Environmental and Resource Economics (2024) 87:1651–1671
https://doi.org/10.1007/s10640-024-00870-1

The COVID-19 Pandemic and Unsustainable PPE Materials: A Correlation and Causality Analysis

Konstantinos N. Baltas[1] · **Robert Mann**[2] · **Nicholaos C. Baltas**[3]

Accepted: 15 April 2024 / Published online: 23 May 2024

Abstract
In this paper, we investigate the economic impact of the COVID-19 pandemic on European and Chinese unsustainable and non-recyclable plastic markets, specifically those used for the production of Personal Protective Equipment (PPE). We explore exogenous economic and commodity price impacts on polypropylene, acrylonitrile and polyvinylchloride, via VECM and Granger causality analysis, with the results remaining robust under testing. We find that price shocks from rubber and EUROSTOXX are significantly correlated with PPE materials, to a greater extent than crude oil, unexpectedly relating price declines in PPE materials to factors beyond medical demand. This will aid a policymakers and industry understand the factors that affect the price of unsustainable and non-recyclable PPE materials, respond to the need for pandemic PPE provision and reduce the potential environmental impact of future pandemics.

Keywords Pandemics · PPE · Plastics · Polymers · Sustainability · Commodity markets · VECM · Causal Inference

JEL Classification C32 · Q31 · Q02 · I10 · L65

1 Introduction

The initial months of the COVID-19 pandemic at the start of 2020 sparked an enormous rise in the demand for Personal Protective Equipment (PPE) for healthcare professionals, key workers and members of the public. This ranged from face masks to rubber gloves, and throughout 2020 the European Centre for Disease Prevention and Control issued multiple

✉ Konstantinos N. Baltas
k.baltas@essex.ac.uk

1 Finance Group, Essex Business School, University of Essex, Colchester, United Kingdom

2 Sembcorp UK, Lazenby, United Kingdom

3 Department of Economics, School of Economic Sciences, Athens University of Economics and Business, Athens, Greece

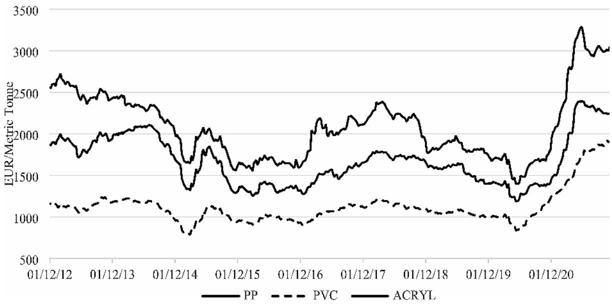

Fig. 1 Price history for European prices of PPE materials (polypropylene, polyvinyl chloride and acrylonitrile) between February 2012 and November 2021. *Note* This figure presents price data for EU ACRYL, PP and PVC from February 2012 to November 2021.

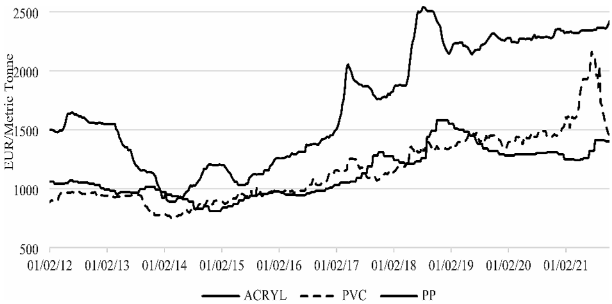

Fig. 2 Price history for Chinese prices of PPE materials (polypropylene, polyvinyl chloride and acrylonitrile) between February 2012 and November 2021. *Note* This figure presents price data for Chinese ACRYL, PP and PVC from February 2012 to November 2021

directives enforcing the use of this equipment as part of a general pandemic response. The materials that are most frequently used for PPE production, such as polymers (polypropylene) and plastics (acrylonitrile, polyvinyl chloride), are often either non-recyclable or environmentally unsustainable (Zhao et al. 2022). Their global use in pandemics and single-use nature can contribute to environmental issues such as chemical pollution, CO2 emissions, and waste (Uddin et al. 2022).

Ordinarily, higher demand for PPE during a pandemic would be expected to inflate the price of the materials used for their production (Gereffi 2020). However, as shown in Fig. 1, EU price benchmarks for these materials fell uniformly over the January-July 2020 period, in spite of demand. The same is also marginally true in Fig. 2 for Chinese price benchmarks, particularly polypropylene (Fig. 2). Understanding the reason for this decline is important from an environmental perspective, as lower prices for non-recyclable and unsustainable plastics incentivises their use in PPE procurement, thus increasing the already significant environmental impact of a coronavirus pandemic (Helm 2020).

This paper sets out to examine the factors that drove this decline in Europe, with a separate comparison with the situation in China, focusing on a Vector Error Correction Model (VECM) analysis. The goal is to understand the economic drivers behind non-recyclable and environmentally unsustainable plastic prices during a global pandemic, and inform the broader discussion around the environmental impact of COVID-19.

We investigate this using cross-commodity causality tests to determine the extent that exogenous variables such as macroeconomic and upstream commodity prices influence the price of these key materials. For this, we utilise, for the first time in the literature, benchmark weekly data for Acrylonitrile Butadiene Styrene, Polypropylene Homopolymer and Polyvinyl Chloride, given their widespread use and availability within global markets.

Prior research on PPE materials prices is scarce, with the majority of research in this area focussed on other, similarly petroleum-derived products. Masih et al. (2010) investigates the price dynamics of crude oil on ethylene markets, including those of North West Europe, and find through the use of Vector Error-Correction models (VECM) that crude oil prices are cointegrated with regional ethylene prices. Additionally, the VECM results imply that whilst North European ethylene prices were weakly endogenous, the Asian ethylene prices are weakly exogenous both in the short and long term. He et al. (2019) analyse spot and term risk premia in a basket of Chinese and American commodities, including linear low-density polyethylene (LLDPE) and PVC, finding that term premia are not driven by liquidity in either market. Spot premia is detected to be driven by three separate momentum factors, namely market, carry and time-series momentum. Gu et al. (2020) uses a VAR-DCC-GARCH framework to analyse returns for recycled PP, polyethylene, polyethylene terephthalate, and their co-movements with crude oil returns. It is observed that correlations between crude oil returns on the recycled plastic returns are insignificant, whilst the volatility spillovers between these markets are direct and significant.

Mello and Ripple 2017 present findings on the price dynamics between polypropylene (PP), propylene, naphtha, and crude oil, focussing on both North European and South Asian markets, with the employment of Vector Error Correction models (VECM). Most relevantly, the higher premium for European PP compared with Asia is attributed to domestic shortages of PP capacity, which in turn cause prices to spike, whilst propylene prices remained more stable due to a reasonable level of propylene supply. We contribute to this strand of literature for the first time by utilising acrylonitrile prices in conjunction with polymer prices, whilst also providing scope for further research into the impact of COVID-19 on other petroleum product markets.

PPE materials themselves are mostly derived from crude oil. Refined oil products such as naphtha, ethane, propane, butane and fuel oil are classified as feedstocks, used in producing olefins such as ethylene and propylene. In turn, ethylene and propylene are used in the production of polymers and plastics (polypropylene, polyvinyl chloride and acrylonitrile). Along with the decline in PPE materials prices, the global benchmark Brent crude oil price fell by 64% from January to March 2020, as the economic impact of COVID-19 became apparent and industrial demand collapsed.

Research into the relationship between oil price shocks and bulk commodities is comprehensive. There are three main relationships expounded upon by the literature. Firstly, oil price declines result from a decrease in global economic activity, which in turn lowers demand for materials (Baumeister and Kilian 2016). Secondly, a decrease in oil prices lowers the cost of transportation, which in turn can be transferred to the prices of other commodities (Tyner 2010). Finally, hikes in global oil prices can lead to policy changes, such as decreased interest rates (Hammoudeh and Yuan 2008) and tightening of oil import license constraints (Rioux et al. 2019), which affects the prices and volatility of commodity markets.

