity trend as field galaxies at higher stellar masses. Additionally, Peluso et al. (2023) concluded that the gas-phase metallicity in the nuclei of AGN host galaxies is enhanced by approximately 0.05 dex compared to that of star-forming galaxies, irrespective of the presence of RPS.

In this study, building on the work of Khoram et al. (2024), we utilize MUSE observations to examine the chemical composition of star-forming disc galaxies within 12 clusters at intermediate redshifts, leveraging a statistically significant sample for the first time. We compare the properties of RPS galaxies with those of undisturbed galaxies in both cluster and field environments from the same survey. This comparison aims to identify the dominant environmental factors influencing the chemical evolution of galaxies.

In Section 2, we present the galaxy samples used in this study, followed by Section 3, which outlines the details of the spectral analysis and the methods used to measure oxygen abundance in the sample. Our findings are presented in Section 4 and discussed further in Section 5.

2 DATA AND SAMPLE SELECTION

We utilize MUSE observations acquired through the MUSE GTO project (Richard et al. 2021), which targeted clusters selected from various surveys including the Massive Clusters Survey (Ebeling, Edge & Henry 2001), Frontier Fields (Lotz et al. 2017), GLASS (Treu et al. 2015), and the Cluster Lensing and Supernova survey with Hubble (Postman et al. 2012) programmes. Observations were confined to the central regions of the clusters, with the typical area covered by MUSE observations corresponding to around 250–330 kpc, contingent on the cluster’s redshift. This corresponds to roughly the inner $0.1\text{--}0.15 R_{200}$. The clusters have masses in the range

of $\sim 10^{13.3} - 10^{14.4}M_\odot$ and velocity dispersions between ~ 800 and 1800 km s^{-1} (Richard et al. 2021). These clusters were observed either through single pointings or mosaics, with exposure durations ranging from approximately 2 to 15 h (effective). For further insights into the observations and data analysis, we refer to Richard et al. (2021).

As outlined in Moretti et al. (2022), Werle et al. (2022), and Vulcani et al. (2024), we selected a sample of 12 clusters² within the redshift range $0.3 < z < 0.5$. This sample encompasses star-forming disc galaxies spanning a stellar mass range of $7.8 \lesssim \log(M_*/M_\odot) \lesssim 11.8$. We then classified galaxies into three groups: (1) Galaxies undergoing RPS are identified by examining extraplanar, unilateral tails, and/or debris with emission lines in the MUSE data cubes and/or *HST* images, (2) Galaxies belonging to the cluster but not experiencing ram-pressure (Control Cluster, or CC), and (3) Galaxies in coeval fields non-members of any cluster (Control Field, or CF). The initial sample contains 28 RPS, 40 CC, and 12 CF galaxies in total (Moretti et al., in preparation). Notably, the $H\alpha$ emission line falls beyond the MUSE wavelength range for galaxies with redshift $\gtrsim 0.42$. Consequently, 12 RPS, 12 CC, and 4 CF galaxies lack $H\alpha$, $[S \text{ II}]\lambda\lambda 6718, 6730\text{\AA}$, and $[N \text{ II}]\lambda\lambda 6548, 6584\text{\AA}$ emission lines. We will keep these galaxies separate for the rest of the analysis and introduce a new calibration method to estimate their metallicities based on $[O \text{ II}]\lambda\lambda 3727, 29$ and $[O \text{ III}]\lambda 5007$ fluxes.

Through statistical analysis and visual inspection of individual galaxy discs, we excluded flawed, contaminated, or faint galaxies from the sample. For example, three RPS galaxies were determined not to be cluster members after phase-space investigations based on the $H\alpha$ redshift. Additionally, in the CC sample, three galaxy discs were found to be contaminated by outflows and/or AGN flux. To ensure robust metallicity estimation, we included only galaxies in which at least two-thirds of the disc spaxels have a flux with signal-to-noise (S/N) > 2 for each emission line used in each metallicity diagnostic (see Section 3). We further excluded interacting galaxies to minimize sources of contamination. Ultimately, we confidently selected 18 RPS, 23 CC, and 9 CF galaxies for disc metallicity measurements. We confirm that both RPS and control galaxies are represented in most clusters, ensuring that our results are not influenced by systematic environmental differences between the two classes.

