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DETECTING BUBBLES IN WORLD ALUMINUM PRICES: EVIDENCE FROM GSADF TEST

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Abstract. The aim of this research is to assess the existence of multiple bubbles in the global aluminum market by employing the Generalized Supremum Augmented Dickey-Fuller (GSADF) methodology. This method offers practical time series analysis tools for identifying periods of rapid price escalation, followed by subsequent collapses. Findings indicate the identification of six explosive bubbles occurring between January 1980 and March 2023, during which the aluminum price strayed from its underlying fundamental value. Additionally, this finding is consistent with the asset pricing model, which generally considers both fundamental and bubble components. Based on the empirical results, the aluminum price bubbles are positively influenced by the copper price, GDP, the U. S dollar index, industrialization of China, China's urbanization rate, whereas the global aluminum production, oil price, and base metal price index have a negative explanatory effect on the aluminum price bubbles. To effectively stabilize the international aluminum price, policymakers are suggested to be vigilant in identifying bubble episodes and monitoring their progression. Additionally, regulatory authorities should implement measures to curb excessive speculative activity during periods of extreme market volatility, thereby mitigating excessive price fluctuations and the formation of aluminum bubbles.

Keywords: aluminum price, generalized sup ADF test, multiple bubbles, macroeconomic factors, supply security, probit regression, determinants.

JEL Classification: E31, E64.

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1. Introduction

The issue of stability and sustainability has gained significant attention in economic and financial conversations, primarily because of notable historical occurrences in recent decades, including the initial and subsequent conflicts in the Gulf, the worldwide financial crisis in 2008, the Russo-Ukrainian conflict, and the ongoing COVID-19 pandemic. Over the last few decades, it has become evident that specific instances of economic bubbles collapsing are often accompanied by crises, like the 1929 Great Depression and the 2008 mortgage crisis (Khan et al., 2021b). According to Stiglitz, the price bubble occurs when the value of an asset surpasses its fundamental worth (Stiglitz, 1990). Investors, in accordance with the theory of rational expectations, increase the present value of a commodity if they predict that it will be sold at a higher price than its projected future value (Yao & Li, 2021). According to reports, aluminum, which is a non-ferrous metal, has gained widespread acceptance and is considered one of the most extensively traded metals on the London Metal Exchange (LME). It accounts for approximately 37% of the overall volume in futures contracts and nearly 48% of the total volume in traded options (Pincheira & Hardy, 2021; Chen et al., 2019). Aluminum, along with other non-ferrous metals, serves as raw materials possessing both commodity and financial characteristics. The prices of these items are frequently impacted by the global economy, the balance between supply and demand, production expenses, the current exchange rate of the dollar, and various other factors, resulting in frequent fluctuations and significant variations (Liu et al., 2020). The unpredictable swings and drastic shifts in the price of non-ferrous metals will directly impact manufacturers' assessment of the trend in raw material prices, subsequently influencing operational decisions.

It has been witnessed that bubbles attract investors during periods of rising aluminum prices, but can result in significant losses when the bubble bursts (Escobari et al., 2017). Policymakers also pay close attention to aluminum bubbles due to their potential to adversely impact economic activity, balance of payments deficits, price stability, exchange rates, and other relevant indicators (Potrykus, 2023; Wang & Kim, 2022). Due to rapid industrialization and economic growth in emerging economies, especially China, prices of aluminum have been prevocational. Despite recent attention paid to aluminum price bubbles, the factors that generate these bubbles and their bursts remain few and need further study. Thus, the aim of this research is to detect whether there are multiple bubbles in world aluminum price and the possible elements that trigger the creation of price bubbles. This recognition can be helpful for policymakers and investors in minimizing their investment losses and preventing damage to the economy.

The previous literature has discussed the various factors that account for the rising of metal prices. Numerous studies have debated the macroeconomic foundations, encompassing the increasing desire in developing economies, the geopolitical circumstances specific to commodities, fluctuations in oil prices, the devaluation of the US dollar, and the volatility in interest rates (Ozgur et al., 2021; Wzorek et al., 2017). Furthermore, the metal prices are driven higher by speculative activity, which is also identified as a catalyst that surpasses the influence of macroeconomic fundamentals. Thus, identifying metal price bubbles can avoid dramatic losses for the investors. Producers and manufacturers of aluminum can enhance their ability to create effective hedging strategies in the futures market. Investors can make more informed investment decisions by analyzing the presence of multiple bubbles in the aluminum market, considering market conditions and potential price risks. This analysis can contribute to the development of a more efficient aluminum market. Fluctuations in the prices of aluminum can have an impact on production costs and require risk management strategies, as it is an important input for different sectors including electronics, dental, jewelry, and manufacturing industry (Ahmed et al., 2022). As a crucial input for various sectors, such as electronics, dental, and jewelry, as well as the manufacturing industry, fluctuations in aluminum prices can impact production costs and necessitate risk management strategies. By identifying and understanding aluminum price bubbles, manufacturers can develop effective hedging strategies to maintain stable production costs (Umar et al., 2021). This can lead to more efficient business operations and improve performance in the physical sector. Moreover, investors and portfolio managers can make informed investment decisions by gaining insight into the aluminum market and its potential price risks. Therefore, providing information on aluminum price bubbles can support more rational investment decisions and risk management strategies.

Therefore, this article attempts to make contributions in several aspects. It is crucial to examine this phenomenon and establish measures to mitigate the impact of price bubbles caused by the significant fluctuation in aluminum prices, benefiting all participants in the market. By offering policymakers valuable insights, the study enables proactive policy formulation through accurate identification of aluminum price bubbles and their underlying factors. The research identifies multiple bubbles caused by shift to aluminum, supply disruptions, low production volumes, and stringent environmental regulations. Through the examination of the timeframes and dates associated with inflationary periods in aluminum prices, it is possible to thoroughly investigate the reasons and consequences, and subsequently implement measures to prevent their occurrence. In addition, the study utilizes a wide range of up-to-date data, encompassing the latest worldwide occurrences, to elucidate the sources of the bubbles. Based on previous literature, limited studies have specifically examined the occurrence of aluminum price bubbles during the COVID-19 period, characterized by its volatility. Furthermore, the utilization of Generalized Supremum Augmented Dickey-Fuller examinations proves to be superior in detecting bubbles in the price of aluminum compared to traditional methods. The two tests have better performance in detecting explosive features in intact samples and can confirm adequate observations to achieve approximate validity. In addition, the research offers a fresh method for analyzing data in the reverse SADF test. It utilizes a recursive approach to calculate the critical value of the ADF statistic in the right-tail and determines the origin and collapse based on the occurrence of the first-time span.

