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RESEARCH ARTICLE

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How environmentally friendly are electric cars? The relationship between lithium usage and water resources, Chile example

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Abstract

The extraction of minerals such as lithium, widely used in the battery technologies of electric vehicles, is a process that necessitates consideration of its environmental impacts. This study aims to examine the environmental impacts of electric vehicles and the effects of lithium mining on water resources, particularly in regions abundant in lithium reserves like Chile. The analyses indicate a long-term relationship between lithium mining and irrigation water sources. This study establishes a foundation for understanding the relationship between the environmental sustainability of electric vehicles and the environmental impacts of lithium mining.

JEL CLASSIFICATION
Q51, Q55, C18

1 | INTRODUCTION

With urban expansion and an increasing urban population, the volume of traffic journeys continues to rise (Lah et al., 2019). The transportation sector particularly holds an exacerbating role in terms of anthropogenic carbon dioxide (CO_2) emissions released into the atmosphere, resulting in a greenhouse gas effect (Solaymani, 2019). Road transportation is responsible for over 90% of these emissions (Creutzig et al., 2016; Nanaki & Koroneos, 2013; Ülengin et al., 2018). Reducing CO_2 emissions is one of the major environmental challenges for transportation. One way to address this issue is by replacing old vehicles using fossil fuels (gasoline and diesel) with new electric cars (Petrović et al., 2020). For this purpose, particularly in the transportation sector, the production of electric cars powered by rechargeable lithium-based batteries has commenced (Salminen et al., 2008; Scrosati & Garche, 2010; Väyrynen & Salminen, 2011). Next-generation electric cars aim for zero emissions and are intended to cause less environmental harm compared with internal combustion fossil-fuel vehicles. However, the degree of success in this endeavor is debatable.

The life-cycle emissions of electric vehicles depend on the CO_2 intensity of energy production. Electric vehicles can provide CO_2 savings compared with traditional vehicles (Dong et al., 2020; Holland et al., 2016). Replacing traditional vehicles with electric vehicles for environmental sustainability also requires a clean source of electricity to charge the batteries (Alkawsi et al., 2021; Mohammed & Jung, 2021; Muratori et al., 2021; United Nations, 2021). In transportation applications, to reduce greenhouse gas emissions compared with fossil alternatives, 90%–100% of the use of electric fuel needs to be obtained from renewable energy sources. In this context, the use of only renewable-based power systems in electricity generation will perform better (Pavan et al., 2019; Turkdogan, 2021; Ueckerdt et al., 2021). Unlike traditional vehicles with internal combustion engines, electric vehicles draw their energy from rechargeable batteries (Alosaimi et al., 2021). When these vehicles operate in fully electric mode, they do not consume gasoline and produce zero exhaust emissions (Benajes et al., 2020; Wang et al., 2022). However, the currently stored electricity is produced from other sources that create air pollution, such as power plants (Karmaker et al., 2020; Xing et al., 2021; Zhang & Hanaoka, 2021). Lithium-ion batteries hold

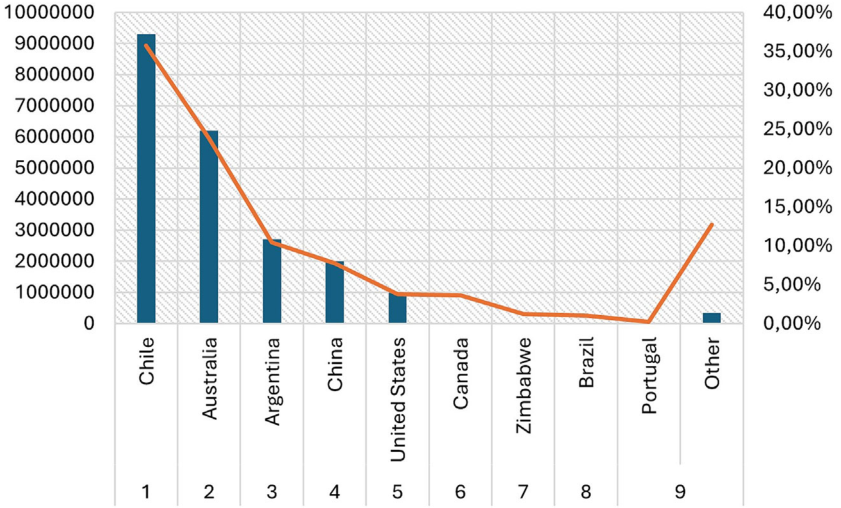

FIGURE 1 World reserves of lithium by country (lithium tonnes) (Natural Resources Canada, 2023).

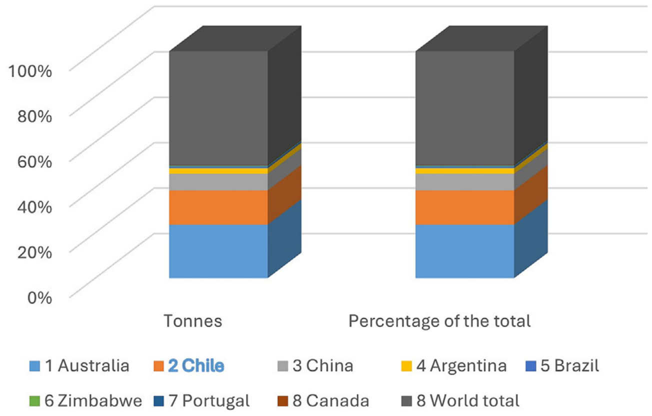

FIGURE 2 World mine production of lithium by country (Natural Resources Canada, 2023).

dominance with a market share of over 75% in the global rechargeable battery market (Costa et al., 2021). Lithium, the lightest metal in the world, is seen as a critical component to accelerate and enable the next incarnation of electric batteries, which are essential inputs for the global electric vehicle industry (Grosjean et al., 2012; Vikström et al., 2013).