As noted in Masih et al. (2010), petrochemical and olefin prices are highly sensitive to crude oil prices. Markets for these products are relatively small and opaque compared to oil, but demand and trade flows have been robust in North West Europe (NWE) and the Mediterranean (MED). The sensitivity of PPE material prices to crude oil prices is a natural consequence of its use as the key feedstock in the production of plastics, polymers, nylon and rubber. However, the illiquidity and limited supply of derivatives contracts means that effective hedging and risk management is far harder than in more developed fossil fuel markets.

Liu et al. (2020) study the impacts of oil price jumps on downstream petrochemical markets, focussing on the post-global financial crisis period, using ARMA-EGARCH specification models. Their findings show that global oil price jumps on China's petrochemical stock returns are significantly negative, while that of the lagged jumps are exactly the opposite. Zhu et al. (2019) uses variational mode decomposition with a bidirectional gated recurrent unit (VMD-BiGRU) neural network to forecast natural rubber futures prices and volatility. The resulting short-term forecasts were most accurate when using the hybrid VMD-BiGRU model. Chang et al. (2011) study the conditional correlations of volatility in Asian rubber returns, and confirm the presence of spillover effects between most pairs of spot and futures returns. Our study includes a focus on European markets, and therefore extends the aforementioned evidence towards more developed markets.

Research on the environmental impact of COVID-19 pandemic is gradually expanding. Most recent research provides general evidence into the causes of pollution over the duration of the pandemic, with Helm (2020) specifically finding that pollution and GDP are still correlated despite pandemic-related disruption. Other research focuses on the environmental impact of PPE. Zhao et al. (2022) finds that the use of a proposed optimal PPE processing system avoids PPE from being landfilled, and reduced incineration and particulate matter formation. Uddin et al. (2022) outlines the need for fundamental business model changes to reduce the impact of PPE on the environment, such as using reusable PPE and sustainable PPE materials. Parashar and Hait (2021) demonstrate different types of pollution caused by PPE plastics and polymers due to the pandemic, as well as detailing the concept of decontamination of used PPE as an alternative to using recycled PPE materials. Klemeš et al. (2020) describe the inability of existing treatment and disposal facilities to cope with the influx of plastic waste owing to the pandemic and the risk posed by secondary contagion from improper waste management.

By analysing the shocks of upstream oil prices on downstream PPE materials, we are also able to provide policy insights as to the future provision for PPE from unsustainable sources. This will complement the research of Ishack and Lipner (2020) with respect to the alternative sources of PPE provision, with implications for policy to reduce the environmental impact of global pandemics. A data vector of Brent prices and other exogenous variables will also provide insight into the various shocks and correlations that explain the movements in these three PPE materials prices. These oil price relationships have not yet been studied within the framework of the COVID-19 pandemic period, nor in the context of the countervailing upward price pressures due to high downstream product demand. With this in mind, our paper tests the robustness of these findings to address whether these conclusions hold within the specific context of PPE materials prices, as well as the unprecedented circumstances of the early COVID-19 pandemic in Europe and China, following from previous studies such as Gereffi (2020). Going further, a causality analysis allows us to provide insights, for the first time in the literature, as to what extent our economic variables drive PPE materials; providing a rationale for their movements during the pandemic period.

Our results determine varying rationales for the price decline in PPE materials at the outset of the COVID-pandemic, although a broad pattern emerges of exogenous shocks. When analysing the translation of price shocks between brent crude oil and plastic derivatives, we find that the shocks are statistically significant, which runs counter to prior findings within the strand of literature on recycled plastics. These findings conclude that oil price impacts on recycled plastic price returns are statistically insignificant (Gu et al.(2020)).We find evidence of causality between European PPE materials prices and stock market fluctuations, as well as a contrastive relationship between Chinese PPE materials prices and other input commodity price fluctuations, reflecting a geographic dimension to the scope of our findings. Our findings suggest that the link between industrial cycles and output is enhanced in the Chinese market, likely because of increased offshoring of manufacturing, as highlighted in Pan et al. (2008). Overall, this highlights how the interconnectedness of global plastic supply chains may risk merely shifting pollution effects from one region to another, rather than abating them altogether. Our findings also show that the upward price pressure from higher PPE demand has been offset by other economic and commodity price factors over the COVID-19 period.

Whilst providing some insight as to the reason for the price decline seen in PPE materials prices over the early 2020 period, we also look to provide routes for further research in this area. Our analysis utilises EU and Chinese PPE materials data for the first time, and contributes to a unique strand in the literature of European and Chinese commodity prices (Baffes et al. 2021; Boranova et al. (2021) and the nascent body of COVID-19 research (Barbier 2020; Elliott et al. (2020). This opens up further research into the extent to which negative environmental impacts from non-sustainable PPE usage are shifted to other countries via manufacturing offshoring, as well as the impact of decontamination of used PPE rather than recycled PPE materials. Our causality analysis on PPE materials prices – also performed for the first time – adds to the strand of literature on how economic, price and pandemic factors affect commodity prices. Our finding of significance for oil price shocks contrasts with previous studies that found no significance between oil shocks and recyclable plastics, offering avenues for further comparative research.

Understanding the reason for PPE price declines is crucial towards being able to reduce reliance on unsustainable and non-recyclable plastics for PPE equipment and reducing the environmental impact of future pandemics. These insights will assist policymakers with designing incentives to reduce the reliance on unsustainable and non-recyclable plastics in PPE procurement and understand the conjunctive impact of pandemics and plastics on the environment.

The remainder of the paper is organized as follows: Sect. 2 discusses the datasets and models utilised in the analysis. Section 3 explains the empirical findings of these models, along with additional robustness tests to define whether our original results hold. The final section provides some concluding remarks.

2 Data and Models

2.1 Data

The EU data are benchmark weekly prices for German Acrylonitrile Butadiene Styrene (EU ACRYL), Northwest Europe Polypropylene Homopolymer (EU PP) and Polyvinyl Chloride (EU PVC). To analyse the Chinese market, we use the daily Shandong Acrylonitrile Spot Price (CH ACRYL), SE Asia Block Copolymer Polypropylene CRF (CH PP) and PVC Dalian Commodity Exchange (CH PVC). Our data represent the most widely used component materials for the broad range of worldwide PPE, specifically sanitary gloves and facemasks, and will allow us to compare and contrast the intra-regional dynamics between key European and Asian markets. The descriptive statistics of the data are shown in Table 1.

Additionally, data were chosen for exogenous prices that would likely explain the variation in these three PPE data (see Table 1). In a similar vein to Mello and Ripple (2017), Liu et al. (2020) and Chang et al. (2011) we use ICE Brent crude oil, EUROSTOXX & SCI indexes and global rubber benchmark prices. Given the enormity of the COVID-19 shock on the macroeconomy, we also control for the various macroeconomic variables to investigate the impact on PPE materials prices, following similar COVID-19 studies (Ji et al. 2020; Bakas and Triantafyllou 2020). To this end we add EU and Chinese PPI data. Finally, given the use of PPE materials in other industrial production, we apply aggregate car production data as a variable to determine the extent that non-medical demand impacts prices.

The primary PPE materials data are obtained from Polymerupdate, the leading Price Reporting Agency for the polymers and petrochemical industry, via Bloomberg. The full available samples are for the following periods: ACRYL and PVC from 25/05/2009 to 03/11/2021 and PP from 18/02/2014 to 03/11/2021. All macroeconomic data were sourced for the same sample periods from Bloomberg. Looking at the descriptive statistics, we can see that the primary data does not conform perfectly to a Normal distribution, positive skewness for ACRL, PVC and PP, and all data display excess kurtosis. Testing for both ADF and KPSS stationarity tests allows us to conclude that none of the datasets are stationary at level.

