Supporting information

Systematic Life Cycle Assessment of Cobalt-Based Blue Ceramic Pigments: Evaluating $CoAl_2O_4$ and Lower-Cobalt Alternatives

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Figures

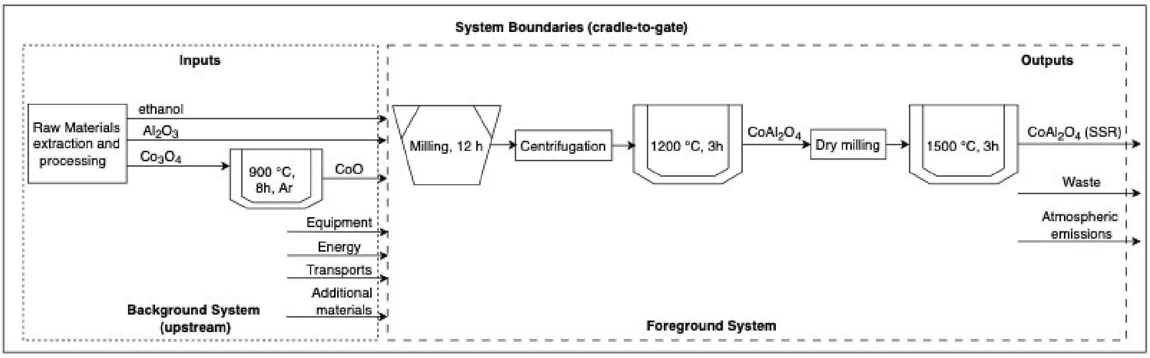

Figure S1 Flowchart for the preparation of $CoAl_2O_4$ through solid-state reaction (A1).

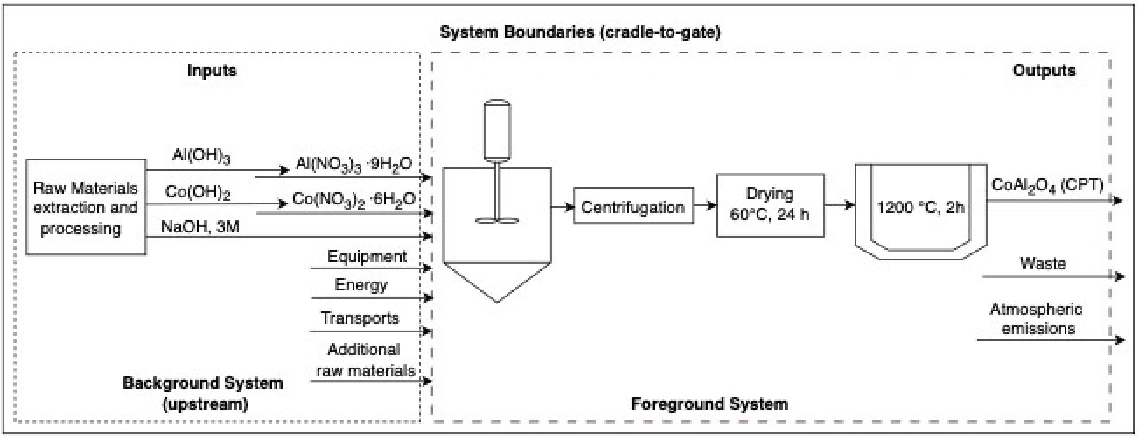

Figure S2 Flowchart for the preparation of $CoAl_2O_4$ through coprecipitation method (A2).