Derived from the Latin “lithos” meaning “stone,” lithium has an atomic number of 3 and is symbolized by “Li.” Lithium is partially consumed in mineral form but is mostly obtained from chemical compounds extracted from minerals or solutions (Helvacı, 2018). Emissions resulting from lithium mining are lower than emissions produced from fossil fuel production. However, extraction methods lead to air and water pollution, land degradation, and underground water scarcity due to their energy-intensive nature (Babidge & Bolados, 2018; Flexer et al., 2018; Zheng, 2023). Mining adversely affects agricultural production due to direct disruption to ecosystems and drought (Butchart et al., 2010; Gibson et al., 2011; Pouzols et al., 2014; Soni, 2019). Lithium mining demands a substantial amount of water; approximately 500,000 L of water is needed to extract one ton of lithium (Tedesco, 2023). It is well-known that water resources play a vital role in human welfare and crop productivity (Kang et al., 2009). Today, water scarcity is increasingly perceived as a global systemic risk (Mekonnen & Hoekstra, 2016; Steffen et al., 2015). Wetlands are of great importance for the continuity of ecosystems (Maltby & Acreman, 2011; Millennium Ecosystem Assessment, 2005).

The current lithium resources are predominantly located geographically in the Andes Mountains, where Bolivia, Argentina, and Chile converge, and in China (Heredia et al., 2020). The Salar and Atacama regions in Chile are defined as primary continental regions for lithium brines. Currently, the Central Andes Mountains provide a significant portion of global lithium production (Cabello, 2021). Figure 1 shows the world's lithium reserves by country, while Figure 2 shows the world's lithium mine production by country.

Accordingly, while Chile holds 41% of the world's lithium reserves, it ranks as the country with the second-highest lithium mining, accounting for 24.8% of the global production. In Chile, a downward trend in continental water has been observed. The total consumption of water resources in this sector, especially due to increased use of sea and desalinated water, decreased by 3% in 2020 compared with 2019, dropping to 12,089 L per second (Peña, 2021). Antofagasta, home to Chile's richest mineral deposits, is one of the driest places in the world (Katwala, 2018; Montana et al., 2016; Prieto et al., 2022; Tiwari et al., 2021). This is a real issue because miners drill a hole in salt flats to extract lithium, pumping mineral-rich salty water to the surface. One of the ways a significant portion of lithium is harvested involves a less harmful process for humans and the environment: lake-brine evaporation (Katwala, 2018; Narins, 2017). During the evaporation process, a slaked lime solution (Ca (OH)2) is added to the salty water to precipitate unwanted elements, particularly magnesium and boron (as magnesium hydroxide and calcium borate salts) (STT, 2023). This evaporation process leads to a significant use of underground water (Li et al., 2019). This situation deprives local communities of drinking water and can harm agriculture by reducing available water for irrigation (Ruffino et al., 2022). Since 2010, rural communities in Central Chile have been strongly affected, with a

TABLE 1 Literature research.

Reference	Relevant studies
Hawkins et al. (2013)	The environmental benefit of electric cars is not clear.
Egbue and Long (2012)	It was found that electric vehicles are not environmentally friendly.
Agusdinata et al. (2018)	It requires lithium batteries to holistically address socio-environmental impacts in the supply chain.
Čekerevac et al. (2021)	It has been shown that the use of electric vehicles is not environmentally justified if electricity is generated from coal.
Wang et al. (2017)	Electric vehicles can only be seen as a green product to some extent.
Garcés and Álvarez (2020)	As a result of the extraction process in the salt flat, millions of tons of water are removed from the system, and the natural conditions in the ecosystem change.
Hao et al. (2017)	The production of lithium-ion batteries in China increases greenhouse gas emissions.
Paz et al. (2023)	Lithium mining is causing climate change. Therefore, it is and will continue to be a controversial issue.
Gaines and Dunn (2014)	Lithium batteries used for electric vehicles contribute to 20% of SOx emissions.
Rangarajan et al. (2022)	There are uncertainties in terms of the energy, average life, cost, safety, and fast charging characteristics of lithium batteries suitable for the automotive sector.
Li et al. (2014)	It has shown that more than 50% of the most characterized emission impacts are caused by batteries used in electric cars.
Mauger and Julien (2017)	The sustainability of lithium batteries for electric vehicles is unclear.
Helmers and Marx (2012)	With regard to energy efficiency, it has been found that electric cars represent an alternative to conventional vehicles. However, this only applies if the electricity is supplied by very efficient power stations or, better yet, by renewable energy production.
Kaunda (2020)	There is a significant lack of data on the impacts of direct extraction and processing of lithium metal.
Liu and Agusdinata (2020)	The water consumption of lithium mining has increased twice.
Crabtree et al. (2015)	The theoretical limits on the performance of active components in Li-ion batteries allow an increase in performance of 50%–100%. A new generation of beyond-Li-ion batteries is needed to transform transport and the power grid.
Izquierdo et al. (2015)	About 80% of global lithium resources are located in Argentina, Bolivia, and Chile. Climate trends over the past decades and future climate models indicate persistent drying trends in these regions.
Qiao et al. (2019)	The greenhouse gas contribution of electric vehicles is 18% less than that of internal combustion engine vehicles. However, this rate may vary. This may become an obstacle to fully utilizing the environmental benefits of electric cars.
Flexer et al. (2018)	About 2/3 of the world's lithium production is obtained from brines. Several years of simulations and pilot studies are needed before large-scale production.
Wen et al. (2020)	With the widespread use of energy production methods such as wind power generation and photovoltaic energy, the full utilization of electrical energy provides an important way for environmental protection and economic development.
Castelvecchi (2021)	The increase in lithium mining brings its own environmental concerns. Current forms of extraction require copious amounts of energy and water.
Vera et al. (2023)	Depending on the deposit, large amounts of water, as much as 100–800 m^3 per tonne of lithium carbonate, are lost through evaporation, raising concerns about the overall sustainability of the process.
Giansoldati et al. (2020)	Reliable and complete information is needed to improve knowledge about the technological and environmental pros and cons of electric cars.
Marazuela et al. (2020)	Over the 1986–2018 period, lithium production reduced the depth of the groundwater table by 15%.
Munk et al. (2016)	One of the negative effects of lithium production is that it causes drought.
Maxwell and Blair (2022)	Lithium can play an important role in reducing greenhouse gas emissions. But a climate-friendly future cannot come at the expense of destroying a region rich in biodiversity.
Abdullayev et al. (2022)	More research needs to be done on the industrial production of lithium from water sources.
Luong et al. (2022)	The potential environmental issues associated with the production and operation of electric vehicles deserve further study while promoting their global deployment.