To test the required number of lags, Hannan-Quin information criteria was used to apply the most stringent penalty term and provide the most parsimonious model, with the lowest criteria being the second lag. We also test for cointegration relationships within our dataset. The results shown in Table 2 highlight that a cointegrating relationship does exist between our datasets:

Table 1 Descriptive statistics of the primary EU and Chinese ACRYL, PP, PVC data, as well as ICE Brent, Rubber, SCI, EUROSTOXX data and EU/Chinese PPI and CAR production data

Descriptive Statistics						
Primary Data	Mean	Std. Dev.	Skewness	Kurtosis	P_{ADF}	TS_{KPSS}
EU ACRYL	1,710.70	289.26	0.35	–0.6	0.43	1.11
EU PVC	1,196.88	230.85	0.97	0.53	0.70	0.60
EU PP	1,711.39	931	–0.91	–0.34	0.05	0.47
CH ACRYL	2,059.82	548.6	0.09	–0.74	0.07	1.95
CH PVC	1,026.35	169.12	1.4	7.35	0.25	0.74
CH PP	761.42	619.42	–0.27	–1.65	0.57	4.61
BRENT	75.73	25.88	0.16	–0.96	0.49	1.44
RUBBER	1.56	0.61	1.29	1.03	0.41	1.61
EUROSTOXX	3,807.08	471.09	0.05	–0.08	0.08	0.57
EU PPI	0.07	0.45	0.49	–0.91	0.11	0.32
EU CAR	91.3	15.52	–2.93	14.34	0.50	0.74
SCI	439.89	78.57	1.11	2.52	0.09	1.43
CH PPI	0.05	0.52	0.62	1	0.01	1.11
CH CAR	7,214,634	4,111,930	0.43	–0.58	0.01	0.59

Note P_{ADF} and P_{KPSS} are p-values of the ADF and the test statistic for the KPSS unit root tests, where the 1% critical value is 0.739

Table 2 Johansen Cointegration test results for ACRYL, PP, PVC weekly data

	Johansen Cointegration test		Sargan Test	
	Critical Value	P-value	Critical Value	P-value
EU ACRYL	167.88	0.0000	9.6419	0.0653
EU PP	134.39	0.0003	9.5516	0.1157
EU PVC	168.72	0.0000	2.9812	0.1378
CH ACRYL	124.01	0.0002	1.7991	0.2422
CH PP	122.04	0.0003	6.3625	0.0238
CH PVC	142.01	0.0000	2.8370	0.1616

Note This table shows the P-values of the Johansen test results both the EU and China PPE materials datasets

Given this result, our estimation will utilise the VECM model to fully capture and treat the interaction among macroeconomic and financial variables as endogenous, in addition to capturing the feedback effect.

Finally, to test for over-identifying restrictions, a Sargan test was also performed. The results in Table 2 confirm that the variables are validly exogenous at a 5% level of confidence, with the exception of the CH PP data. From this, we can construct our VECM, whilst being mindful that the estimators for the PP data model cannot be assumed to be the best, linear and unbiased estimators.

2.2 Models

2.3 21 VECM

If a set of variables are found to have one or more cointegrating vectors then, a VECM (Vector Error Correction Model) can be utilised.

The VECM is a restricted VAR designed for use with nonstationary series. The parameterisation is built around cointegration relations that are restricted the long-run behaviour of the endogenous variables, allowing convergence to their cointegrating relationships while also allowing for short-run adjustment dynamics. The cointegration term is also known as the error correction term as the deviation from long-run equilibrium is corrected gradually through a series of partial short-run adjustments.

The simplest possible model is a two-variable system with one cointegrating equation and no lagged difference terms, for which the cointegrating equation is:

$$y_{2,t} = \beta y_{1,t} \tag{1}$$

And thereby the corresponding VEC model is:

$$\Delta y_{1,t} = \alpha_1(y_{2,t-1} - \beta y_{1,t-1}) + ?_{1,t} \tag{2}$$

$$\Delta y_{2,t} = \alpha_2(y_{2,t-1} - \beta y_{1,t-1}) + ?_{2,t} \tag{3}$$

In the example model, the only right-hand side variable is the error correction term. In long run equilibrium, this term is zero. However, if there is deviation from the long run equilibrium, the error correction term will be non-zero, and thus each variable adjusts to partially restore that equilibrium relation. This ultimately provides the general form of a VECM model:

$$\Delta Y_t = a_1 + a_2 ec_{t-1} + a_3 \Delta Y_{t-1} + a_4 \Delta X_{t-1} + ?_t \quad (4)$$

With a crucial parameter in the estimation of the VECM dynamic model being the coefficient of the error correction term.

2.4 22 Granger Causality

In addition to assessing the correlative relationships in our dataset, we will also assess the causative relationships, in order to motivate a rationale for the fall in PPE materials prices during the COVID-19 pandemic.

The Granger causality test (Granger 1980) is the classical method to test the causality between time series. To test if a variable X causes another variable Y, the principle of this test is to predict Y using its own history, and to predict it using it history plus the history of the variable X, and finally to evaluate the difference between these two situations to see if the added variable has some effect on the predictions of the target variable.

Formally, two Vector Auto-Regressive (VAR) models are considered. The first one uses the precedent values of Y, and the second uses both passed values of X and Y in order to predict Y:

$$Model_1 Y_t = \alpha_0 + \sum_{i=1}^{p} \alpha_i Y_{t-i} + u_t$$

$$Model_2 Y_t = \alpha_0 + \sum_{i=1}^{p} \alpha_i Y_{t-i} + \sum_{i=1}^{p} \beta_i X_{t-i} + u_t$$

where p is the lag parameter, [α0,..., αp] and [β0,..., β p] are the parameters of the models, and U is a white noise error term.

To quantify the causality, we have to evaluate the variances of the errors of $Model_1$and $Model_2$. In this case, the Granger causality index (GCI) can be used, and it is expressed as follows:

$$GCI = \log\left(\frac{\sigma_1^2}{\sigma_2^2}\right)$$

where σ_1^2 and σ_2^2 are the variances of the errors of $Model_1$and $Model_2$respectively. In order to evaluate the statistical significance of the difference between these variances, the Fisher test can be used, where the statistic is as follows:

$$F = \frac{(RSS_1 - RSS_2) - p}{\frac{RSS_2}{(n-2p-1)}}$$

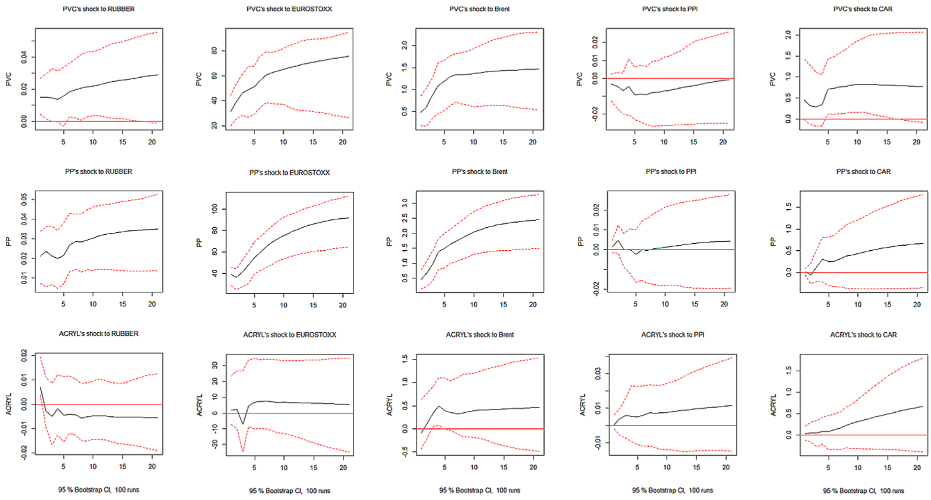

Fig. 3 Impulse Response Functions deriving from the Vector Error Correction Model (VECM) system for the EU ACRYL, EU PP and EU PVC prices

RSS_1 and $RSS_2$are the residual sum of squares related to $Model_1$and $Model_2$respectively, and *n* is the size of the lagged variables. Two hypotheses have to be considered: $H_0 : \forall i \in \{1, \ldots, p\}, \beta_i = 0$ $H_1 : \exists i \in \{1, \ldots, p\}, \beta_i \neq 0$

H_0 is the hypothesis that X does not cause Y. Under H_0, F follows the Fisher distribution with $(p, n - 2p - 1)$ as degrees of freedom.