According to the results of this study, there have been six bubbles in the AP from January 1980 to March 2023. The primary factors responsible for the initial two bubbles are primarily the result of significant supply disruptions, rapid industrialization, and urbanization in developing nations, as well as the depreciation of the U. S. dollar. The strong worldwide economic expansion, swift industrialization and urbanization in China and India, soaring oil cost, instability of bauxite provision, along with nonessential factors like devaluation of the U. S. currency, speculation, and financial turmoil, are the primary causes of the third and fourth AP bubble. Furthermore, the occurrence of the fifth and sixth bubble can be attributed to the economic rebound following COVID-19, supply chain disruptions, geopolitical circumstances, and speculative activities. According to the probit regression, the AP bubbles are positively influenced by the copper price, GDP, and the U. S dollar index, whereas the global aluminum production amount, oil price, and base metal price index have a negative explanatory effect on the AP bubbles. Continuously following the valuable insights on the market's stakeholders' motivations is crucial to prevent any potential crisis. Likewise, it is imperative to create a system that can effectively identify the adverse impacts of disturbances on the global aluminum industry.

In the rest of the paper, information is arranged as follows. In Section 2, we discussed the latest literature. In Section 3, we introduced the methodology. In Section 4 we showed the data and empirical results. Section 5 we draw the conclusions and present several suggestions.

2. Literature review

Considerable research has been conducted on the presence of numerous stock bubbles in valuable and industrial metals, which holds great importance for investors and policymakers when formulating their investment strategies and macroeconomic policies. Based on the literature, a bubble is generally defined as the presence of an asset price that diverges from its fundamental value (Stiglitz, 1990). According to the rational expectation theory, if investors believe they can sell an asset for a higher price in the future, they may be willing to pay more than its fundamental value, leading to an increase in the asset's price. According to Brunnermeier (2016), bubbles are typically linked to a sudden surge in asset prices, which is then followed by a subsequent collapse.

There has been a long-standing debate about the factors that contribute to the price bubble. Numerous researches have indicated that economic factors play a crucial role in influencing global nonferrous metals markets. According to certain experts, alterations in currency exchange rates can lead to variations in the prices of aluminum. This is because the dollar serves as the currency for settling aluminum and other commodities. Consequently, when all other factors remain constant, fluctuations in the value of the dollar can result in changes in the prices of significant global commodities (Chen & Graedel, 2012). Batten et al. (2010) have conducted an analysis on it. The study revealed that the impact of monetary and financial variables on the variability of returns from precious metals cannot be fully explained by common factors. Conversely, it demonstrated that monetary and financial factors partially explain the volatility of returns in gold, platinum, and palladium (Batten et al., 2010). In a similar topic, Bastourre et al. (2012) provided empirical support for the hypothesis that depreciation of the US dollar, declining interest rates, and reduced global risk aversion contribute to the upward movement of commodity prices. Additionally, Baffes and Savescu (2014) concluded that fluctuations in the value of the US dollar, inventories of physical metals, and input costs significantly influence metal prices.

In addition, speculation has been considered a major factor influencing metal prices. Bosch and Pradkhan (2015) analyzed the prices of valuable metals in futures markets from 2006 to 2013. They concluded that speculative activity played a negligible part in causing fluctuations in future prices of precious metals. In addition to economic occurrences, the speculative capital has also been impacted by it, thereby playing a role in the significant fluctuations observed in aluminum prices in recent years (Wzorek et al., 2017). Aluminum is an investable asset, and speculation has an important influence in promoting bubble behavior (Boschi & Pieroni, 2009). Cifarelli and Paladino (2010) held the point that increases in market speculation could result in considerable adjustments to prices' underlying value. Mayer et al. (2017) analyzed the volatility in metal prices and concluded that speculative trading activity plays an insignificant role in explaining the metal price volatility. After the worldwide economic downturn, Figuerola-Ferretti and McCrorie (2016) showcased the growing significance of speculative behavior in the prices of valuable metals. According to Sun et al. (2013), previous research has demonstrated the presence of a cointegration connection between the liquidity of money and the prices of aluminum in China. Furthermore, it has been found that monetary liquidity has a strong positive impact on prices over extended durations (Sun et al., 2013). Furthermore, research conducted by Pierdzioch et al. (2016), Reboredo and Ugolini (2016) demonstrates that the relationship between interest rate fluctuations and oil prices will also affect the non-ferrous metal market.

According to microeconomic theory, fluctuations in supply and demand have an impact on the fundamental value of non-ferrous metals, resulting in price changes (Boschi & Pieroni, 2009). Brooks et al. (2015) hold the idea that the significant increases and subsequent declines in commodity prices primarily rely on underlying factors rather than being the outcome of speculative actions. Labys et al. (1999) substantiate the importance of macroeconomic influences on metal prices. Specifically, variations in manufacturing output have been discovered to significantly impact the prices of metals (Labys et al., 1999). Recent research indicates that the escalating export of raw materials from China has had a substantial impact on the global aluminum market, leading to a significant surge in the supply of this metal (Liaqat et al., 2020). At the same time, the increased demand for aluminum due to the economic growth of the most dynamically developing countries (e.g. India) has been noted (Wzorek et al., 2017). Choi et al. (2020) employ the SVAR model to investigate the dynamic impacts of worldwide supply and demand disturbances on commodity prices and the findings indicate that demand shocks play a more significant role than supply shocks in influencing the prices of six nonferrous metals, namely copper, aluminum, lead, zinc, nickel, and tin.