3 DATA ANALYSIS

First, we correct the MUSE spectra for the Milky Way dust extinction, as extensively discussed in Moretti et al. (2022). The data cubes are then spatially smoothed using a boxcar kernel of 5×5 pixels (approximately 1 arcsec, corresponding to the average seeing of the cubes). From these smoothed cubes, we extract the stellar-only component by fitting the spectrum within each spaxel using the SINOPSIS code (Fritz et al. 2017) along with the latest stellar population models from Bruzual & Charlot (2003), assuming a Chabrier (2003) initial mass function (IMF). The emission-only spectrum is then obtained by subtracting the fitted stellar component. Gas kinematics, emission line fluxes, and the respective errors are derived utilizing HIGHHELP software (Radovich et al., in preparation), built upon the `\TEXSC\{LMFIT}` Python package³(Newville et al. 2016).

²Abell2744, Abell370, AS1063NE, AS1063SW, MACS0257, MACS0416N, MACS0416S, MACS0940, MACS1206, RXJ1347, SMACS2031, SMACS2131

³<https://lmfit.github.io/lmfit-py/>

¹Referred to as the virial radius, is the radius within which the mean density of a galaxy cluster is 200 times the critical density of the Universe.

In this work, to delineate the boundaries of each galaxy, we create an SDSS *g*-band image (Sloan Digital Sky Survey; York et al. 2000) by conducting synthetic photometry on the MUSE data cube. Using this image, we generate masks to identify pixels with flux values exceeding the background level by 5σ . This approach was initially introduced in Moretti et al. (2022) and further elaborated on in Khoram et al. (2024).

Spaxels within the galactic discs are treated differently based on the presence or absence of $H\alpha$ within the observed spectral range, depending on their redshifts.

3.1 With $H\alpha$

When $H\alpha$ is contained in the galaxy spectral range (68 per cent/70 per cent/89 per cent of the RPS, CC, and CF samples, respectively), we use the BPT diagram (Baldwin, Phillips & Terlevich 1981) and the O3–N2 demarcation line by Kewley et al. (2001) to exclude non-star-forming spaxels. 89 per cent of the spaxels in the control sample (i.e. both CC and CF) and 85 per cent of spaxels in RPS galaxies are star-forming within the discs. Fluxes are then corrected for intrinsic dust extinction using the Cardelli, Clayton & Mathis (1989) extinction curve assuming an intrinsic Balmer decrement of $H\alpha/H\beta = 2.86$. Moreover, for galaxies with $H\alpha$ and the $[N\text{II}]\lambda 6584$ emission lines, we derive the metallicity using the calibration introduced by Pettini & Pagel (2004, hereafter P04) according to the formula $12 + \log(O/H) = 8.73 - 0.32 \times O3N2$. This is an empirical method, calibrated via electron temperature measurements, that determines the oxygen abundance in HII regions based on the O3N2 index, defined as $\log([\text{O III}]\lambda 5007/H\beta)/([\text{N II}]\lambda 6584/H\alpha)$. This method is applicable when O3N2 is less than 1.9, corresponding to a minimum metallicity of approximately 8.1. Note that $3 \times [\text{N II}]\lambda 6584$ flux is employed as substitute to $[\text{N II}]\lambda 6584$ in 3 cases where the latter line falls beyond the covered wavelength range.