3 Empirical Findings

3.1 VECM Results

Firstly, we estimate the VECM[1]. Next, we present the resulting Impulse Response Functions (IRFs) for each of our estimations in Fig. 3.

Note The above figure shows the impulse responses of the variables for Rubber, Eurostoxx index, ICE Brent prices and EU PPI and CAR data. The *x*-axis represents the lag of each impulse response.

In each case, the Brent crude oil and Rubber prices have the largest and most persistent shock on the respective PPE materials prices. This follows from the use of oil as a feedstock, and thereby price shocks translating into higher or lower costs for producers. The direct effect from Car production is only significant for PVC. This is expected given cer-

[1] A common VECM framework was chosen that provided the clearest indication of significance for each of the data. This involved rubber prices, EUROSTOXX/SCI index prices, Brent crude oil prices, PPI and CAR data. The ordering of the variables was chosen in line with prior analyses in the literature (Gu et al. 2020) that concluded that the descending order of response should be anticipated based on the likelihood of shocks transmitting from the independent variable to the dependent variable. Thus, the front-ended variables affect the following variables contemporaneously but are themselves affected by other variables after a lag.

tain intercorrelations between oil prices and car production/usage (Tyner 2010). Given the decrease in EU economic activity displayed by the EU PPI data, lower demand for transport will likely have a dampening effect on both oil prices (for fuel usage) and the PPE materials prices (for manufacturing usage). A similar correlation is plausible for rubber prices, in line with conclusions in Chang et al. (2011). The environmental impact of this dampening is indicated by a dramatic fall in pollution, as noted in Helm (2020), with lower coal-fired power generation (especially in China) and oil-powered transport driving down CO2 emissions over the period. However, these energy-related emissions reductions must be weighed against the increase in plastic waste resulting from higher PPE usage for the full environmental impact to be assessed. Indications from the Hubei Province in China show a 370% increase in PPE waste during the outbreak (Klemeš et al. 2020).

Taking a closer look at the Ice Brent oil price shocks specifically shows that shock persistence is not uniform across the PPE data. The positive shock is much more pronounced with PP, and persists throughout all lags, whilst for ACRYL the positive shock is only significant at the 4th lag. This would imply that European oil price movements would correlate to movements in ACRYL prices with an approximate 4-week lag. This provides empirical evidence of the varying effects of oil price innovations across differing PPE materials prices, an aspect of the data not expressly defined prior to this study.

We also present variance decompositions (VDs), which show the percentage of the variation for one variable that is explained by the shock effects within another variable. Table 3 presents the total effect accumulated over 2, 6 and 10 weeks for EU ACRYL, EU PP, EU PVC prices. The decompositions broadly fit the example of the IRFs, in that the variables determined at the highest impact also had the largest orthogonal innovations in the decomposition. As the time horizon increases the forecast error variance of the prices of all three different PPE materials is explained in an increasing pace by the level of rubber, EUROSTOXX index and Brent crude oil prices as well as by the level of PPI AND CAR (though not for PVC).

Turning to the Chinese data, we present the IRFs for the VECM in Fig. 4.

In this instance, we detect lower significance for our variables. As well as a different pattern of significant variables. We also find the CH PPI is significant for both PVC and ACRYL, in contrast to the EU data. This suggests that the link between industrial cycles and

Table 3 Variance Decompositions of the EU ACRYL, EU PP and EU PVC VECM models

Variance Decompositions						
Period	EU ACRYL	RUBBER	EUROSTOXX	ICE BRENT	EU PPI	EU CAR
2	99.6757	0.2250	0.0578	0.0109	0.0163	0.0144
6	98.3661	0.3746	0.5921	0.0717	0.4905	0.1050
10	97.6595	0.5185	0.6605	0.0697	0.9335	0.1584
	EU PP	RUBBER	EUROSTOXX	ICE BRENT	EU PPI	EU CAR
2	99.8338	0.0503	0.0467	0.0173	0.0403	0.0116
6	96.9943	0.0765	1.2329	0.2586	0.7597	0.6781
10	95.2000	0.1191	1.2178	0.5578	1.5150	1.3903
	EU PVC	RUBBER	EUROSTOXX	ICE BRENT	EU PPI	EU CAR
2	99.6739	0.0004	0.2267	0.0829	0.0099	0.0063
6	98.9371	0.1451	0.1644	0.5107	0.2236	0.0190
10	97.9954	0.5599	0.1326	0.7914	0.4715	0.0492

Note This figure presents the variance decompositions of shocks on from the three PPE materials to the Rubber, Eurostoxx, ICE Brent and EU GDP variables

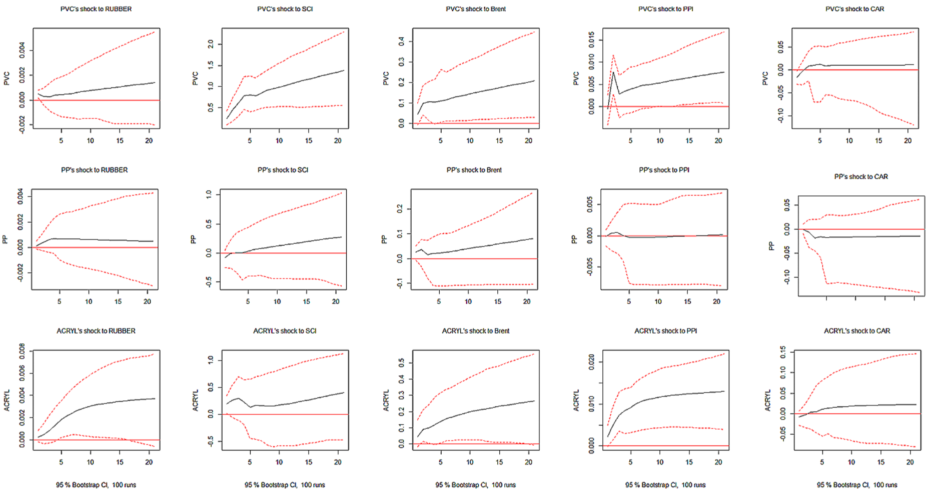

Fig. 4 Impulse Response Functions deriving from the Vector Error Correction Model (VECM) system for the CH ACRYL, CH PP and CH PVC prices. *Note* The above figure shows the impulse responses of the variables for Rubber, SCI index, ICE Brent prices and Chinese PPI and CAR data. The *x*-axis represents the lag of each impulse response

output is enhanced in the Chinese market, potentially due to the increase in offshored, base product manufacturing from the EU and the US as noted in Pan et al. (2008). This highlights that the underlying causal relationship between higher production and higher carbon emissions is not abated by higher carbon prices and Western climate change targets; rather these emissions are shifted to countries that this production is offshored to. Therefore, policymakers will need to take a whole-world view of the environmental impacts of national industrial strategy and PPE production to reduce these impacts going forwards.

Looking further into the impulse for PVC to PPI specifically we note that the significance displays a time-varied spread, whereby the 2nd lag significance is relatively strong, followed by a period of insignificance, and finally a more muted period of significance is shown after lag 12. The impact of the more recent 2nd lag could be due to the Just-In-Time nature of plastics manufacturing and resultant need for higher supply in the earliest opportunities, with the need for stored capacity over the medium term underlying the later impulse response.

Finally, the VDs shown in Table 4 show that the variance decomposes at a much slower rate to our Chinese exogenous variables than our EU dataset, with RUBBER providing the largest composition for the CH ACRYL and CH PVC, with BRENT also providing a relatively strong figure for PVC. This may be due to the broader range of consumer products produced by Chinese manufacturers, necessitating a wider range of use for polymer and plastic materials other than for PPE usage.