Various methods have been employed to investigate the presence of financial market bubbles. The Supremum Augmented Dickey-Fuller test is a rigorous statistical procedure used to ascertain the existence of bubbles, in contrast to alternative approaches which may be based on subjective judgments that depart from foundational principles or moderate assumptions. The research findings of Phillips et al. (2015) suggest that the technique shows great efficacy in cases where there is only one occurrence of a bubble event in the dataset (Phillips et al., 2015). However, when the sampling period is prolonged, numerous asset price bubbles may become evident. Detecting multiple bubbles with cyclical collapses in econometrics poses a greater challenge compared to identifying individual bubbles, often resulting in a diminished ability to recognize them using current testing methods (Brunnermeier, 2016). Therefore, Phillips et al. (2015) provide Generalized Supremum Augmented Dickey-Fuller (GSADF) test for testing and measuring bubble phenomena in the presence of multiple bubbles. Several research studies have shown that the GSADF technique is effective in identifying the existence of bubbles. According to Su et al. (2017), GSADF method can be utilized to investigate the presence of multiple bubbles in the price of West Texas Intermediate (WTI) crude oil. Caspi et al. (2018) hold the idea that the objective was to chronicle periods of historical oil price volatility using the GSADF test method. Sharma and Escobari (2018) test for the existence of single and multiple episodes of explosive behavior in three energy sector indices (crude oil, heating oil, and natural gas) and the results from the GSADF tests provide strong statistical evidence of explosive behavior in all energy series. According to Floros and Galyfianakis (2020), bubbles in the crude oil price and energy index have been detected. Su et al. (2020) investigate the moderately volatile nature of copper prices and identify the initiation and conclusion of bubble occurrences utilizing the GSADF method. Ozgur et al. (2021) identify possible bubbles in the prices of metals like gold, platinum, and palladium. Wang et al. (2023b) utilized the GSADF method to investigate the presence of periodic bubble phenomena in nickel price. Wang et al. (2023a) introduced a novel and reliable method for evaluating the enthusiasm and downfall of bubble episodes through consistent date-stamping assessment.

This article seeks to contribute to various areas by accurately identifying multiple instances of aluminum price bubbles, thereby offering significant insights into the formation and characteristics of such bubbles. While the volatility in nonferrous metal markets has been extensively examined in previous literature, there has been a lack of separate discussion on the behavior of the aluminum bubble. The causes which result in the aluminum price bubbles have also been considered in this article. Second, this article uses extensive and latest research period which include the COVID-19 period. Finally, while numerous researches are focusing on the bubbles in metal prices, this article stands out from the current literature and capitalizes on the GSADF test's methodological strengths in identifying bubbles in aluminum prices. Additionally, it leverages machine learning algorithms to offer valuable insights as early warning indicators for price bubbles in these markets.

3. Methodology

The theoretical analysis of identifying multiple bubbles from market fundamentals is conducted in this paper using the asset pricing model (Lucas, 1978) . According to Tirole's theory (Tirole, 1985), it is widely acknowledged that commodity prices can deviate from market fundamental values due to slightly explosive behaviors. According to Gürkaynak (2008), the basic values of the aluminum commodity are determined based on the absence of arbitrage.

$$P_t = (1+r_f)^{-1} E_t (V_{t+1} + U_{t+1}), \tag{1}$$

where P_t is the aluminum price in the period t, E_t is the expectation, r_f is the free-risk rate, V_{t+1} is the returns within period $t+1$ and U_{t+1} represents the invisible elements.

$$P_t^c = \sum_{i=0}^{\infty} (\frac{1}{1+r_f})^i E_t \left(V_{t+i} + U_{t+i}\right) \text{ for } i = 0,1,2, \tag{2}$$

where P_t^c is the fundamental price, V_{t+i} is the dividend within period $t+i$. It shows the determinants of the fundamental price.

$$D_t = (1+r_f)^{-1} E_t (D_{t+1}), \tag{3}$$

where is the series of random variables which could content the homo-generous expectational equation?

$$P_t = P_t^c + D_t. \tag{4}$$

Market fundamentals and bubbles are the two parts of the fundamental model. In Eq. (4), an element of market fundamentals is added to the solution to Eq. (1).

There is an assumption about B_t to determine price. When $B_t = 0$ it represents that the value of bubbles is zero and the price is fundamental. If $B_t \neq 0,$ it can be seen that there are explosions and the price of bubbles is not zero.

Phillips et al. (2015) has improved *SADF* which can identify the bubbles not only in financial but also in physical assets. Homm and Breitung (2012) has proved the *SADF* test to be useful in identifying in cyclical collapsing behaviors and superior to other bubble tests as follows:

$$P_t = aT^{-\beta} + \phi P_{t-1} + \varepsilon_t, \tag{5}$$

where a is a constant, T is sample size, $\phi > 1/2,$ $\varepsilon \sim NID\left(0, \sigma^2\right),$ $\phi = 1.$ Eq. (5) is a random walk process. We can suppose that s_1 is the starting date, s_2 is the ending date and s_w is the window size and $s_2 = s_1 + s_w.$ The Equation is as follows:

$$\Delta P_t = \alpha_{s1,s2} + \beta_{s1,s2} P_{t-1} + \sum_{i=1}^{j} \eta_{s1,s2}^i \Delta P_{t-i} + \varepsilon_t, \tag{6}$$

where P_{t-1} is the asset price $\varepsilon_t \sim NID\left(0, \sigma\right),$ j is the number of lag order, and it can be explained by significance tests (Liaqat et al., 2019). It is possible to define the unit root null hypothesis as $\beta = 1.$ An alternative hypothesis is that $\beta > 1,$ which shows that p_{t-1} is explosive. To overcome the restriction in periodically collapsing bubbles of unit root tests, the supreme of *ADF* T-statistics is used by Phillips and Perron (1988). SADF is an evaluation of the repeating *ADF* model. Also, *ADF* statistic time series can be detected by detecting the hypothesis of sup value. The range of window size s_w is from s_0 to 1, and $s_2 = s_1 + s_w.$ The ADF_0^{S2} statistic is from 0 to s_2 for a sample, which shows as

$$SADF\left(s_0\right) = \overset{SUP}{]} ADF_0^{S2}. \tag{7}$$

The *SADF* technique has demonstrated efficacy in separating individual bubbles within a sample. However, when the time period is extended to accommodate multiple bubbles, *SADF* may prove ineffective in accurately identifying more than two bubbles, leading to potentially unreliable and misleading results. To address this limitation, the *GSADF* test offers greater flexibility in window widths through the adjustment of starting and ending points, thereby enhancing its effectiveness in detecting the presence of multiple bubbles compared to the *SADF* test.