3.2 No $H\alpha$

For galaxies with $H\alpha$ outside the observed spectral range (32 per cent/30 per cent/11 per cent of the RPS, CC, and CF samples, respectively), we use a relation based on the R23 index, defined as $[\text{O III}]\lambda 5007 + [\text{O II}]\lambda\lambda 3727, 29/H\beta$, and its correlation with metallicity introduced in Sanders et al. (2021). Using all the star-forming spaxels from the control sample (CC and CF), we establish a second-order relation between the R23-based metallicity and that derived using P04 (Z_{P04}) as given in equation (1) with the standard deviation of 0.09 dex from the polynomial fit.

$$12 + \log(O/H)_{R23} = 0.18 \times Z_{P04}^2 - 2.34 \times Z_{P04} + 15.21 \quad (1)$$

As illustrated in Fig. 1, 95 per cent of the disc (integrated flux) metallicity values fall within the uncertainty range of this relation. Consequently, with the $[\text{O III}]\lambda 5007$, $[\text{O II}]\lambda\lambda 3727, 29$, and $H\beta$ fluxes, we can reliably estimate P04 metallicities for objects whose $H\alpha$ line falls outside the MUSE wavelength range, with a reasonable level of confidence. As detailed in Moretti et al. (in preparation), we estimate dust extinction in the absence of the Balmer decrement using an empirical relation based on the $[\text{O II}]/H\beta$ ratio for massive galaxies ($\log M > 10$). For lower mass galaxies, we assume a constant $A_V = 1$.

In both cases, whether $H\alpha$ is present in the spectral coverage or not, metallicity uncertainties are computed using Monte Carlo simulations, where all recorded line fluxes are randomly perturbed 1000 times according to their measurement errors, assuming a Gaussian noise distribution. The resulting metallicities are taken as

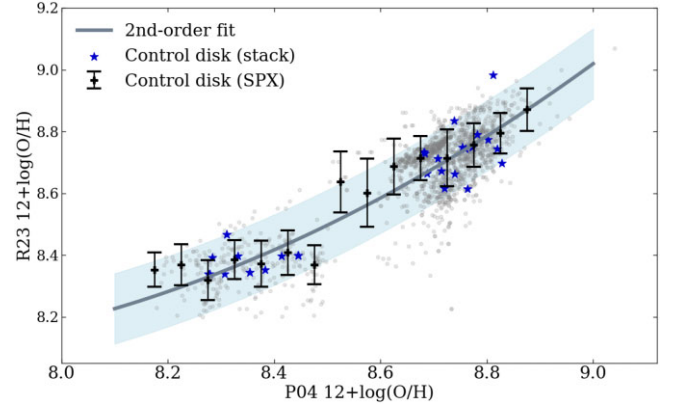


Figure 1. Metallicity values based on the R23 index from Sanders et al. (2021, S21) and the O3N2 index from Pettini & Pagel (2004, P04), superimposed with the second-order relation derived from all star-forming spaxels (grey) in the control sample. The standard deviation of data points from the fit (0.09 dex) is illustrated with the shaded region. Black data points denote the median S21 spaxel metallicities in 0.02 dex P04 bins, with error bars representing the 1σ percentiles for visual clarity. Blue stars represent the global (i.e. integrated) disc metallicities of the control sample.

the median of these simulations, with the reported uncertainties given by their standard deviations. However, it is important to note that these values likely underestimate the true uncertainties, as systematic contributions are not accounted for.

4 RESULT

We derive the disc metallicity for each galaxy from their integrated spectra, following the criteria outlined in Section 3. As illustrated in Fig. 2, both galaxies with and without $H\alpha$ in their spectral range (see Section 3) are included, with those lacking $H\alpha$ indicated by a diamond superimposed on their data points. We compare the disc’s gas-phase metallicity of RPS, CC, and CF galaxies as a function of their stellar mass. We provide MZR (error-weighted second-order polynomial fit) for our sample, spanning the stellar mass from 10^8 to $10^{12} M_\odot$.