TABLE 2 Variables.

Variable	Variable definition	Source
W	The amount of renewable domestic freshwater resources per capita (m^3)	Data_worldbank, 2023
L	Lithium reserve amount (ton)	Cabello, 2022
LW	Natural logarithm of the amount of renewable inland freshwater resources per capita	
LL	Natural logarithm of lithium reserve amount	

dramatic decrease in groundwater levels and even some wells drying up (Vargas-Payera et al., 2023). Considering that most lithium is extracted in dry regions with scarce water resources globally, the dimensions of this damage increase (Moran et al., 2022). Furthermore, the remaining liquid after lithium extraction may contain toxic or radioactive elements and must be cleaned and stored before release (EVBox, 2023). Unfortunately, while paving the way for an electric future, lithium is a depletable mineral similar to coal and gas. Lithium can be defined as a non-renewable mineral that enables renewable energy. It is often promoted as the next oil (Euronews, 2023).

In this article, unlike other studies, the relationship between lithium production, used in electric cars and defined as a clean energy source, and water resources is examined, specifically focusing on Chile. Contemporary literature and empirical studies emphasize the importance of renewable energy in mitigating the negative effects of electric cars compared with fossil-fueled vehicles and focus on potential deficiencies. The findings from our paper will provide empirically comprehensive information about the relationship between lithium use and depleting water resources.

2 | LİTERATURE REVİEW

In the literature, there are predominantly studies indicating that electric cars are more environmentally friendly compared with fossil-fueled vehicles or that this is uncertain. While there are a few studies focusing on the impact of lithium production on water resources, no direct study examining the relationship between lithium used in electric cars and water resources has been found. In this context, Table 1 lists the relevant studies.

3 | DATA AND METHODOLOGY

3.1 | Data

The study used data for the period 1987–2020 concerning the per capita renewable inland freshwater resources and lithium reserve quantities specific to Chile to investigate the relationship between lithium mining practices and water. Analyses were performed after taking the natural logarithm of the data. Explanations for the variables used in the study are provided in Table 2.

3.2 | Method

When working with econometric time series, as many methods are based on the assumption of the stationary nature of the series, it is essential to first investigate whether the series contain unit roots, in other words, to explore the degrees of stationarity. While examining the graphs and correlograms of the series might provide insights into the stationarity, unit root tests are used to reach more definitive conclusions regarding the examination of the series' stationarity.

3.2.1 | Unit root tests

In testing for stationarity, classical unit root tests like the Augmented Dickey–Fuller (ADF) (Dickey & Fuller, 1981) and Phillips–Perron (PP) (Phillips & Perron, 1988) tests are commonly preferred. The ADF test includes lagged values of the dependent variable as independent variables in the model to eliminate autocorrelation issues in the error term. Therefore, the determination of the appropriate lag length requires the use of selection criteria such as the Akaike (1974) Information Criterion (AIC) and the Schwarz (1978) or Bayesian Information Criterion (SIC). The econometric model containing the ADF test, which includes a constant and trend, is represented in Equation (1). The fundamental hypothesis being tested in the equation indicates that the series contains a unit root and is nonstationary.

$$\Delta y_t = \beta_0 + \beta_1 T + \theta y_{t-1} + \sum_{i=1}^{k} \delta_i \Delta y_{t-i} + u_i \tag{1}$$

The econometric model containing the PP test, which is developed based on a more flexible assumption allowing weakly dependent and heterogenous error terms compared with the ADF unit root test and includes a constant and trend, is represented in Equation (2).

$$\Delta y_t = \beta_0 + \beta_1 T + \theta y_{t-1} + u_i \tag{2}$$

3.2.2 | Unit root tests with structural breaks

When findings suggest that time series are nonstationary according to unit root tests like ADF and PP, it is necessary to re-examine the series using unit root tests that account for structural breaks. One of the reasons for obtaining evidence of nonstationarity in time series might be the presence of structural breaks. Therefore, even if the series appears nonstationary in ADF and PP tests, it could still be stationary, or if there is a break and it is not considered, different degrees of stationarity might be identified.