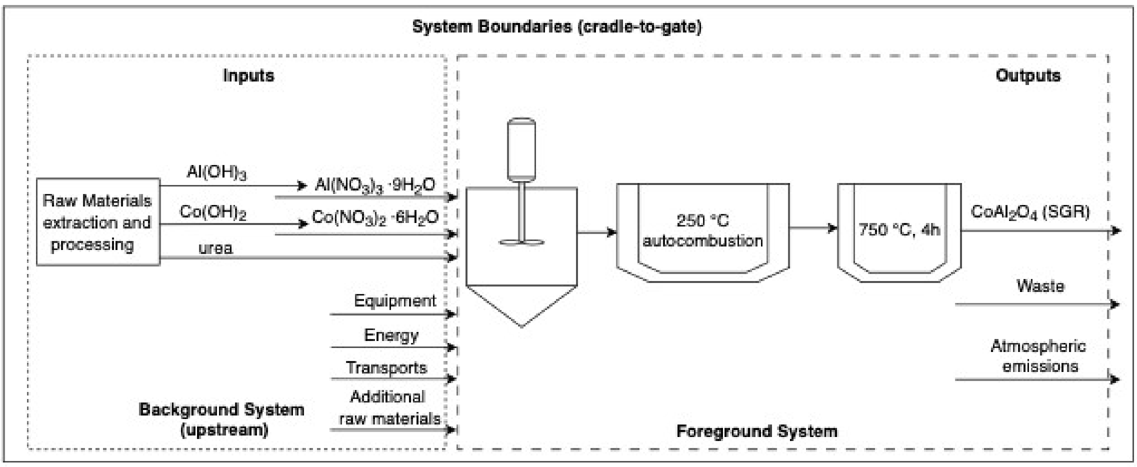

Figure S3 Flowchart for the preparation of $CoAl_2O_4$ through sol-gel autoignition method (A3).

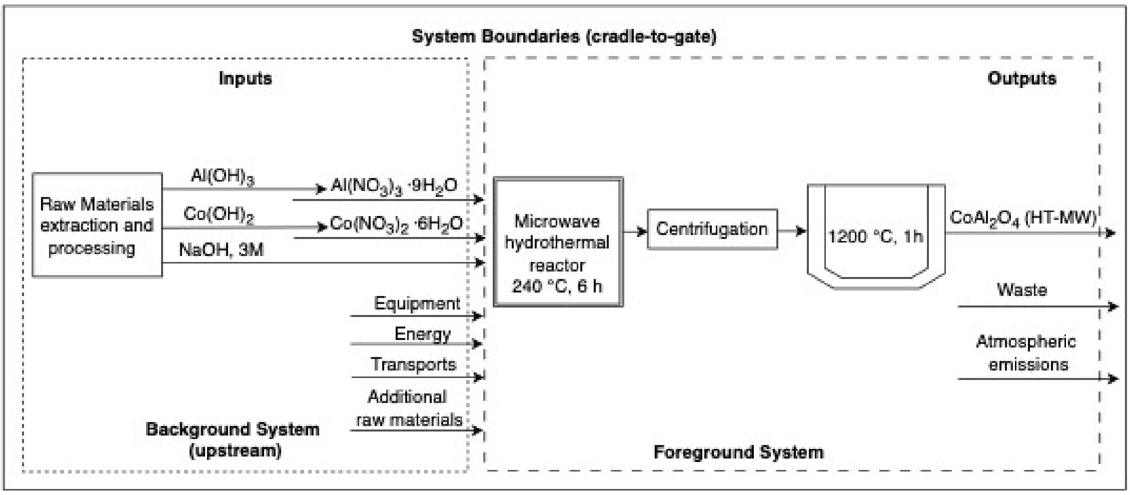

Figure S4 Flowchart for the preparation of $CoAl_2O_4$ through microwave-assisted hydrothermal method (A4).

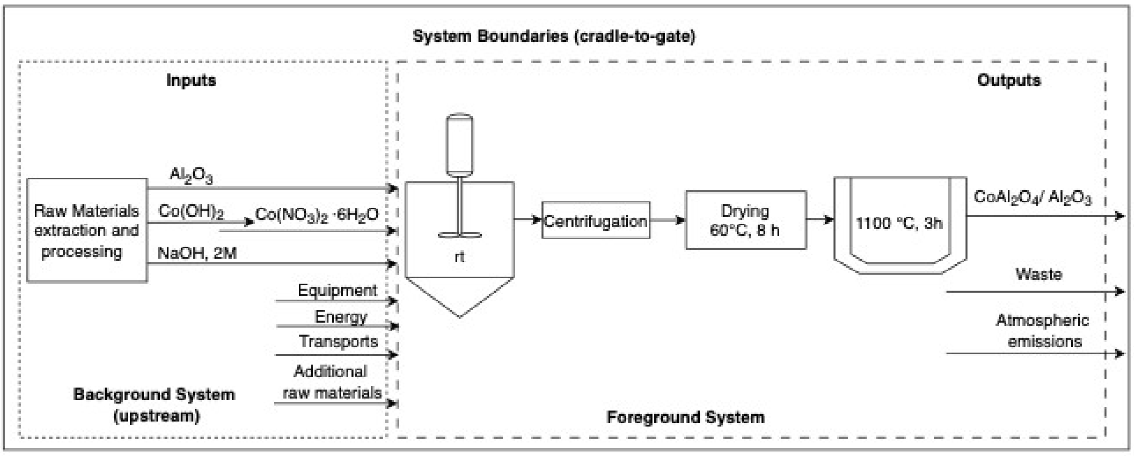

Figure S5 Flowchart for the preparation of hybrid pigment $CoAl_2O_4$/kaolin through microwave assisted hydrothermal method (pigment B).