In Fig. 2, the orange line corresponds to the mass–metallicity relation of RPS galaxies, represented by red plus symbols, while the blue line indicates the fit to the CC and CF galaxies, shown as blue squares and green stars, respectively. We confirm that excluding CF galaxies from the blue fit does not affect the control MZR, as CC and CF galaxies with similar stellar masses exhibit comparable metallicity values. Furthermore, we compared our results to the MZR derived by Kewley & Ellison (2008), as shown in Fig. 2. Their analysis was based on a sample of 27 730 star-forming galaxies with $z < 0.1$ from the SDSS DR4 catalogue, using fibre-integrated spectra. The study originally employed the P04 metallicity calibration and the Salpeter (1955) IMF, which we converted to the Chabrier (2003) IMF for consistency with our analysis.

As illustrated in Fig. 2, a meaningful comparison between RPS and the control sample with $\log(M_*/M_\odot) < 9$ is limited due to the small number of CC and CF galaxies in this range. However, in the mid- to high-mass regimes, RPS galaxies exhibit noticeably higher metallicities compared to galaxies of similar mass in the control sample. The distinction becomes more apparent in Fig. 3, which represents the metallicity residuals for the entire sample relative to the CC+CF MZR (the blue line in Fig. 2), separately for galaxies with stellar masses below and above $10^{10} M_\odot$. The median metallicity