The Zivot–Andrews (1992) test, one of the tests that account for structural breaks used in the analysis, is estimated with models contained in Equations (3)–(5), which internally determine the structural break.

$$y_t = \mu + \theta_1 DU_t(\lambda) + \beta t + \alpha_1 y_{t-1} + \sum\nolimits_{j=1}^{k} c_j \Delta y_{t-j} + e_t \tag{3}$$

$$y_t = \mu + \gamma_1 DT_t(\lambda) + \beta t + \gamma DT_t + \alpha_2 y_{t-1} + \sum\nolimits_{j=1}^{k} c_j \Delta y_{t-j} + e_t \tag{4}$$

$$y_t = \mu + \theta_2 DU_t(\lambda) + \gamma_2 DT_t(\lambda) + \beta t + \alpha_3 y_{t-1} + \sum\nolimits_{j=1}^{k} c_j \Delta y_{t-j} + e_t \tag{5}$$

In Equations (3)–(5), ($t = 1, 2, \ldots, T$) is the trend variable, (T_b) is the break time, and ($\lambda = T_b / T$) is the relative break year. Model (3) represents a break in the mean, model (4) represents a break in the slope, and model (5) represents a break in both the mean and slope.

The analysis employed not only the Zivot–Andrews test but also the Lee–Strazicich (2003) and Lee–Strazicich (2013) unit root tests. The model equations used for testing the unit root with structural breaks in Lee–Strazicich (2003) and Lee–Strazicich (2013) are based on the data generation process described in Equations (6) and (7) (Mert & Çağlar, 2019).

$$y_t = \delta Z_t + e_t \tag{6}$$

$$e_t = \beta e_{t-1} + \varepsilon_t \tag{7}$$

Although the equation estimated according to the LM principle is included in model (8), ($\widehat{S}_t = y_t - \tilde{\psi}_x - Z_t \tilde{\delta}_t$) and ($t = 2, \ldots, T$) In addition, ($\tilde{\psi}_x$, $y_1 - Z_1 \tilde{\delta}$) is denoted by, where (y_1) and (Z_1) denote the initial values of the matrices and ($\widehat{\delta}$) denotes the coefficient matrix. Z_t denotes the vector of exogenous variables and by changing this vector, single and double break tests emerge.

$$\Delta y_t = \widehat{\delta} Z_t + \phi \widehat{S}_{t-1} + \varepsilon_t \tag{8}$$

In the Lee–Strazicich (2013) Unit Root Test, the vector of exogenous variables (Z_t) is constructed by considering a single break. Break models are expressed in two different structures: level breaks and level-trend breaks. While (T_B) denotes the time of the break, information on the level and (&) trend break models is given in Equations (9) and (10), respectively.

$$\mathrm{Z_t} = [1, \mathrm{t}, \mathrm{D_t}]\; t \geq T_B + 1 \text{ için } \mathrm{D_t} = 1, \mathrm{dd} = 0 \tag{9}$$

$$\mathrm{Z_t} = [1, \mathrm{t}, \mathrm{D_t}, \mathrm{DT_t}]\; t \geq T_B + 1 \text{ için } \mathrm{DT_t} = t - T_B, \mathrm{dd} = 0 \tag{10}$$

In the Lee-Strazicich (2003) Unit Root Test, the vector of exogenous variables (T_{Bj}) is constructed by taking into account the double break. (&) denotes the time period in which the break occurs, and the information about the break models at level and level & trend are given in Equations (11) and (12), respectively.

$$\mathrm{Z_t} = [1, \mathrm{t}, \mathrm{D_{1t}}, \mathrm{DT_{1t}}],\; j = 1, 2 \text{ iken } t \geq T_{Bj} + 1 \text{ için } \mathrm{Dj_t} = 1, \mathrm{dd} = 0 \tag{11}$$

$$\mathrm{Z_t} = [1, \mathrm{t}, \mathrm{D_{1t}}, \mathrm{D_{2t}}, \mathrm{DT_{1t}}, \mathrm{DT_{2t}}]\;\; t \geq T_B + 1 \text{ için } \mathrm{DTj_t} = t - T_{Bj}, \mathrm{dd} = 0 \tag{12}$$

The test statistic ($\widehat{\phi}$), used in these tests to indicate that the underlying hypothesis contains a unit root with refraction and is not static, is contained in Equation (13) to refer to the parameter derived from Equation (8).

$$\tau = t - stat\left(\widehat{\phi}\right) = \frac{\widehat{\phi}}{sh\left(\widehat{\phi}\right)} \tag{13}$$

Another unit root test that takes structural breaks into account is the Narayan and Popp (2010) (NP) double break unit root test. The effects of deterministic (d_t) and stochastic μ_t components, which cannot be observed during the data creation process in the series, are taken into account. The NP test is based on two assumptions on deterministic components. These are, respectively, as follows: Model 1 (M1) allows for two breaks in the model with constant and Model 2 (M2) allows two breaks in constant and constant-trend models. Therefore, the specifications of both models differ in how the deterministic component is defined. Theoretical models of M1 and M2 are included in Equations (14) and (15), respectively.

$$\begin{aligned}\Delta y_t = {} & a_1 + b_1 y_{t-1} + \beta_1 D(T_{\mathrm{B}})_{1,t} + \beta_2 D(T_B)_{2,t} + \delta_1 DU_{1,t-1} + \delta_2 DU_{2,t-1} \\ & + \sum_{j=1}^{k} c_j \Delta y_{t-j} + e_{1t}\end{aligned} \tag{14}$$

$$\begin{aligned}\Delta y_t = {} & a_1 + a_2 t + b_1 y_{t-1} + \beta_1 D(T_B)_{1,t} + \beta_2 D(T_B)_{2,t} + \delta_1 DU_{1,t-1} \\ & + \delta_2 DU_{2,t-1} + \varphi_1 DT_{1,t-1} + \varphi_2 DT_{2,t-1} + \sum_{j=1}^{k} c_j \Delta y_{t-j} + e_{2t}\end{aligned} \tag{15}$$

In the equations, $DU_{i,t} = 1\,(t > T_{B,i})$ and $DT_{i,t} = 1\,(t > T_{B,i})\,(t - T_{B,i})$ (while $i = 1,2$)) show the dummy variables for the break occurring at times T_{B1} and T_{B2} in constant and constant-trend models, respectively.