3.2 Causality Tests

Given the presence of cointegrating relationships in our data (Table 2) we also perform causality tests to detect the extent of causality relationships between our variables for the full datasets (Table 5).

Table 4 Variance Decompositions of the CH ACRYL, CH PP and CH PVC VECM models

Variance Decompositions						
Period	CH ACRYL	RUBBER	SCI	ICE BRENT	CH PPI	CH CAR
2	99.8716	0.0492	0.0224	0.0215	0.0305	0.0049
6	99.5005	0.2477	0.1027	0.0923	0.0514	0.0054
10	99.1618	0.4357	0.2210	0.1397	0.0380	0.0039
	CH PP	RUBBER	SCI	ICE BRENT	CH PPI	CH CAR
2	99.9745	0.0181	0.0019	0.0003	0.0000	0.0051
6	99.9304	0.0107	0.0125	0.0017	0.0013	0.0435
10	99.9287	0.0072	0.0092	0.0014	0.0010	0.0525
	CH PVC	RUBBER	SCI	ICE BRENT	CH PPI	CH CAR
2	99.8815	0.0438	0.0011	0.0698	0.0032	0.0006
6	98.8440	0.4472	0.0278	0.5276	0.1495	0.0039
10	98.0043	0.8645	0.0204	0.7982	0.3089	0.0037

Note This figure presents the variance decompositions of shocks on from the three PPE materials to the Rubber, SCI, ICE Brent and CH GDP variables

Table 5 Granger Causality and Non-Linear Granger Causality tests results

	EU PVC		EU PP		EU ACRYL	
	Granger	p-value	Granger	p-value	Granger	p-value
RUBBER	0.0066	0.12	0.0013	0.64	0.0071	0.10
BRENT	0.0149	0.01	0.0048	0.21	0.0011	0.68
EUROS-TOXX	0.0207	0.01	0.0158	0.01	0.0054	0.17
PPI	0.0006	0.82	0.0018	0.55	0.0029	0.39
CAR	0.0066	0.11	0.0081	0.07	0.001	0.72
	Non-Linear Granger	p-value	Non-Linear Granger	p-value	Non-Linear Granger	p-value
RUBBER	0.0401	0.07	0.0051	0.99	0	1
BRENT	0	1	0	1	0	1
EUROS-TOXX	0.0013	0.05	0	1	0	1
PPI	0	1	0.0046	0.99	0	1
CAR	0	1	0	1	0	1

Notes This table shows the Granger and Non-Linear Granger Causality statistics for the China PPE dataset using our causality dataset along with test p-values

First looking at the granger causality for the EU dataset, we find that we reject the Null hypothesis that any of the variables cause a change in the movement of the ACRYL. For the remaining indexes, the variable with the most reliably significant effect is the EUROS-TOXX. We note that the Brent variable is significant for the EU PVC, appending prior results in the literature, and may stem from the increased usage and importance of crude oil in the pricing of PPE materials in Europe. Extending our analysis to detect whether the causality for non-linear Granger Causality, we find that the only significant causality runs from EUROSTOXX to PVC, complementing the findings from the linear causality.

Looking at the granger causality for the China dataset (Table 6), we find that the causality is more statistically significant than the EU dataset. Here the Brent variable is most significant (for PP and ACRYL) along with Rubber and PPI (for PVC and ACRYL). Whilst the granger causality statistics are lower than that of the EU dataset, they display a greater causality from composite and upstream production products.

This implies that the costs of production are far more causal in China than that of demand, however this is tempered by the non-linear causality which shows significance for PVC and PP. Therefore, there is still a causal effect from the strength of companies in the SCI equity index, but takes a non-linear form.

The reason for the differing causal inter-relationships between geographic regions can broadly be attributed to differing economic systems, whereby an economy with a larger manufacturing sector such as China experiences greater cost-push (Zaleski 1992) and demand-pull (Zhang 2012) price action from related manufacturing supply chains. This is borne out by the results that prices for other industrial commodities, specifically rubber and oil, are more causal than the abstract economic variables utilised in the dataset, and this finding appends other studies such as Mello and Ripple (2017). In contrast, higher causality of stock market returns is shown for EU PPE materials, whereas for the Chinese dataset this relationship is non-linear, indicating less direct price action. Given the negative environmental effects of producing these commodities, especially the emission factor from the burning of fossil fuels, this provides further evidence of the negative environmental balance being shifted from regions such as the US and the EU towards China.

However, it is of note is that Brent is causal for EU PVC, which is likely due to the fact PVC is a key input material in car manufacturing, a major part of the Northwest Europe/German manufacturing complex. An important implication of these findings is that European PPE materials prices (with the exception of PVC) are implied to be less susceptible to commodity price fluctuations than in Asia, but also more likely to be affected EUROSTOXX market volatility.

Table 6 Granger Causality and Non-Linear Granger Causality tests results

	CH PVC		CH PP		CH ACRYL	
	Granger	p-value	Granger	p-value	Granger	p-value
RUBBER	0.0024	0.02	0.0009	0.23	0.0026	0.02
BRENT	0.0025	0.17	0.0026	0.02	0.0038	0.01
SCI	0.0001	0.89	0.0007	0.32	0.0015	0.09
PPI	0.002	0.04	0.0001	0.94	0.0051	0.01
CAR	0.0001	0.84	0.0003	0.54	0.0005	0.39
	Non-Linear Granger	p-value	Non-Linear Granger	p-value	Non-Linear Granger	p-value
RUBBER	0	1	0	1	0.0127	0.01
BRENT	0	1	0	1	0	1
SCI	0.035	0.01	0.0173	0.01	0	1
PPI	0	1	0	1	0	1
CAR	0	1	0	1	0	1

Notes This table shows the Granger and Non-Linear Granger Causality statistics for the EU PPE dataset using our causality dataset along with test p-values

3.3 Robustness Tests

We also perform robustness tests of our main results. As shown in Junttila et al. (2018), correlations between oil-products and other commodities can undergo large changes during times of economic crisis. This supports the use of a breakpoint test to determine whether such as change has taken place. Specifically, we reanalyse our results using breakpoints around the COVID-19 period (Famiglietti and Leibovici 2022) to determine the effect of asymmetric global shocks on PPE materials prices.

Additional breakpoint tests are also conducted over 2021 to ascertain the impact of supply issues owing the pandemic and the resulting crisis in Europe energy markets. However, no significant breakpoints were detected, thus the following results concentrate on the COVID-19 period only.

To investigate the specific effect of the COVID-19 pandemic, we run the same analysis splitting our dataset into pre- and intra-COVID samples around Q1 2020 (where COVID-19 cases had been detected in both Europe and China) and Q2 2020 to Q2 2021 (during the pandemic). The specific sample periods are 25/05/2009 to 28/02/2020 for the Pre-COVID dataset 06/03/20 to 03/11/2021 for the Intra-COVID dataset. [2]

The IRF results are shown in Figs. 5 and 6. The intra-COVID sample IRF results are lower in significance than that of the full sample, which we can attribute to the much lower sample size, however the VD results presented in Table 7 show a marked increase in the apportion of variance to our exogenous factors, over and above that for the pre-COVID sample results, apparent across all time horizons. This result is consistent with our supposition that economic and other commodity price factors have had significant influence on the