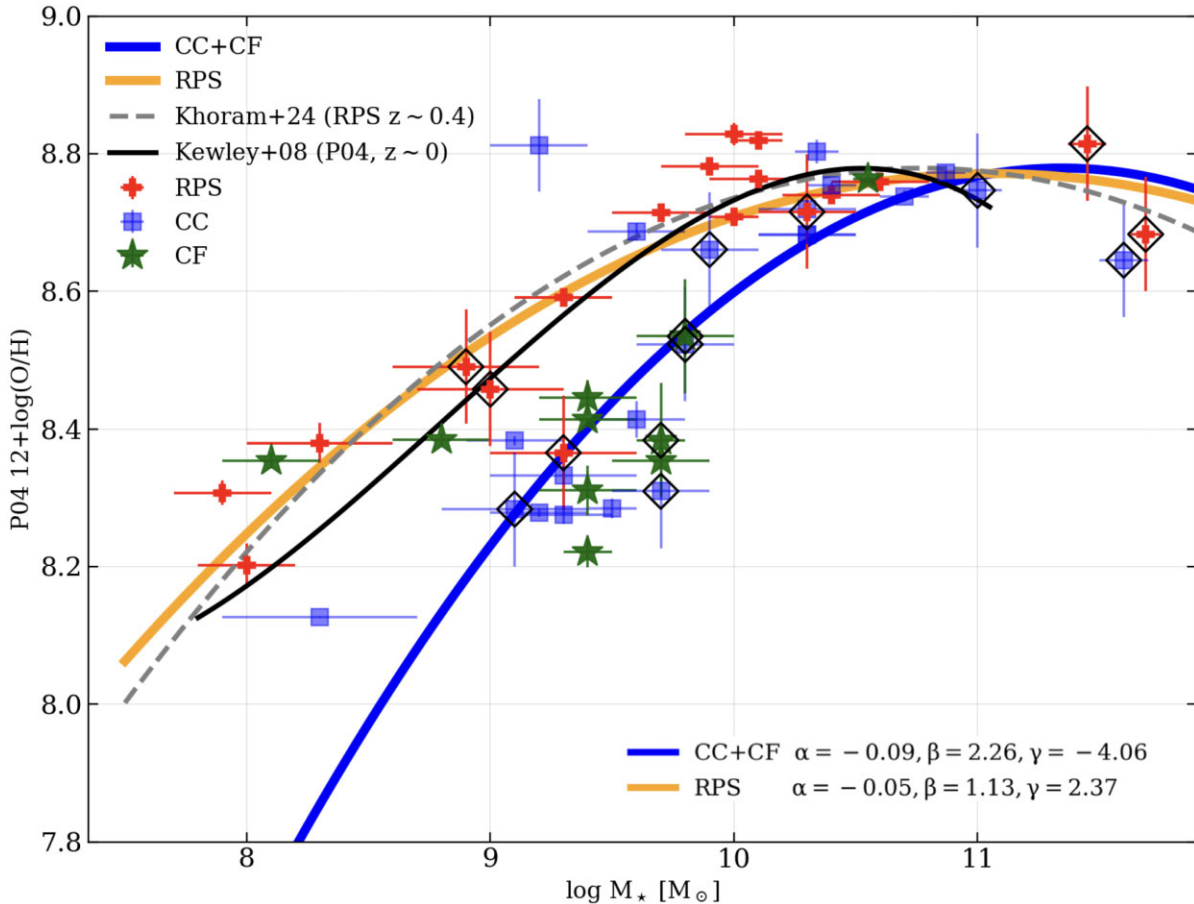


Figure 2. Measured global MZR for all galaxies in the sample from integrated disc spectra (see Section 3). The orange line represents an error-weighted second-order polynomial fit to RPS galaxies (plus symbols), while the blue line shows the same fit to CC and CF galaxies, depicted by squares and stars, respectively. For comparison, the dashed line shows the fit from Khoram et al. (2024) for RPS galaxies in the Abell 370 and Abell 2744 clusters. The solid black line represents the MZR derived by Kewley & Ellison (2008) employing the P04 metallicity calibration and Chabrier (2003) IMF. Data points with superimposed diamonds mark galaxies where $H\alpha$ falls outside their wavelength coverage, and their metallicities are derived from $[O II]\lambda\lambda 3727, 29$ fluxes (see Section 3). The fit parameters are displayed in the bottom-right of the figure, corresponding to the coefficients in the general second-order equation $(12 + \log(O/H)) = \alpha \cdot \log M_*^2 + \beta \cdot \log M_* + \gamma$.

residual for RPS galaxies is approximately 0.2 dex across the entire mass range. However, the most significant deviation, about 0.3 dex, is observed in the low- to mid-mass range around $\log(M_*/M_\odot) \sim 9.5$, with this difference gradually diminishing at higher masses.

This result suggests that environmental influences have a more significant impact on lower and mid-stellar mass galaxies compared to their higher mass counterparts.

5 DISCUSSION

Although stellar mass is the primary factor driving chemical enrichment in galaxies, other physical conditions also play a role in their chemical evolution (e.g. Maiolino & Mannucci 2019). A number of studies have demonstrated that environmental factors can affect the metal enrichment of galaxies within similar stellar mass ranges (e.g. Maier et al. 2019; Ciocan et al. 2020; Chartab et al. 2021; Sotillo-Ramos et al. 2021; Andrade et al. 2024). Our results indicate that, regardless of cluster membership, ram-pressure stripping alters significantly the metal content in galaxies’ gas (see Figs 2 and 3).

Previous studies (e.g. Peng & Maiolino 2014; Maier et al. 2016, 2019; Ciocan et al. 2020) have shown that cluster membership alone can lead to a metallicity enhancement of approximately 0.06–0.1 dex compared to field galaxies at $z \simeq 0-0.4$. These findings are based

on comparisons between cluster and field galaxy populations. The primary explanation proposed for this effect was strangulation (or starvation), a mechanism that depletes the diffuse hot gas reservoir within the galaxy’s halo, while leaving the disc’s gas largely unaffected. Additionally, Peng & Maiolino (2014) introduced the idea that gas inflow into the halo of a galaxy within a dense cluster environment becomes progressively enriched with metals. This enrichment leads to higher metallicities in low-mass cluster galaxies compared to similar galaxies in less dense, field environments. However, they did not propose a specific mechanism by which this metal-enriched gas inflow persists in dense galaxy clusters. Recent studies (Ciocan et al. 2020; Andrade et al. 2024) have speculated that, in addition to strangulation, RPS may also contribute to this enhancement. However, they did not provide detailed analysis or further exploration of this idea.