3.2.3 | Cointegration tests with structural breaks

Gregory and Hansen (1996) Cointegration Test and Hatemi-J (2008) Cointegration Test are commonly used structural break cointegration tests. The Gregory and Hansen (1996) cointegration test can be expressed as a multivariate extension of Zivot and Andrews' univariate tests for structural breaks. In the Gregory–Hansen Cointegration Test, the hypothesis of structural break cointegration against the alternative of no structural break cointegration is tested. The Gregory and Hansen (1996) cointegration test is examined with three models in the cointegrated vector, where (17) contains the model with a level break, (18) contains the model with a trend level break, and (19) contains the model with both a fixed and a slope break (in a regime). The Gregory–Hansen Cointegration Test is found in Equations (17)–(19) by considering dummy variables representing structural changes in Equation (16). In Equation (16), (n) denotes the number of observations, $\tau \in (0,1)$ represents the number of breaks, and ($n\tau$) indicates the break point.

$$\varphi_{t\tau} = \begin{cases} 0, & t \le [n\tau] \\ 1, & t > [n\tau] \end{cases} \tag{16}$$

$$y_{1t} = \mu_1 + \mu_2 \varphi_{t\tau} + \alpha^T y_{2t} + + \varepsilon_t \tag{17}$$

In Equation (17) refers to a level of fracture (C), and the prebreak constant term (μ_1) refers to (μ_2) representing the effect of the break in the constant term and (α^T) the coefficient vector of the arguments.

$$y_{1t} = \mu_1 + \mu_2 \varphi_{t\tau} + \beta t + \alpha^T y_{2t} + + \varepsilon_t \; t = 1,2\ldots,n \tag{18}$$

Equaiton (18) refers to the break in the constant in the presence of the trend. It is also described as the inclination (C/T) model.

$$y_{1t} = \mu_1 + \mu_2 \varphi_{t\tau} + \alpha_1^T y_{2t} + \alpha_2^T y_{2t} \varphi_{t\tau} + \varepsilon_t \; t = 1,2\ldots,n \tag{19}$$

In Equation (19) refers to the model of regime change (C/S). In this model, you can change α_1^T the preregime coefficient of integration, unlike breaking at a level α_2^T represents a change in the inclination coefficient after regime change.

For the testing, the cointegration in Equation (17), ADF^*,Z_α^*, and $Z_t{}^*$ statistics are used in Equations (18) and (19). The calculation of statistics (20) is done as in the following equation:

$$ADF^* = \underset{\tau \in T}{\min} ADF(\tau); \quad Z_t{}^* = \underset{\tau \in T}{\min} Z_t(\tau); \quad Z_a{}^* = \underset{\tau \in T}{\min} Z_a(\tau) \tag{20}$$

The Hatemi-J (2008) cointegration test was created by adding two structural break points to the Engle and Granger (1987) cointegration test, with two possible regime changes.

The Hatemi–J model (C/S), which is formed by breaking dummies in Equation (21), is contained in equation number (22).

$$D_{1t} = \begin{cases} 0, & t \le [n\tau_1] \\ 1, & t > [n\tau_1] \end{cases} \qquad D_{2t} = \begin{cases} 0, & t \le [n\tau_2] \\ 1, & t > [n\tau_2] \end{cases} \tag{21}$$

$\tau_1 \epsilon (0,1)$ ve $\tau_2 \epsilon (0,1)$ it shows the breaking points to be.

$$y_t = \alpha_0 + \alpha_1 D_{1t} + \alpha_2 D_{2t} + \beta_0' x_t + \beta_1' D_{1t} x_t + \beta_2' D_{2t} x_t + u_t \tag{22}$$

In the Hatemi–J test, the basic hypothesis states that there is no coherence and is tested with ADF^*,Z_α^* and $Z_t{}^*$ statistics.

In addition to the GH and HJ cointegration tests, it is possible to perform a cointegration test with the Maki (2012) cointegration test in case of multiple breaks. Especially when there are three or more structural breaks in the cointegration equation, this method is superior to the other two methods. In the working algorithm of the test; each period is taken as a possible breaking point; t statistics are calculated, and the points where t is smallest are accepted as breaking points. In this method, all series to be analyzed must be I(1). Maki (2012) developed four different models to test whether there is a cointegration relationship between the series in the presence of structural breaks. These are, respectively, as follows: Model 0: there is a break in the constant term in the trendless model, Model 1: there is a break in the constant term and slope in the trendless model, Model 2: there is a break in the constant term and slope in the trend model, and Model 3: there is a break in the constant term, slope and trend. The equations of the models are located in models (23)–(26), respectively.

$$y_t = \mu + \sum_{i=1}^{k} \mu_i K_{i,t} + \beta x_t + u_t \tag{23}$$

$$y_t = \mu + \sum_{i=1}^{k} \mu_i K_{i,t} + \beta x_t + \sum_{i=1}^{k} \beta_i x_i K_{i,t} + u_t \tag{24}$$

$$y_t = \mu + \sum_{i=1}^{k} \mu_i K_{i,t} + \gamma x + \beta x_t + \sum_{i=1}^{k} \beta_i x_i K_{i,t} + u_t \tag{25}$$

$$y_t = \mu + \sum_{i=1}^{k} \mu_i K_{i,t} + \gamma t + \sum_{i=1}^{k} \gamma_i t K_{i,t} + \beta x_t + \sum_{i=1}^{k} \beta_i x_i K_{i,t} + u_t \tag{26}$$

K_i is dummy variables and T_B represents the date of structural break, when $t > T_B$, $K_i = 1$; in other cases, $K_i = 0$.