The *GSADF* test expands upon the *SADF* test by utilizing a larger sample sequence data. *GSADF* allows the feasible starting points s_1 to change within a little range from 0 to $s_2 - s_0$, and the ending point s_2 varies from s_0 to 1. Therefore, the *GSADF* test is better than the *ADF* test in detecting bubbles in long time episodes. With the feasible ranges of s_1 and s_2, the test is used as to be the biggest *ADF* statistic and denoted by *GSADF* (s_0). That is,

$$GSADF\left(s_0\right) = \sup_{s2\in[s0.1].s1\in[0.s2-s0]}(ADF_{s1}^{s2}). \tag{8}$$

When there is an intercept in the regression model and a random walk is the null hypothesis, the limit distribution is:

$$ADF_{s1}^{s2} = \left\{ \frac{(1/2)s_w[x(s_2)^2 - x(s_1)^2 - x_w] - \int_{s1}^{s2} x(s)ds[x(s2) - x(s1)]}{s_w^{1/2}\left\{ s_w \int_{s1}^{s2} x(s)^2 dx - \left[\int_{s1}^{s2} x(s)ds \right]^2 \right\}^{1/2}} \right. . \tag{9}$$

Statistical analysis of the *SADF* and *GSADF* models is conducted using standard normal distributions with $s_w = s_2 - s_1$ representing a standard Wiener process. The finite nature of the standard Wiener process necessitates the generation of a finite number of points, achieved by creating Gaussian random variables in equally spaced intervals denoted as $q_1, q_2 \ldots q_n$. To effectively compute and identify bubble processes, a bootstrap methodology can be employed and validated through Monte-Carlo simulation. Pavlidis et al. (2019) reveal that this method can keep in step with the unanimous process off the fundamentals and offer a date-stamping strategy.

This paper further examines the impact of macroeconomic factors on aluminum bubbles, taking into account the timeline of enthusiasm in the global copper market. Following Su et al. (2020), we define *Bt* as

$$B_t = \begin{cases} 0, \text{ if } BSADF_t\left(r_0\right) < cv_t^{\beta T} \\ 1, \text{ if } BSADF_t\left(r_0\right) < cv_t^{\beta T} \end{cases}, \tag{10}$$

where t = 1, 2, ..., T. According to Eq. (10), *Bt* equals 1 when a bubble is detected on the t-th date. The impact of macroeconomic factors on the aluminum bubble *Bt* is estimated by employing probit regression. We value it as below;

$$B_t = A_t' \alpha + u_t, \tag{11}$$

where A_t is the macroeconomic determinants of aluminum price like aluminum supply, copper price, oil price, GDP, base metal price index, US dollar rate. The probit model is described as

$$P\left(B_t = 1 | A_t\right) = \varphi\left(A_t' \alpha\right). \tag{12}$$

The parameters are a mean of cause-effect which is estimated by the log-likelihood function and is labelled as:

$$\ln L = \sum_{t=1}^{T} B_t \ln\left[\varphi\left(A_t \alpha\right)\right] + \sum_{t=1}^{T} \left(1 - B_t\right) \ln\left[1 - \phi\left(A_t' \alpha\right)\right]. \tag{13}$$

However, the marginal effect offers evidence about the degree of influence.

$$\frac{\partial p\left(B_t = 1 | A_t\right)}{\partial A_j} = \varphi\left(A_t \alpha\right) \times \alpha_j. \tag{14}$$

4. Data

The formation of several moderately explosive episodes in the aluminum market is examined in this study using LME aluminum spot prices from January 1980 to March 2023. The information utilized in this study is acquired from the database of the International Monetary Fund, which has been accessible to the general public since January 1980 (Su et al., 2020). The LME aluminum price is widely acknowledged as the primary global standard for determining the cost of aluminum, representing worldwide supply and demand conditions (Pincheira & Hardy, 2021). To analyze the possible reasons for aluminum price bubbles, we have considered various macroeconomic factors such as the supply of aluminum, GDP, oil prices, copper prices, fluctuations in the dollar, the US policy rate, the industrialization of China and China's urbanization rate. The factors collected from literature have been demonstrated to play a vital role in shaping the price of aluminum and the occurrence of price bubbles. Information can be obtained from the World Bank Database (World Bank, n.d.), IMF database (International Monetary Fund, n.d.), Wind Economic database (n.d.) and the National Bureau of Statistics (n.d.) website of China. According to the previous literature, the commodity price booms mainly due to the economic activity dynamics in China and other emerging economies (Su et al., 2020; Liao et al., 2018; Arango et al., 2012). Lombardi et al. (2012) also employed global industrial production as a proxy for the global economic activity and the demand for metals to examine the metal price movements. Additionally, the study utilized global industrial output as a substitute for worldwide economic performance and the need for metals in order to analyze fluctuations in metal prices. According to research, there is a correlation between the price of oil and the price of metal due to the impact of oil price fluctuations on production and transportation expenses in the metal industry (Dutta, 2018). According to Henckens and Worrell (2020), aluminum is presently employed as a replacement for copper in numerous electrical applications. According to economic theory, price hikes will ultimately result in more affordable options like alternatives, novel substances, or higher rates of recycling (Pincheira & Hardy, 2021). Thus, aluminum price has been selected as a variable in the research. The USD index is considered a financial factor and serves as a genuine measure of the US dollar's effective exchange rate. This index can be obtained from the IMF database (International Monetary Fund, n.d.). The prevalence of the US currency in metal transactions indicates the impact of variations in the actual worth of the US dollar on metal price fluctuations. Therefore, Su et al. (2020) and Ozgur et al. (2021) highlighted the impact of US dollar depreciation in portfolio allocation and decisions and their implications on commodity prices.