To our knowledge, only one study, Franchetto et al. (2020), has addressed the presence of RPS galaxies in the cluster sample and distinguished them from other galaxy types. The authors demonstrated that, for a given mass, cluster, and field galaxies at $z \simeq 0$ show only minor differences in metallicity at 1Re, which are not statistically significant. At the higher mass end, RPS galaxies also show comparable levels of metal enrichment, comparable to our findings. While their sample includes a few low- and intermediate-

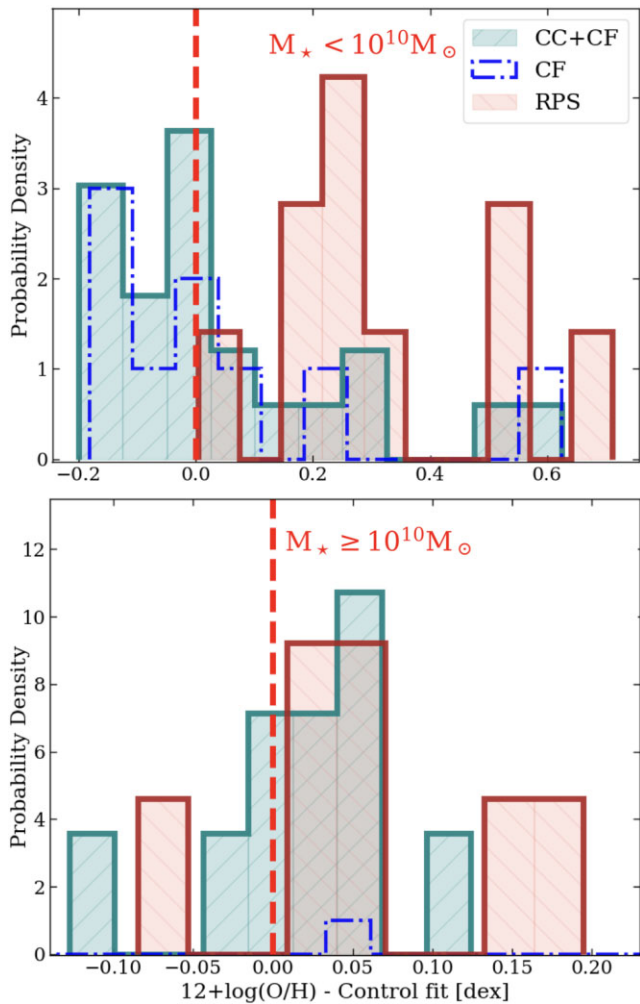


Figure 3. The normalized metallicity residuals of RPS and control galaxies, relative to the control (CC+CF) fit, are shown in Fig. 2. Galaxies are categorized into two groups based on their stellar mass, below and above $10^{10}M_{\odot}$, to emphasize the distinct behaviour across different mass ranges

mass RPS galaxies that show higher metallicity compared to both cluster and field samples, the authors refrained from drawing robust conclusions about these differences due to the limited sample size at $\log(M_{\star}/M_{\odot}) \lesssim 10.4$. In addition, both numerical simulations and analytical models predict that the effectiveness of RPS increases with redshift, driven by its dependence on the density of the ICM (Kravtsov & Borgani 2012; Mostoghiu et al. 2019; Singh, Gulati & Bagla 2019), implying a heightened impact of RPS in the redshift range of our sample.