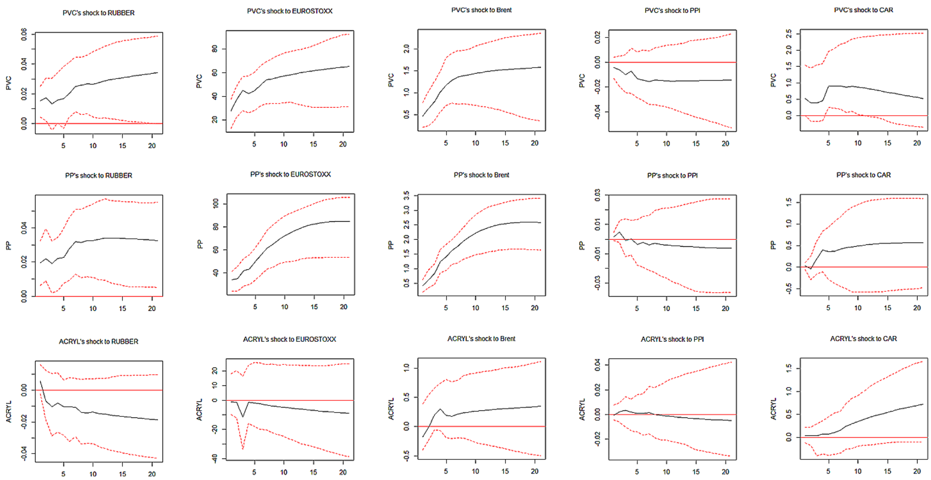

Fig. 5 Impulse Response Functions deriving from the VECM system for the EU ACRYL, EU PP and EU PVC prices of the Pre-COVID breakpoint dataset. *Note* The above figure shows the impulse responses of the variables for Rubber, Eurostoxx index, ICE Brent prices and EU PPI and CAR data. The *x*-axis represents the lag of each impulse response

[2] We also split our datasets for other dates between Q4 2019 and Q2 2020 to test for any differentiation in our results, however there was no significant change, and thus for brevity we present only the results for the March 2020 cut-off datasets.

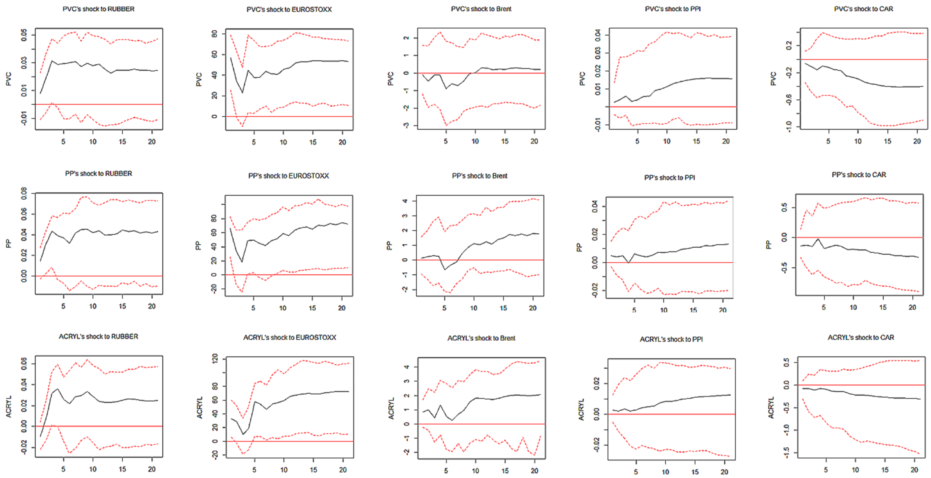

Fig. 6 Impulse Response Functions deriving from the VECM system for the EU ACRYL, EU PP and EU PVC prices of the Intra-COVID breakpoint dataset. *Note* The above figure shows the impulse responses of the variables for Rubber, SCI index, ICE Brent prices and Chinese PPI and CAR data. The *x*-axis represents the lag of each impulse response

Table 7 Variance Decompositions of the EU ACRYL, EU PP and EU PVC VECM models for the March breakpoint dataset

Pre-Covid Variance Decompositions						
Period	EU ACRYL	RUBBER	EUROSTOXX	ICE BRENT	EU PPI	EU CAR
2	99.3687	0.3203	0.0077	0.2899	0.0070	0.0064
6	98.6073	1.0073	0.0685	0.0859	0.2150	0.0161
10	97.9556	1.5444	0.0631	0.0477	0.3777	0.0116
	EU PP	RUBBER	EUROSTOXX	ICE BRENT	EU PPI	EU CAR
2	99.7726	0.1307	0.0162	0.0203	0.0286	0.0317
6	97.0134	0.3598	0.4876	0.4683	0.3951	1.2759
10	94.4146	0.6523	0.4293	1.0129	0.7557	2.7352
	EU PVC	RUBBER	EUROSTOXX	ICE BRENT	EU PPI	EU CAR
2	99.6189	0.0003	0.2836	0.0869	0.0030	0.0072
6	99.1144	0.0603	0.2547	0.5141	0.0188	0.0376
10	98.5873	0.2578	0.2736	0.7276	0.0152	0.1385
Intra-Covid Variance Decompositions						
Period	EU ACRYL	RUBBER	EUROSTOXX	ICE BRENT	EU PPI	EU CAR
2	92.1528	0.0356	1.9593	0.0174	1.1472	4.6877
6	46.9171	4.9317	22.9426	0.3163	9.7053	15.1871
10	35.7807	6.2568	32.2544	0.3841	11.3621	13.9620
	EU PP	RUBBER	EUROSTOXX	ICE BRENT	EU PPI	EU CAR
2	96.1312	0.0040	0.6639	0.2348	1.4765	1.4896
6	53.9491	0.9911	11.9629	0.0796	10.9537	22.0636
10	48.7110	1.2268	15.4578	0.0806	11.6664	22.8575
	EU PVC	RUBBER	EUROSTOXX	ICE BRENT	EU PPI	EU CAR
2	96.4561	0.1469	2.4795	0.3344	0.0216	0.5614
6	75.0730	5.3213	7.6287	0.0922	3.8639	8.0208
10	68.8381	7.4465	10.0806	0.6142	4.2255	8.7950

Note This figure presents the variance decompositions of shocks on from the three PPE materials to the Rubber, Eurostoxx, ICE Brent and EU PPI and CAR variables of the March breakpoint dataset price of PPE commodities, sufficient to outweigh the price impact of higher demand for PPE during the COVID-19 period.

The IRF results for the Chinese data are shown in Figs. 7 and 8, and display a similar characteristic to the EU results in that the significance is mostly reduced during the intra-COVID sample period. Of note, however, is the effect of Brent on PVC, which becomes significant during the COVID period. This suggests an increase in the effect of global oil prices on the price of PVC. The increased significance of upstream product prices likely follows

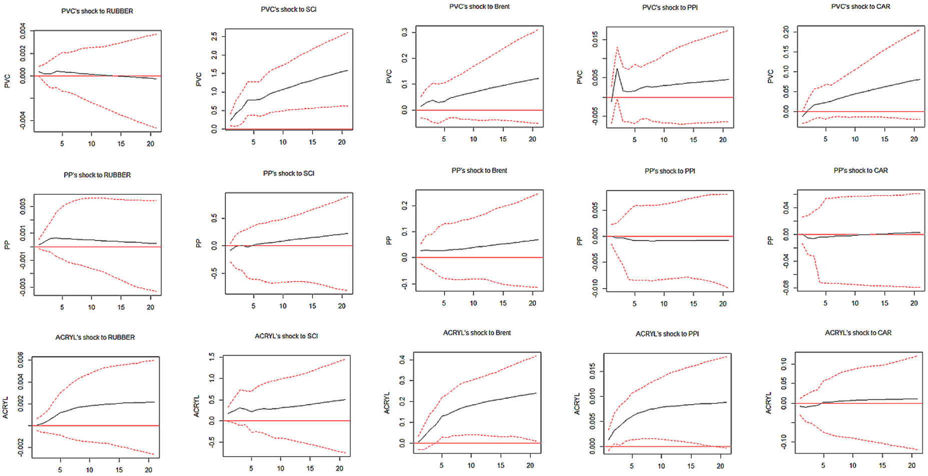

Fig. 7 Impulse Response Functions deriving from the VECM system for the CH ACRYL, CH PP and CH PVC prices of the Intra-COVID breakpoint dataset. *Note* The above figure shows the impulse responses of the variables for Rubber, Eurostoxx index, ICE Brent prices and EU PPI and CAR data. The *x*-axis represents the lag of each impulse response