Significant price fluctuations of aluminum have been observed since the 1980s, as depicted in Figure 1. Following a gradual and consistent decline from 1980 to 1986, the cost of aluminum experienced a significant surge, reaching nearly $3500 per ton in 1988, before subsequently declining as a result of heightened availability. Since that, the aluminum price has fluctuated moderately till 2003 from a range of $1110 to $2059 per ton. Since the start of 2003, there has been a noticeable upward trend in the price of aluminum, reaching a major high in May 2006 and a secondary high in February 2007 as a result of significant economic growth in China (Ashkenazi, 2019). Following a brief decrease, it experienced a subsequent increase, reaching $3012 per ton in July 2008. As a result of the worldwide economic downturn, the price of aluminum plummeted significantly, reaching a low of $1338 per ton in early 2009. Between 2009 and June 2011, the cost of aluminum experienced an ascending trajectory, reaching its pinnacle at $2557 per ton. Subsequently, it continued to fluctuate consistently until the onset of the COVID-19 pandemic. Due to the coronavirus lockdown, the worldwide aluminum market is being impacted, leading to an anticipated decrease in demand and a subsequent drop in prices to the lowest point of $1459 per ton since 2009. Nevertheless, due to the surging worldwide demand for economic rebound post-COVID-19, the cost of aluminum has witnessed a significant surge, reaching an unprecedented peak of $3498 per metric ton. This surpasses the previous record set in 2008 before entering a subsequent period of continuous decline, marked by its volatile nature. Due to the volatile fluctuations, it is believed that the price of aluminum may experience several instances of bubbles.

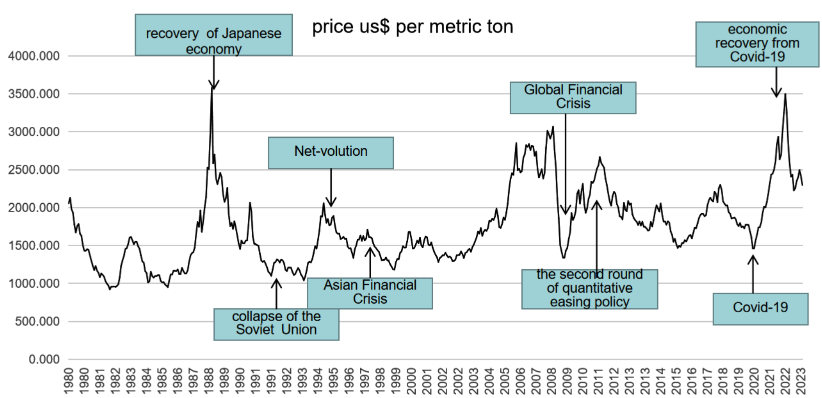


Figure 1. LME aluminum spot price, January 1980 to March 2023

5. Empirical results

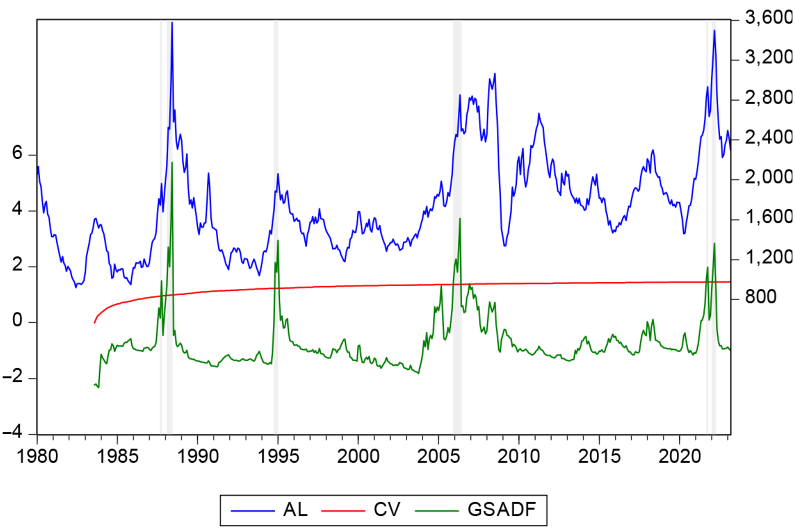
This article utilizes the SADF and GSADF methods to examine the presence of various bubbles in aluminum prices. Table 1 contains the recorded statistics of SADF and GSADF, along with their corresponding sample critical values. Through analysis, it is concluded that aluminum foam exists in the global aluminum market. For the complete data series, SADF and GSADF were 3.709 and 5.743 respectively. Respectively these overstepped 1% right-tail critical value (i.e., 3.709 > 2.015, 5.743 > 2.807). The null hypothesis H_0: $\beta = 1$ has been rejected. According to tests conducted by the GSADF and the SADF, it is concluded that the price of aluminum has risen, and we can identify possible bubbles.

Table 1. The results of the tests conducted by the SADF and GSADF

Aluminum price	SADF	GSADF
	3.709***	5.743***
Critical value		
90%	1.212	2.035
95%	1.487	2.279
99%	2.015	2.807

Note: Critical values for both tests are obtained from Monte Carlo simulations with 10,000 replications. ***Denotes significance at 1% level.

According to GSADF test results, the estimation of aluminum price can be shown in Figure 1. In Figure 1, In the graph below, the middle curve represents 95% of the critical value, while the bottom curve represents 95% of the critical value. Considering the generation and rupture of bubbles, there are six bubbles during the whole sampling period. GSADF test has been proved to be superior to SADF. In the GSADF test, the window widths can be varied to increase sample sizes for detecting explosive behavior, and the test rarely produces false positives. This allows us to identify the aluminum market's multiple bubbles and causes.



Note: Shadows are sub-periods surrounded by bubbles

Figure 2. GSADF test of the price of aluminum

The GSADF test detects six bubbles in the aluminum price over the sample period. Figure 2 has illustrated the bubble periods during 1980–2023. The first two bubbles appeared in 1987:9 to 1987:10 and 1988:2 to 1988:6. Figure 2 shows that the aluminum price rose 104.9 per cent from $1746.1 to $3578. 1 per metric ton, the largest rising range. The price bubble is driven more by supply than by demand, in consideration of the massive supply disruptions and capacity constraints in major aluminum producing countries. Based on the findings of the International Aluminum Institute (IAI), it is evident that global aluminum production experienced a decline during the initial half of 1987. Notably, both the United States and China witnessed a decrease in their respective aluminum production, with the former observing a decline of approximately 4%. Consequently, this reduction in aluminum supply has exerted upward pressure on its prices. In addition, the global demand for aluminum has increased in 1980s. It has been stated that aluminum has found extensive application across various contemporary industrial sectors, notably in construction and automotive domains (Ashkenazi, 2019). Consequently, the demand for aluminum has witnessed a substantial surge, thereby exerting an upward pressure on its price. Moreover, the value of the U.S dollar experienced a decline in relation to various currencies in 1987. Given the international nature of aluminum as a commodity, its pricing conventionally relies on the US dollar denomination (Pincheira & Hardy, 2021). Consequently, when the US dollar depreciates, the value of aluminum escalates in alternative currencies, thereby inducing an increase in its overall price (Figuerola-Ferretti & McCrorie, 2016).