One could argue that, due to having composite and/or low S/N spaxels in the outer parts of RPS galaxies (e.g. Moretti et al. 2022), global metallicity values predominantly reflect the more central regions of these galaxies, with any enhancements originating there. However, Khoram et al. (2024) have shown that the metallicity profile of RPS galaxy discs at intermediate redshifts remains flat or slightly positive in a range of $M_{\star} < 10^{10} M_{\odot}$, where the largest differences between RPS and control metallicities are observed. Additionally, various studies (e.g. Belfiore et al. 2017; Carton et al. 2018; Khoram & Belfiore 2025) have shown that galaxies with $M_{\star} < 10^{9.5} M_{\odot}$ at local to intermediate redshifts exhibit relatively flat metallicity gradients, suggesting that the average global metallicity remains unchanged even when the outermost disc regions are excluded. This

stability supports the idea that a physical mechanism may underlie the observed enhancement in RPS metallicities.

Considering the metal content of galaxies as a balance between stellar evolution over their lifetime and the inflow of cold, metal-poor gas, the metallicity enhancement in RPS galaxies could be explained by the influence of ram-pressure on these two factors. Compared to typical star-forming galaxies in both clusters and the field, RPS galaxies display elevated SFR on both global and local scales, likely driven by processes such as gas compression and mass flows induced by ram-pressure (e.g. Poggianti et al. 2016; Vulcani et al. 2018, 2020; Bacchini et al. 2023; Giunchi et al. 2023). By analysing the full sample of 12 clusters in this study and applying the same BPT diagram criteria to identify star-forming spaxels for SFR estimation, Vulcani et al. (2024) observed a mild SFR enhancement in RPS galaxies with ionized gas tails compared to the control sample (non-RPS galaxies). Enhanced SFR in RPS galaxies were found also in lower redshift clusters (Vulcani et al. 2018; Roberts & Parker 2020). On the global galactic scale, the SFR enhancement is mild, while, the analysis of post-starburst features in the spectra of galaxies in our clusters (Werle et al. 2022) has shown that locally, wherever in the disc there is gas left, the burst of star formation is strong and forms a significant fraction of the local mass (see fig. 5 in Werle et al. 2022). Since the measured metallicity reflects the gas that remains in the galaxy, the SFR increase can significantly influence the gas metallicity observed in RPS galaxies.

Note that the RPS signature we observe, characterized by long tails of ionized gas, typically becomes visible a few hundred Myr after ram-pressure begins to affect an infalling galaxy (Smith et al. 2022; Werle et al. 2024). Prior to this, the galaxy’s surrounding hot gas halo is rapidly stripped by RPS (Kulier et al. 2023). Additionally, the chemical enrichment driven by RPS-enhanced star formation occurs on short time-scales, governed by the lifetimes of the most massive stars. The interplay of these effects likely explains the measurable chemical enrichment and the mildly enhanced SFR observed in these galaxies.

In addition, some studies (e.g. Hughes et al. 2013; Peng, Maiolino & Cochrane 2015) have demonstrated that RPS is responsible for cutting off the inflow of the cold metal-poor gas to the central regions. Consequently, it is possible for gas inflow to be halted while the galaxy continues forming stars, resulting in a metallicity enhancement on short time-scales. In this scenario, the metallicity enhancement observed in RPS galaxies results from a combination of two key factors: (1) increased metal production driven by the locally enhanced SFR, and (2) the suppression of inflow of low-metallicity gas caused by ram-pressure stripping. Simulations further show that these effects reinforce each other to some extent. Using results from the EAGLE simulation (Schaye et al. 2015), Kulier et al. (2023) demonstrated that stellar feedback enhances the efficiency of ram-pressure stripping. This interplay indicates that the SFR enhancement associated with RPS not only amplifies gas stripping but also inhibits the inflow of cold, metal-poor gas, thereby altering the metallicity and chemical enrichment of RPS galaxies.

We confirm that the observed enhancement in SFR among metal-rich RPS galaxies, compared to normal galaxies unaffected by stripping, stands in clear contrast to the hotly debated fundamental metallicity relation (e.g. Mannucci et al. 2010; Maiolino & Mannucci 2019; Curti et al. 2020; Khoram & Belfiore 2025). This finding further supports the notion that environmental effects are the primary drivers of the differences observed in Fig. 2 between the CC+CF and RPS samples.