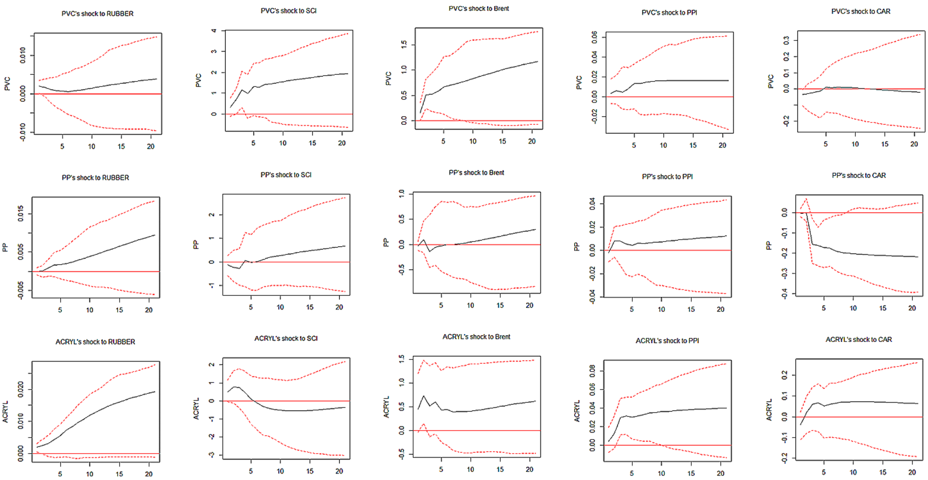

Fig. 8 Impulse Response Functions deriving from the VECM system for the CH ACRYL, CH PP and CH PVC prices of the Intra-COVID breakpoint dataset. *Note* The above figure shows the impulse responses of the variables for Rubber, SCI index, ICE Brent prices and Chinese PPI and CAR data. The *x*-axis represents the lag of each impulse response

from the constrained supply environment during a pandemic, as global trading flows experience heavy disruption. A heightened sensitivity to oil prices also implies a greater challenge for Chinese authorities in constraining the environmental impact of future pandemics.

The VD results presented in Table 8 also show an increase in the apportion of variance to our exogenous factors, over and above that for the pre-COVID sample results, however the effect is more muted than in the EU dataset. This result highlights the extent that other commodity price factors have had significant influence on the price of PPE commodities to a greater extent than with the EU data, in particular the PPI, Brent and car production variables. In the pre-COVID-19 period these variables accounted for negligible variance in the PPE materials prices, however this increases markedly in the intra-COVID period, with car production in particular accounting for the greatest proportion of PP price variance at the 10th lag. Together this demonstrates that, whilst PPE prices (other than PP) did not decline in the COVID period as did EU prices, the same kind of transition to a commodity-complex correlation has taken place in Chinese PPE materials prices.

Table 8 Variance Decompositions of the CH ACRYL, CH PP and CH PVC VECM models for the March breakpoint dataset

Pre-Covid Variance Decompositions						
Period	CH ACRYL	RUBBER	SCI	ICE BRENT	CH PPI	CH CAR
2	99.8648	0.0675	0.0381	0.0072	0.0182	0.0043
6	99.4802	0.2553	0.1579	0.0390	0.0627	0.0050
10	99.0719	0.4508	0.3549	0.0617	0.0547	0.0060
	CH PP	RUBBER	SCI	ICE BRENT	CH PPI	CH CAR
2	99.9606	0.0315	0.0030	0.0000	0.0001	0.0048
6	99.9274	0.0282	0.0191	0.0032	0.0003	0.0218
10	99.9326	0.0196	0.0184	0.0074	0.0002	0.0218
	CH PVC	RUBBER	SCI	ICE BRENT	CH PPI	CH CAR
2	99.9765	0.0229	0.0000	0.0001	0.0001	0.0004
6	99.5541	0.3063	0.0259	0.0812	0.0105	0.0220
10	99.1768	0.6145	0.0146	0.1328	0.0332	0.0282
Intra-Covid Variance Decompositions						
Period	CH ACRYL	RUBBER	SCI	ICE BRENT	CH PPI	CH CAR
2	99.5200	0.1075	0.0816	0.0010	0.2870	0.0029
6	98.7925	0.1111	0.0394	0.1226	0.2159	0.7186
10	97.2606	0.1347	0.0542	0.4748	0.1280	1.9478
	CH PP	RUBBER	SCI	ICE BRENT	CH PPI	CH CAR
2	99.7947	0.1032	0.0082	0.0800	0.0007	0.0132
6	98.0180	0.3704	0.1266	0.3539	0.2071	0.9240
10	97.4948	0.2495	0.2621	0.3656	0.1580	1.4700
	CH PVC	RUBBER	SCI	ICE BRENT	CH PPI	CH CAR
2	98.4287	0.2030	0.1189	0.9968	0.0275	0.2250
6	93.3342	1.0227	0.1450	3.3163	1.7737	0.4081
10	89.5440	1.7087	0.2623	4.6711	3.2783	0.5356

Note This figure presents the variance decompositions of shocks on from the three PPE materials to the Rubber, SCI, ICE Brent and CH PPI and CAR variables of the March breakpoint dataset

4 Conclusion and Further Discussion

In this paper, we empirically investigate the decline in prices for polypropylene, acrylonitrile and polyvinyl-chloride PPE materials during the onset of the COVID-19 pandemic in Europe and China. Price datasets for all three of the most used non-recyclable and environmentally unsustainable PPE materials are assessed via a VECM model, as well as linear- and non-linear Granger causality, utilising relevant economic and commodity datasets.

Our results determine that the rationale for the COVID-pandemic price decline in PPE materials is not uniform across different PPE material types. However, a broad pattern of exogenous shocks engendered by the pandemic is evidenced in the movements of PPE materials prices. The shock correlations between crude oil and plastic derivatives are significant, albeit to a greater extent for polypropylene than acrylonitrile and polyvinyl-chloride, which runs counter to the intuition based on the findings of Gu et al. (2020) on recycled plastics. This opens routes for further comparative research into the provision of PPE during pandemics from both sustainable and unsustainable materials.

For the EU, the countervailing upward price pressures of high downstream medical demand have patently not been sufficient to offset other economic and commodity price factors to raise PPE materials prices, which also contrasts findings of previous studies such as Gereffi (2020). However, for the Chinese market, evidence from Granger Causality tests indicate that upstream production costs are causal to a greater extent than demand; a fact not previously highlighted in the literature. This suggests that the link between industrial cycles and output is enhanced in the Chinese market, potentially due to the increase in offshored base product manufacturing from the EU and the US, as noted in Pan et al. (2008).

A crucial result for policymakers is that the interconnectedness of global plastic supply chains means that efforts to reduce the environmental impact of PPE procurement can merely shift pollution effects to major manufacturing nations such as China. The finding that commodity price factors are more causal in China suggest that environmental policy (such as CO2 abatement schemes and carbon border taxes) will need to be combined with trade policy that reflects the global environmental costs of PPE procurement, not just that of domestic supply. As noted in Helm (2020), these impacts may be partially offset by lower coal-fired power generation and transport emissions during a pandemic period. However, energy-related emissions reductions must be ultimately weighed against the increase in plastic waste resulting from higher PPE usage for the full environmental impact to be assessed. The concept of the Plastic Waste Footprint (PWF) described in Klemeš et al. (2020) is an apt solution to such cross-border environmental issues, embedding the importance of downstream processes in sustainability efforts.

Also, for the first time, our VECM analysis highlights that European rubber prices and stock market indices are significantly correlated with PPE material prices, to a greater and more reliable extent than oil prices. This is also borne out via causality testing, which provides further evidence of the price relationship between economic factors and polymers & plastics, with potential avenues for further research focussing on economic and environmental variables such as carbon prices and sustainable natural rubber data. Specific avenues include the extent to which emissions and other negative environmental impacts from non-sustainable PPE usage are shifted to other countries via manufacturing offshoring, and the impact of decontaminating used PPE rather than using recycled PPE materials.