After obtaining significant results in the cointegration tests, it is possible to derive the long-term coefficients using the Phillips and Hansen (1990) Fully Modified Ordinary Least Squares (FMOLS) method to model the relationship between first-order stationary I(1) variables and the cointegrated significant relationship. The FMOLS method provides consistent, asymptotically unbiased results and is known to be successful even in small samples.

The FMOLS method with an (n + 1)-dimensional time series vector is expressed as in Equation (27).

$$Y_t = X_t' \beta + D_{1t}' \gamma_1 + u_{1t} \tag{27}$$

The deterministic trend variables $D_t = \left(D_{1t}', D_{2t}'\right)$ in Equation (27) and the stochastic variables n in system (28) are determined by the equation system X_t.

$$X_t = \Gamma_{21}' D_{1t} + \Gamma_{22}' D_{2t} + \varepsilon_{2t} \qquad (\Delta \varepsilon_{2t} = u_{2t}) \tag{28}$$

The FMOLS predictor predicts that the error terms in equation number (27) are symmetrical and unilateral long-term covariance

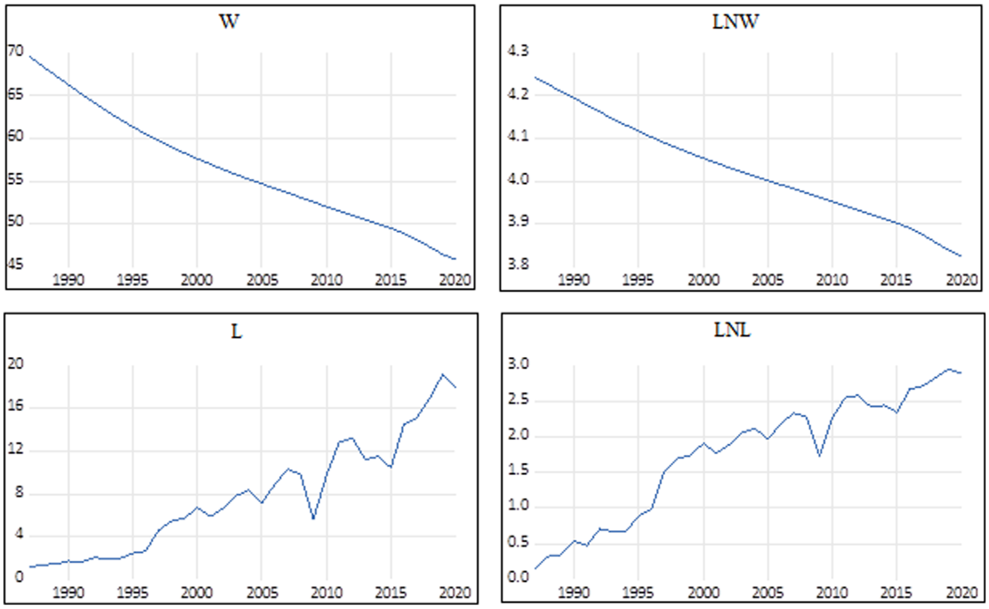

FIGURE 3 Graphs of variables.

TABLE 3 Descriptive statistics.

	W	L	LW	LL
Average	56.40250	7.766882	4.025760	1.753890
Median	55.52700	6.938500	4.016857	1.936689
Maximum	69.61500	19.20000	4.242980	2.954910
Minimum	45.85400	1.154000	3.825462	0.143234
Std. deviation	6.693599	5.253006	0.117673	0.857237
Skewness	0.328626	0.487935	0.157162	−0.484097
Kurtosis	2.090706	2.270610	2.017212	1.911228
Jarque-Bera	1.783293	2.102805	1.508285	3.007333

Note: 5% at the significance level, the main hypothesis is rejected.

matrices ($\hat{u}_{1t}$), and ($\hat{u}_{2t}$) in equation number (28) the long-term covariance matrices ($\hat{\Lambda}$) and ($\hat{\Omega}$) are estimated. The Fully Corrected Smallest Frames (FMOLS) predictor (29) is included in the equation.

$$\hat{\theta} = \begin{bmatrix}\hat{\beta}\\ \hat{\gamma}\end{bmatrix} = \left(\sum_{t=1}^{T} Z_t Z_t'\right)^{-1}\left(\sum_{t=1}^{T} Z_t Y_t^{+} - T\begin{bmatrix}\hat{\lambda}_{12}^{+\prime}\\ 0\end{bmatrix}\right) \tag{29}$$

It is expresses $Z_t = (X_t', D_t')$ in Equation (29).

4 | RESULT ANALYSİS

The analysis commenced with the examination of graphs and descriptive statistics related to the variables. Subsequently, the investigation progressed in the following order: stationary assessments, tests for structural breaks in cointegration, and then long-term coefficient estimations. Graphs of the natural logarithm-transformed data for the internal freshwater resources and lithium quantities, along with the original series, are presented in Figure 3. The descriptive statistics are represented in Table 3.