From a different perspective, the MZR evolution demonstrates a clear and consistent evolution with redshift, where the metallicity

decreases at a fixed mass as the redshift increases. At lower redshifts, this evolution is more pronounced in lower mass galaxies, whereas higher mass galaxies seem to have achieved their present-day metallicity by approximately $z \sim 1$ (see Zahid et al. 2013; Maiolino & Mannucci 2019, and references therein). As illustrated in Fig. 2, the metallicities of RPS galaxies remain closely aligned with the Kewley & Ellison (2008) MZR at $z \sim 0$, represented by the solid black line. In contrast, the control sample exhibits lower metallicities, as expected, highlighting an overall enhancement in the metallicity of RPS galaxies compared to the average values predicted for their redshift.

In summary, our findings show a clear distinction between RPS and non-RPS cluster galaxies, the former having higher metallicities than the latter, with no-RPS galaxies sharing the same mass–metallicity relation of field galaxies. This result favours the scenario that cluster membership solely cannot be responsible for experiencing different chemical evolution and metal content of galaxies within the similar stellar mass range. We also challenge the scenario which introduces strangulation (or starvation) as the primary explanation proposed for this effect (e.g. Maier et al. 2016, 2019; Ciocan et al. 2020). It is important to note that, given the relatively small size of our sample compared to studies that have derived the MZR at local and intermediate redshifts, further investigation is required to robustly confirm the findings presented in this work.

6 SUMMARY AND CONCLUSIONS

In this study, we analysed a total sample of 50 star-forming disc galaxies to investigate the impact of RPS on the gas-phase metallicity of galaxies across 12 clusters in the redshift range $0.3 < z < 0.5$. Using MUSE spectroscopy, we measured the gas-metallicity of galaxy discs and compared RPS galaxies to CC and CF galaxies. Our analysis yielded several key findings:

(i) The global MZR for RPS galaxies shows a systematic metallicity enhancement compared to the control sample, particularly in the low- to intermediate-mass regime ($\log(M_*/M_\odot) \sim 8.0$ to 9.5). This enhancement diminishes at higher stellar masses, suggesting that environmental effects are more significant in shaping the chemical evolution of lower mass galaxies. Metallicity residuals relative to the control MZR confirm that RPS galaxies exhibit elevated metallicities, with the median deviation of approximately 0.2 dex observed in the mid-mass range. This result indicates that RPS significantly alters the chemical enrichment of galaxies beyond the typical effects associated with cluster membership alone.

(ii) The metallicity enhancement in RPS galaxies can be attributed to a combination of two primary mechanisms:

(a) Enhanced SFR: Locally elevated SFRs in RPS galaxies, driven by gas compression and mass flows due to ram-pressure, boost metal production in the remaining gas. This is supported by our observation of locally intense star formation bursts in RPS regions.

(b) Suppressed gas inflows: RPS cuts off the supply of metal-poor gas to the central regions, preventing dilution and allowing metal-enriched gas to dominate the disc's chemical composition.

(iii) While previous studies suggest that cluster membership alone enhances metallicities by $0.06 - 0.1$ dex compared to field counterparts, our results demonstrate that RPS can lead to significant enrichment. This finding underscores the complex interplay between SFR enhancement, gas dynamics, and environmental stripping

processes. Furthermore, theoretical models suggest that feedback from enhanced star formation not only amplifies stripping efficiency but also suppresses gas inflows, further reinforcing the observed metallicity trends.

Our findings provide robust evidence that RPS plays a crucial role in shaping the chemical evolution of galaxies, particularly in dense cluster environments. The observed metallicity enhancement in RPS galaxies underscores the importance of environmental effects in galaxy evolution and offers a deeper understanding of how stripping processes and star formation interact to regulate the metal content of gas in galaxy discs. Future work combining high-resolution simulations and spatially resolved observations will further elucidate the detailed mechanisms driving these trends.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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