The second bubble which occurs in 1988:2 to 1988:6 has also been stated driven by the similar factors. Firstly, in 1988, the global supply of aluminum experienced a notable tightness in relation to the dynamics of supply and demand. This scarcity primarily stemmed from the sluggish growth in aluminum production among producing nations, juxtaposed with a persistent rise in demand. Notably, the swift industrialization and expansion of the construction sector in Asia have played a pivotal role in augmenting the need for aluminum, thereby exacerbating the imbalance between supply and demand and subsequently driving up its price (Zhu & Jin, 2021). Second, the aluminum production process necessitates a substantial amount of energy, particularly electricity. In 1988, the escalation of global crude oil prices ensued in heightened energy expenditures (Wang & Kim, 2022). This factor significantly contributed to the surge in aluminum prices, as the augmented energy costs directly impacted the expenses associated with aluminum production (Wzorek et al., 2017). Concurrently, the United States and Canada enacted protectionist trade policies and imposed restrictive measures on aluminum goods, including the imposition of tariffs and import bans (Manberger & Stenqvist, 2018). Consequently, the supply of aluminum products experienced a decline, thereby propelling the escalation of aluminum prices. Last but not least, according to economic theory, price increases are expected to result in the emergence of lower-cost alternatives, such as substitutes, innovative materials, or increased recycling rates (Bartoš et al., 2022). This trend is evident in the case of copper, which used to be the second most commonly used metal but has been increasingly replaced by aluminum due to its higher cost (Campbell & Perron, 1991). Furthermore, aluminum has been identified as a viable substitute for copper in numerous electrical applications (Manberger & Stenqvist, 2018). The data from the London Metal Exchange (LME) indicates a significant rise in copper prices, from $2283 per ton to $3496 per ton which has consequently driven the demand for substitute metals like aluminum. The primary catalysts for the aluminum price bubble in 1987 and 1988 encompassed a reduction in aluminum supply, heightened demand, the devaluation of the US dollar, imposition of import tariffs, escalating copper prices, and surging oil prices.

The third bubble began in October 1994 and ended in January 1995 which lasts 4 months. Figure 2 shows that the aluminum price increased from 1694.26 to 2059.36 per metric ton, an increase 21.5%. Generally, commodity booms coincide with positive market fundamentals and a developing world economy (Sánchez Lasheras et al., 2015). In 1994, there were indications of a global economic recovery, particularly with robust economic expansion observed in the United States and Europe, resulting in an increased demand for industrial metals like aluminum. The United States, under Clinton's administration, embarked on a transition towards the "new economy" era, characterized by the prominence of information technology. During this period, not only did the GDP sustain a consistently high growth rate of approximately 4% for several consecutive years, but inflation also experienced further alleviation compared to the 1980s, while the unemployment rate reached an unprecedented low level (Figuerola-Ferretti & McCrorie, 2016). Thus, the economic recovery has significantly bolstered the demand for aluminum in the realm of industrial manufacturing. Concurrently, there existed sanguine prospects for economic expansion in the Asian region, particularly with regards to the swift progress of emerging markets like China and India. Consequently, these developments have engendered heightened expectations for aluminum demand, thereby exerting upward pressure on aluminum prices. Meanwhile, aluminum production requires a large amount of bauxite as a raw material (Zheng et al., 2022). In 1994, the instability of the primary bauxite exporting country has had a significant impact on the supply of bauxite. It has been reported that the closure of the Webb Estuary, a crucial bauxite export port, severely limited Australia's bauxite exports, resulting in a noticeable decline in export volume (Ashkenazi, 2019). Concurrently, Equatorial Guinea, the primary worldwide supplier of bauxite aluminum ore, encountered a military overthrow, resulting in political and economic turmoil that impacted bauxite exports to some degree, ultimately causing a shortage in meeting the growing demand for consumption (Ashkenazi, 2019). Overall, the imbalance between rigid supply and explosive demand gave an impetus to the surge in the aluminum price and result in the price bubbles during this phase.

The fourth bubble appeared between December 2005 and June 2006. This bubble lasted longer than ever, nearly seven months. The significant increase in demand for industrial metals, especially in developing countries, is the main reason for this bubble-like trend caused by massive demand shocks. In 2005 China's GDP grew by 11.3% making the demand for aluminum increased significantly. A major economic plan was introduced by China during this time frame in the Eleventh Five-Year Plan, including accelerating the urbanization process and revitalizing the equipment industry, which also increased the huge demand for aluminum (Zhu & Jin, 2021). During China's period of rapid economic growth, there has been a substantial increase in the demand for infrastructure construction, resulting in the widespread utilization of aluminum as a crucial building material. The construction, transportation, and power sectors have witnessed a substantial consumption of aluminum materials, thereby stimulating the growth in demand for this resource (Yu et al., 2021). Additionally, in 2005 to 2006, the escalating prices of energy sources, including crude oil and coal, have contributed to the rise in energy costs associated with aluminum production (Khan et al., 2021a). Moreover, in 2006, the Indonesian government has implemented stricter policies requiring the majority of bauxite to be used for domestic processing in order to increase local industry development and increase economic income which also contribute to the increasing of aluminum costs (Wang et al., 2023a). Furthermore, there has been a notable escalation in the price of copper during this specified timeframe. According to the latest data provided by LME, the cost of copper has experienced a significant increase, rising from $4056 to $8059 per ton between November 2005 and May 2006. In the realm of electrical applications, aluminum has been widely regarded as a viable alternative to copper (Manberger & Stenqvist, 2018). Consequently, the surge in copper prices has inevitably led to an augmented demand for its substitute (Bartoš et al., 2022). Thus, in terms of this background of tight supply and demand situations, aluminum price bubble would be triggered unsurprisingly.