Our findings relate the decline in these European and Chinese PPE materials prices at the onset of the COVID-19 pandemic to factors beyond medical PPE demand. Specifically, European PP and ACRYL materials prices are shown to have a causal relationship with stock market fluctuations, whereas for the Chinese dataset this relationship is non-linear. Chinese PPE materials prices are also shown to be more related to other input commodity price fluctuations, likely due to price action from related manufacturing supply chains. This appends other studies such as Mello and Ripple (2017) and offers policy implications due to EU PPE materials prices having less susceptibility to commodity price fluctuations than in Asia, but greater susceptibility to broader economic and financial shocks. As lower prices for non-recyclable and unsustainable plastics incentivises their use in PPE procurement, policymakers will need to ensure greater availability of sustainable alternatives to offset this incentive, not merely exporting the environmental impacts to other manufacturing nations, which supports the findings of Uddin (2022). Studies such as Parashar and Hait (2021) highlight the potential for mechanical crushing of used PPEs into smaller units to enable chemical disinfection, which has been reported to efficiently deactivate infectious pathogens and allow recycling of PPE itself, rather than recycling of PPE materials. As normal manufacturing declines and PPE materials prices fall, the temptation will be to ramp up production, rather than recycle used equipment.

As our findings highlight, it is important to incentivise this kind of recycling rather than manufacturing in the early stages of a pandemic to reduce PPE and plastic waste.

These findings will provide valuable insight for policymakers, medical sector participants, manufacturers, and other industrial end-users to enable better forecasting of PPE material prices as well as policy to reduce reliance on unsustainable and non-recyclable plastics for PPE equipment; thus helping to reduce the environmental impact of future pandemics.

Declarations

Conflict of Interest The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work carried out in this paper.

Data Availability.
The data and the command files are available upon request.

References

Baffes J, Kabundi A, Nagle P (2021) The role of income and substitution in commodity demand. Oxf Econ Pap 74(2):498–522. https://doi.org/10.1093/oep/gpab029

Bakas D, Triantafyllou A (2020) Commodity price volatility and the economic uncertainty of pandemics. Econ Lett 193:109283. https://doi.org/10.1016/j.econlet.2020.109283

Barbier EB (2020) Greening the post-pandemic recovery in the G20. Environ Resource Econ 76:685–703. https://doi.org/10.1007/s10640-020-00437-w

Baumeister C, Kilian L (2016) Understanding the decline in the price of oil since June 2014. J Association Environ Resource Economists 3(1):131–158. https://doi.org/10.1086/684160

Boranova V, Huidrom R, Nowak S, Topalova P, Tulin P, Varghese R (2021) Wage growth and inflation in Europe: a puzzle? Oxf Econ Pap 73(4):1427–1453. https://doi.org/10.1093/oep/gpab051

Chang C, Khamkaew T, McAleer M, Tansuchat R (2011) Modelling conditional correlations in the volatility of Asian rubber spot and futures returns. Math Comput Simul 81(7):1482–1490. https://doi.org/10.1016/j.matcom.2010.07.004

Elliott RJR, Schumacher I, Withagen C (2020) Suggestions for a Covid-19 Post-Pandemic Research Agenda in Environmental Economics. Environmental and Resource Economics, 76, 1187–1213 (2020). https://doi.org/10.1007/s10640-020-00478-1

Famiglietti M, Leibovici F (2022) The impact of health and economic policies on the spread of COVID-19 and economic activity. Eur Econ Rev 144:104087

Gereffi G (2020) What does the COVID-19 pandemic teach us about global value chains? The case of medical supplies. J Int Bus Policy 3(3):287–301. https://doi.org/10.1057/s42214-020-00062-w

Granger C (1980) Testing for causality. J Economic Dynamics Control 2:329–352

Gu F, Wang J, Guo J, Fan Y (2020) Dynamic linkages between international oil price, plastic stock index and recycle plastic markets in China. Int Rev Econ Finance 68:167–179. https://doi.org/10.1016/j.iref.2020.03.015

Hammoudeh S, Yuan Y (2008) Metal volatility in presence of oil and interest rate shocks. Energy Econ 30(2):606–620. https://doi.org/10.1016/j.eneco.2007.09.004

He C, Jiang C, Molyboga M (2019) Risk premia in Chinese commodity markets. J Commod Markets 15:100075. https://doi.org/10.1016/j.jcomm.2018.09.003

Helm D (2020) The environmental impacts of the Coronavirus. Environ Resource Econ 76:21–38. https://doi.org/10.1007/s10640-020-00426-z

Ishack S, Lipner S (2020) Applications of 3D Printing Technology to address COVID-19–Related supply shortages. Am J Med 133(7):771–773. https://doi.org/10.1016/j.amjmed.2020.04.002

Ji Q, Zhang D, Zhao Y (2020) Searching for safe-haven assets during the COVID-19 pandemic. Int Rev Financial Anal 71:101526. https://doi.org/10.1016/j.irfa.2020.101526

Junttila J, Pesonen J, Raatikainen J (2018) Commodity market based hedging against stock market risk in times of financial crisis: the case of crude oil and gold. J Int Financial Markets Institutions Money 56:255–280. https://doi.org/10.1016/j.intfin.2018.01.002

Klemeš JJ, Fan Y, Tan R, Jiang P (2020) Minimising the present and future plastic waste, energy and environmental footprints related to Covid-19, Renewable and Sustainable Energy Reviews, 127, p. 109883. https://doi.org/10.1016/j.rser.2020.109883

Liu F, Shao S, Zhang C (2020) How do China's petrochemical markets react to oil price jumps? A comparative analysis of stocks and commodities. Energy Econ 92:104979. https://doi.org/10.1016/j.eneco.2020.104979

Masih M, Algahtani I, De Mello L (2010) Price dynamics of crude oil and the regional ethylene markets. Energy Econ 32(6):1435–1444. https://doi.org/10.1016/j.eneco.2010.03.009

Mello L, Ripple R (2017) Polypropylene Price dynamics: Input costs or downstream demand? Energy J 38(4). https://doi.org/10.5547/01956574.38.4.ldem

Pan J, Phillips J, Chen Y (2008) China's balance of emissions embodied in trade: approaches to measurement and allocating international responsibility. Oxf Rev Econ Policy 24(2):354–376. https://doi.org/10.1093/oxrep/grn016

Parashar N, Hait S (2021) Plastics in the time of covid-19 pandemic: Protector or polluter? Sci Total Environ 759:144274. https://doi.org/10.1016/j.scitotenv.2020.144274

Rioux B, Galkin P, Wu K (2019) An economic analysis of China's domestic crude oil supply policies. Chin J Popul Resour Environ 17(3):217–228. https://doi.org/10.1080/10042857.2019.1650247

Tyner W (2010) The integration of energy and agricultural markets. Agric Econ 41:193–201. https://doi.org/10.1111/j.1574-0862.2010.00500.x

Uddin MA, Afroj S, Hasan T, Carr C, Novoselov KS, Karim N (2022) Environmental impacts of personal protective clothing used to combat COVID- 19. Adv Sustainable Syst 6(1). https://doi.org/10.1002/adsu.202100176

Zaleski P (1992) Industry concentration and the transmission of cost-push inflation: Evidence from the 1974 OPEC oil crisis. Journal of Economics and Business, 44(2), pp.135–141. doi: 10.1016/0148-6195(92)90012-YZhang, X., 2012. China's Inflation: Demand-Pull or Cost-Push? Asian Economic Papers, 11(3), pp.92–106. https://doi.org/10.1162/ASEP_a_00169

Zhao X, Klemeš JJ, Fengqi You (2022) Energy and environmental sustainability of Waste Personal Protective Equipment (PPE) treatment under covid-19. Renew Sustain Energy Rev 153:111786. https://doi.org/10.1016/j.rser.2021.111786

Zhu Q, Zhang F, Liu S, Wu Y, Wang L (2019) A hybrid VMD–BiGRU model for rubber futures time series forecasting. Appl Soft Comput 84:105739. https://doi.org/10.1016/j.asoc.2019.105739