The graphs in Figure 3 reveal that both the original and logarithmic series of per capita renewable internal freshwater resources display similar behaviors. It is evident that there is a declining trend for both series. A decrease in water resources was observed from 1987 to 2020. Regarding the lithium reserve quantity, both the raw and logarithmic series exhibit somewhat similar behaviors, displaying an increasing trend and indications of breaks in the series.

When examining the descriptive statistics presented in Table 3, it is evident that the average per capita renewable internal freshwater resources amount to 56.40 m3, with the maximum quantity reaching 69.61 m^3. The average lithium reserve amount is found to be 7.77 tons. It is noted that, apart from the logarithmic series of lithium reserves, all other series exhibit positive asymmetry. Additionally, it was found that both the raw and logarithmic series of water and lithium quantities follow a normal distribution.

Following the examination of the diagnostic findings for the logarithmic time series of water and lithium used in the analyses, their stationarity was explored. The stationarity tests for the series were initially conducted without considering breaks, using the ADF and PP tests. The obtained results are detailed in Table 4.

When examining the findings from the ADF and PP unit root tests in Table 4, it is observed that based on the results of the ADF test in the stationary model, both the water and lithium series are stationary at the first difference, while the water series is stationary at levels according to the stationary and trend models. However, according to the PP test, the water variable is nonstationary in both models, while the lithium series becomes stationary at the first difference. Even though there is no common conclusion from the tests, a consensus of nonstationarity was observed. As a result, to verify whether the nonstationarity originates from a break in the series, structural break unit root tests were conducted (Table 5).

TABLE 4 ADF and PP unit root test results.

Variable	ADF		PP	
	With constant	With constant and trend	With constant	With constant and trend
LW	0.5215	−5.5004*	−1.2819	−2.4103
ΔLW	−3.4596**	-	−1.7314	−1.2856
LL	−1.3886	−2.4773	−2.2965	−2.3357
ΔLL	−6.5277*	−6.5068*	−8.9598*	−14.0845*

Abbreviations: ADF, Augmented Dickey–Fuller; PP, Phillips–Perron.
*1%
**5%
***10% shows the importance levels.

TABLE 5 Unit root test results with structural breaks.

		Zivot_Andrews		Lee_Strazicich unit root (2013)		Lee_Strazicich unit root (2003)		Narayan and Popp unit root (2010)	
	Model	Date of break	Test statistic	Date of break	Test statistic	Date of break	Test statistic	Date of break	Test statistic
LW	A	2006	−3.124363	2016	−2.962749	2001,2017	−5.65811 6*	1993, 2007	−4.213***
	B	2015	−3.715145						
	C	1997	−3.118434	2003	−4.614267**	1997,2017	−9.196889*	1996, 2002	−2.258
LL	A	1997	−5.688048*	1994	−2.967617	2008,2012	−3.004657	1996, 2008	−6.131*
	B	2001	−4.201219***						
	C	1997	−5.838679*	1996	−5.086405*	1996,2014	−5.937720**	1996, 2008	−5.841**

Note: A (intercept), B (trend), C (intercept+ trend).
*1%.
**5%
***10% shows the importance levels. For NP, the critical values are determined as −5.259, −4.514, −4.143 for the M1 model and −5.949, −5.181, −4.789 for the M2 model, respectively.

From the structural unit root tests; Zivot–Andrews unit root test, Lee–Strazicich single-double break unit root tests, and Narayan–Popp unit root tests were conducted. Upon reviewing the Zivot–Andrews test results, it was observed that for the water variable, it is nonstationary at the level with breaks in constant, trend, and constant & trend, while the lithium variable is stationary at the level. The conclusion was reached that the lithium variable is stationary at the level according to Models A and C, indicating that the significant break occurred in 1997.

When examining the findings from the Lee-–Strazicich single-break unit root test, it was observed that for Model A, both the water and lithium variables are nonstationary, whereas for Model C, both are stationary. The result suggested significant breaks in 2003 for the water series and 1996 for the lithium series, indicating that the series became stationary due to breaks.

When examining the findings from the Lee–Strazicich two-break unit root test, it was concluded that for Models A and C, the water series became stationary with breaks, hence signifying the significance of the break dates. However, for the lithium series, it was found to be nonstationary according to Model A but stationary according to Model C.

Finally, when the Narayan–Popp unit root test results were examined, it was seen that in model A (Model 1), which expresses a break in the constant, the water and lithium series were stationary with breaks. For Model C (Model 2), which represents a constant and trend break, it was found that the water series was not stationary, but the lithium series was stationary.

Considering the findings from the unit root tests accounting for structural breaks, as both series exhibit different levels of stationarity when breaks are considered, yet both indicate stationarity at the first difference, it was decided that testing for the cointegration relationship between the series with break cointegration tests would be appropriate.

The Gregory–Hansen test results in Table 6 reject the null hypothesis, indicating no cointegration based on the ADF and Zt statistics for both C and C/S models. This finding demonstrates a long-term relationship between the internal sweet water quantity and lithium reserves, with a single break in both level and regime. However, when considering two breaks, the Hatemi–J test reveals no cointegration relationship. When the findings of the Maki Cointegration Test, which takes multiple structural breaks into consideration, were examined in Table 7, it was concluded that the basic hypothesis cannot be rejected and therefore there is no cointegration relationship.

TABLE 6 Gregory–Hansen and Hatemi–J cointegration test results.