The fifth bubble began in September 2021 and ended in October 2021, the bubble last only one mouth and burst rapidly. Aluminum prices increased from $2834.56 to $2934.39 per metric ton. COVID-19 has been recognized as the greatest macroeconomic impact, which has had an impact on commerce, the global economy, and people in general (Galán-Gutiérrez & Martín-García, 2022). The shortage of aluminum supply worldwide is one of the main reasons for the rise in aluminum prices. The global epidemic has been acknowledged as the cause of imbalances in the global supply chain, which have been further exacerbated by escalating fuel costs, limited availability of shipping vessels, and extended durations for loading and unloading at ports. Consequently, global shipping prices and expenses have surged, while the accessibility of aluminum inventories in Asia to markets like Europe and the United States has become challenging. In response to the escalating international market prices and in an effort to mitigate the impact on domestic metal product prices, Russia, being the world's second largest primary aluminum producer (6%) and the largest exporter of aluminum ingots (17%), has implemented export tariffs in August, of which aluminum was levied 15% export tariffs, specifically, the price of each ton increased by $254 (Yi et al., 2022). Dogan et al. (2022) have also hold the idea that COVID-19 pandemic has triggered uncertainty and volatility in commodity prices, investors are more likely to regard nonferrous metals as safe haven due to risk diversification.

Based on data from the World Health Organization's Coronavirus (COVID-19) Dashboard, there has been a discernible decline in weekly confirmed cases of COVID-19 from August to October 2021. Economic recovery has further boosted global demand for aluminum. As we all know, commodities are typically cyclical assets, rising and falling in tandem with the global economy, which makes them the first to benefit from a recovery that may be unleashed by a virus vaccine. In the current era, the global economy has been experiencing a gradual recuperation from the adverse effects of the COVID-19 pandemic. Consequently, this economic resurgence will inevitably generate a surge in the demand for commodities. The stability of commodity prices is intricately linked to the well-being of the national economy and the livelihood of individuals. Furthermore, the revival of industries, national infrastructure development, and social stability are inextricably intertwined with the availability and security of commodities (Bosch & Pradkhan, 2015). Among the non-ferrous commodities, aluminum holds significant importance as a crucial industrial material for fostering the growth of the national economy. Furthermore, in September 2020, China made a declaration to reach its peak carbon dioxide emission by approximately 2030 and attain a state of "carbon neutrality" by 2060 (Jiang & Chen, 2022). This commitment has led to an increased demand for aluminum in China, as it is widely acknowledged as a preferred material for the production of renewable energy equipment due to its advantageous properties such as corrosion resistance, lightweight nature, and high strength (Ashkenazi, 2019).

The supply side is also noticeable that merits consideration. Guinea boasts the largest reserves of bauxite on a global scale and holds the prestigious title of being the leading producer of bauxite worldwide. Statistical evidence indicates that Guinea's bauxite reserves account for approximately 50% of the total global reserves (Wang et al., 2023b). As a result, Guinea occupies a pivotal position within the global bauxite supply chain. Thus, any fluctuations in Guinea's bauxite supply situation have the potential to exert an influence on the stability and pricing of the global aluminum industry. In September 2021, President Alpha Condé orchestrated a coup in Guinea, leading to the consequential disruption of bauxite production (Wilhelm, 2020). The prevailing instability in the region poses potential risks of production facility closures, supply chain disruptions, and transportation challenges. Moreover, the international community responded to the coup by imposing sanctions, specifically restricting Guinea's bauxite exports. Consequently, an inevitable outcome of these developments is an anticipated rise in the price of aluminum.

The last bubble began in January 2022 and ended in April 2022. Figure 2 shows that the aluminum price increased from 3005.98 to 3246.99 per metric ton, an increase 8%. In the beginning of 2022, the global economy commenced its recuperation from the repercussions of the COVID-19 pandemic, thereby engendering a heightened requisition for diverse sectors, encompassing industrial production and construction (Dogan et al., 2022). Consequently, there has been a notable upsurge in the demand for aluminum commodities. However, it is imperative to acknowledge the significance of the geopolitical crisis, specifically the Russia-Ukraine conflict, as Russia holds the esteemed position of being the world's second largest primary aluminum producer and the foremost exporter of aluminum ingots (Zhou & Lu, 2023). Consequently, the crisis is bound to exert an inevitable influence on the global supply of aluminum. Furthermore, the conflict has prompted various nations, including the United States, United Kingdom, and Canada, to impose trade restrictions or sanctions on Russia (Wang et al., 2023a). Consequently, this will impede the exportation of Russian aluminum products, thereby exacerbating the price of supply sources. Furthermore, in the latter part of 2021, Europe encountered a significant energy crisis which can be attributed to a confluence of factors, encompassing adverse weather phenomena, insufficiencies in energy supply, and escalating prices (Wzorek et al., 2017). Notably, energy constitutes a pivotal cost component in the production of aluminum, encompassing expenses related to electricity and fuel. Consequently, any escalation in energy prices is anticipated to augment the cost of aluminum production, thereby exerting upward pressure on aluminum prices. Consequently, the disparity between the supply and demand has led to the bubbles in aluminum prices.

According to the above discussion, metal prices may have increased due to a variety of factors. The most significant determinants include aluminum supply, oil prices, copper price, global economic recovery, alternative metal price, U.S dollar movements, interest rate and rapid developing in China. Specifically, global aluminum production amount, crude oil price index, GDP, LME copper spot price, base metal price index, U.S dollar index, monetary policy-related interest, industrialization of China and China's urbanization rate have represented the factors that influence aluminum price bubbles. Hence, we utilize the probit regression model to evaluate the fundamental macroeconomic determinants of the volatile nature of aluminum price bubbles, and the results are presented in Table 2. The log likelihood value exceeds the critical value of 50%, indicating the variables have a significant explanatory power. As a result, we provide a more detailed explanation of the influence of each variable.

The negative and statistically significant coefficient of global aluminum production amount indicates that it has a regulatory effect on the occurrence of bubbles. Insufficient supply of aluminum, caused by a decrease in physical supply that falls below demand, exerts upward pressure on the price, increasing the probability of a bubble forming. Furthermore, it can be observed that the crude oil price exhibits a negative correlation with the occurrence of aluminum price bubbles. A decrease in the oil price is likely to lead to a subsequent decrease in the price of aluminum, consequently stimulating higher demand and thereby increasing the probability of aluminum price bubbles. Third, GDP is confirmed positively affect bubble occurrence. The outcome indicates that bubble phenomena are more prone to happen with an increase in the GDP. Furthermore, it has been verified that the price of copper is both positive and statistically significant, indicating that the copper price exerts a favorable regulatory influence on the emergence of bubbles. Moreover, the increase in copper prices has inevitably resulted in a heightened need for alternative materials like aluminum (Bartoš et al., 2022). Thus, the increasing demanding of aluminum will result in the possibility of aluminum price bubbles. Fifth, base metal price index is confirmed to negatively affect bubble occurrence. According to the findings, bubble behavior is more prone to happen with the appreciation of the dollar. Fluctuations in the price of aluminum are inevitable due to changes in the value of the U. S. dollar, as the international aluminum price is usually expressed in dollars, which encourages slightly volatile price movements. Moreover, it has been verified that the impact of monetary policy-related interest rates on the occurrence of bubbles is predominantly negative. However, the influence of the interest rate associated with monetary policy is not statistically significant. In addition, the industrialization of China has shown positively affected bubble occurrence. Specifically, the marginal effect explains the change in the dependent variable due to a unit change in the independent variable. In this way, a unit change in industrialization in China leads to a 4.5% rise in aluminum price. Considering aluminum is commonly utilized across a range of industries, including steel, aerospace, and door and window manufacturing, which suggests that heavy-industry experienced accelerated growth, leading to heightened demand for aluminum and subsequently higher aluminum prices (Shi et al., 2018). Last but not least, China's urbanization rate has been demonstrated a to exert a positive effect on the occurrence of aluminum price bubble. The increasing demand for aluminum in China is primarily driven by the rapid pace of industrialization and urbanization, as the metal is widely utilized in various sectors such as construction, infrastructure, transportation, and consumer goods (Li et al., 2022).

Table 2. Probit Regression test

Variable	Coefficient	Std.Error	z-Statistic	Marginal effect
GAP	–0.0006543**	0.000362	–1.81	–0.0000225
OP	–0.0195127**	0.0104556	–1.87	–0.0006723
GDP	0.0005137***	0.000133	3.86	0.0000177
CP	0.0011544***	0.000249	4.64	0.0000398
BMPI	–0.028267***	0.0104827	-2.7	–0.000974
USD	0.0354179**	0.014483	2.45	0.0012204
MPI	0.0030243	0.0402816	0.08	0.0001042
IND	1.309536	0.7183056	1.82	0.0451211
URB	0.2668773	0.0865405	3.08	0.0091955
CV1	–0.0001054***	0.000029	–3.63	–0.00000363
CV2	–0.0008142**	0.0004467	–1.82	–0.0000281
cons	–26.75913	8.400387	–3.19	
Log likelihood		–72.314		
LR statistic		93.14		
Prob > chi2		0.000		

Note: ** represent significance at the 1% levels.

6. Conclusions

The GSADF technique has been employed in this study. The investigation was conducted to analyze exuberance and the subsequent downfall of volatile bubble-like tendencies within the global aluminum market. According to the empirical findings, there were six instances of bubbles in the global aluminum market, occurring in 1987, 1988, 1994–1995, 2005–2006, 2021, and 2022. The primary factors responsible for the initial two bubbles are primarily the result of significant supply disruptions, rapid industrialization and urbanization in China, as well as the depreciation of the U. S. dollar. The strong worldwide economic expansion, swift industrialization and urbanization in China, soaring oil cost, instability of bauxite provision, along with nonessential factors like devaluation of the U. S. currency, speculation, and financial turmoil, are the primary causes of the third and fourth AP bubble. Furthermore, the occurrence of the fifth and sixth bubble can be attributed to the economic rebound following COVID-19, supply chain disruptions, geopolitical circumstances, and speculative activities. According to the probit regression, the AP bubbles are positively influenced by the copper price, GDP, the U. S dollar index, industrialization of China and China's urbanization rate, whereas the global aluminum production amount, oil price, and base metal price index have a negative explanatory effect on the AP bubbles.

The identification of key factors contributing to the occurrence of multiple aluminum price bubble episodes is significantly enhanced by pinpointing the initial and ending points of these episodes. Through relevant analysis, a multitude of policy recommendations can be generated. Specifically, the integration of the futures market and the growing influence of the financial aspect of aluminum have led to a gradual correlation between the aluminum spot price and futures pricing. Hence, it is crucial to develop the global pricing system for aluminum considering not only the fundamentals of demand and supply but also incorporating financial aspects. Furthermore, in light of the rise of financialization in the aluminum industry, it is necessary for policymakers to establish a proactive system that can anticipate fluctuations in the spot price of aluminum. This will enable them to promptly recognize and address any detrimental impacts caused by financial shocks on the global aluminum market. Furthermore, nations heavily impacted by the fluctuating aluminum prices ought to enhance their strategic reserves for aluminum. This will help mitigate excessive market price fluctuations and alleviate the adverse effects on their respective economies. In addition, it is important for governments to encourage the expansion of import/export networks and actively pursue collaboration on a global scale. In this study, the conclusion has provided several suggestions for government, enterprises, investors and market participants. However, there are limitations still existing in the research. First, conclusions are limited to the time period spanning January 1980 to March 2023 and may not be readily extrapolated to different temporal contexts or market conditions. The generalizability of the findings to diverse scenarios or geographic areas may be hindered by the distinctive nature of the dataset and research methodology employed. Second, the study recognizes various factors, including exchange rate fluctuations, supply and demand imbalances, and external market conditions, that have the potential to impact the emergence and dissolution of price bubbles. Nevertheless, the intricate nature and interactions of these factors may not be fully accounted for in the analysis, thereby constraining the comprehensive comprehension of pricing bubble theory. As a consequence, future studies can examine bubble behavior in different commodity prices. In addition, the study could be extended to examine other metal bubbles and make comparisons to illustrate the result during different periods, such as before and after the pandemic.

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Author contributions

Conceptualization, methodology, formal analysis, writing paper, software, original draft preparation, M.N.; reviewing and editing, supervision, X.W. Both authors have read and agreed to the published version of the manuscript.

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