Test	Model	ADF	T_B	Z_t	T_B	Z_α	T_B
GH	C	−4.9133999**	1996	−4.9895812**	1996	−29.909649	1996
	C/S	−4.9118237***	1996	−4.9879805**	1996	−29.902592	1996
HJ	C	−5.5072101	1996 2002	−5.155	1996 2002	−31.352	1996 2002
	C/S	−5.118	1994 1996	−5.040	1994 1994	−31.580	1996 2002

Abbreviation: ADF, Augmented Dickey–Fuller.
*1% için.
**5%
***10% shows the importance levels. Critical values for Gregory–Hansen, ADF for model C & $Z_t = -4.61$ (5%) $Z_\alpha = -40.48$, ADF for model C/S & $Z_t = -4.95$ (5%); −4.68 (10%), $Z_\alpha = -47.04$. Critical values for Hatemi–J test ADF & $Z_t = -6.015$ (5%) $Z_\alpha = -76.003$.

TABLE 7 Maki multiple structural break cointegration test results.

Model	Test stat. ($m \leq 1$)	TB	Test stat. ($m \leq 2$)	TB	Test stat. ($m \leq 3$)	*TB*	Test stat. ($m \leq 4$)	TB	Test stat. ($m \leq 5$)	TB
M0	−2.208	1988	−2.572	1988 2016	-	-	-	-	-	-
M1	−4.412	2016	-	-	-	-	-	-	-	-
M2	−4.148	2001	−4.964	1995 2001	−5.064	1995, 2001, 2012	−5.064	1991,1995, 2001, 2012	−5.064	1991,1995, 2001, 2008, 2012
M3	−4.427	1997	−5.443	1997, 2015	−5.443	1997, 2009, 2015	−6.405	1997, 2002, 2009, 2015	−6.405	1990, 1997, 2002, 2009, 2015

TABLE 8 Model estimation results.

The dependent variable: LW	FMOLS (GH-C)	FMOLS (GH-C/S)
Independent variables	Coefficient	Coefficient
LL	−0.179428*	−0.185976*
C	5.509199*	5.561723*
D96	0.093942*	0.045432
LL*D96	-	0.006041

Abbreviation: FMOLS, Fully Modified Ordinary Least Squares.
*Indicates signifinance at the 1% level.

When all the findings obtained from the cointegration tests were evaluated together, it was seen that the only significant long-term relationship was in the Gregory–Hansen test. As the Gregory–Hansen test showed a significant long-term relationship in 1996 both at the level and regime, a dummy variable was created for the break year, and the FMOLS method was employed to obtain long-term coefficients.

The findings of the FMOLS model are presented in Table 8. Upon examination, in the model considering a single break at the intercept, all coefficients are statistically significant. The significance of the break year in 1996 is observed, highlighting the necessity of its consideration. In the model with a break at the intercept, the negative coefficient for lithium is consistent with economic expectations. It is found that a 1% increase in lithium reserves will lead to a 0.17% decrease in water quantity.

5 | CONCLUSION

Electric cars offer significant environmental advantages by reducing dependence on fossil fuels and lowering carbon footprints. However, achieving these advantages involves environmental challenges, particularly in the production of electric car batteries. This article analyzes the impact of lithium mining on water resources from 1987 to 2020 in Chile, which holds some of the world's largest lithium reserves. The findings indicate a long-term relationship between lithium mining and water resources, with a notable level break in 1996 marking a period of intensified impact. The implications of these findings on environmental sustainability, policy development, and industry practices are extensive and crucial for advancing sustainable electric vehicle (EV) adoption. Let us explore these aspects in detail.

1. Environmental sustainability

The evaporation method used for lithium extraction consumes significant amounts of water, which can deplete local water resources, especially in arid regions like the Atacama Desert in Chile. The depletion of water can lead to the destruction of local ecosystems, affecting both flora and fauna. Wetlands, for example, may dry up, leading to the loss of habitat for various species. The extraction process can also lead to contamination of water sources with harmful chemicals, further impacting the environment and local communities. While electric cars are promoted for their potential to reduce carbon emissions, the environmental impact of lithium extraction must be considered in the overall carbon footprint assessment. The energy-intensive nature of lithium extraction and processing can offset some of the benefits of reduced emissions from vehicle use. Ensuring the sustainability of lithium resources is crucial. Overexploitation can lead to resource depletion, making it imperative to find a balance between current extraction practices and future availability.

2. Policy development

Policymakers need to develop and enforce regulations that mandate sustainable mining practices. This can include setting limits on water usage, requiring the treatment and reuse of water, and ensuring minimal disruption to local ecosystems. Implementing stringent environmental impact assessment requirements before approving new mining projects can help identify potential issues and mitigate them beforehand. Governments can provide funding and incentives for the development of more efficient and less environmentally damaging extraction methods. This can include investing in technology that reduces water usage or finds alternative methods for lithium extraction. Encouraging or mandating battery recycling can help reduce the demand for freshly mined lithium, thus mitigating some of the environmental impacts associated with lithium extraction. Given that lithium is a globally traded resource, international collaboration is essential to establish global standards for sustainable lithium extraction and processing. Countries can work together to share best practices and technologies.

3. Industry practices

Companies involved in lithium mining should adopt best practices that minimize environmental impact. This can include using less water-intensive methods or investing in technology that reduces the environmental footprint. Companies should commit to corporate social responsibility (CSR) initiatives that focus on environmental sustainability. This can involve investing in local communities and ensuring that their operations do not negatively impact local water resources. Research into alternative materials for batteries that have a lower environmental impact than lithium can help reduce dependence on lithium. This can include the development of batteries using more abundant and less environmentally damaging materials. Increasing the efficiency and lifespan of batteries can also help reduce the frequency of battery replacements, thus lowering the overall demand for lithium.

Lithium extraction's environmental impact necessitates sustainable practices, robust policies, and industry innovations to balance ecological preservation with the growing demand for electric vehicle batteries.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author.

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