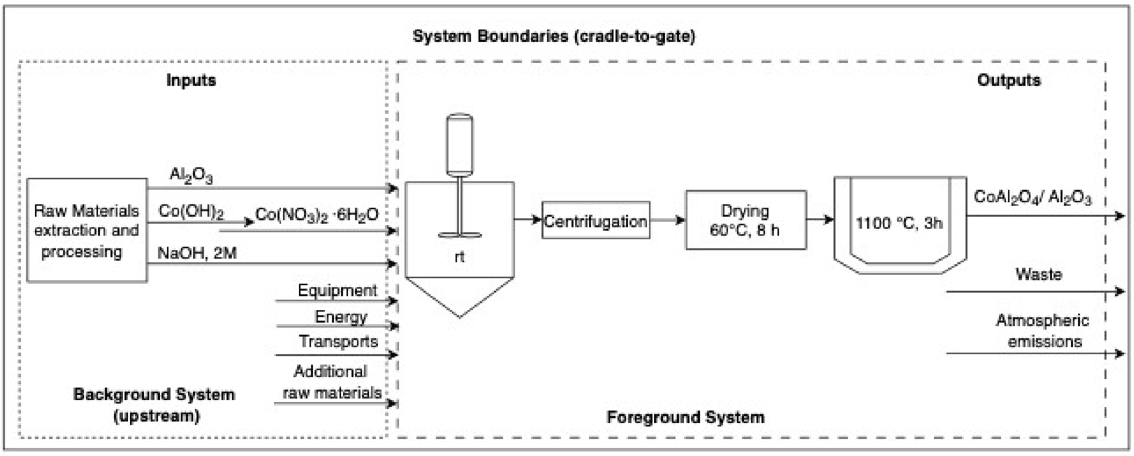

Figure S6 Flowchart for the preparation of hybrid pigment $CoAl_2O_4/Al_2O_3$ through heterogeneous precipitation method (pigment C).

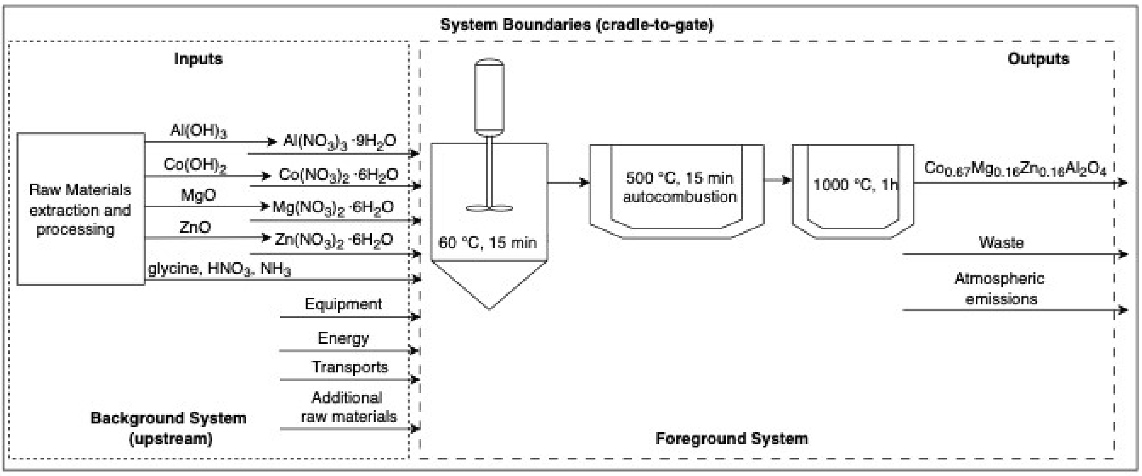

Figure S7 Flowchart for the preparation of $Co_{0.67}Mg_{0.16}Zn_{0.16}Al_2O_4$ through sol-gel autoignition method (pigment D).

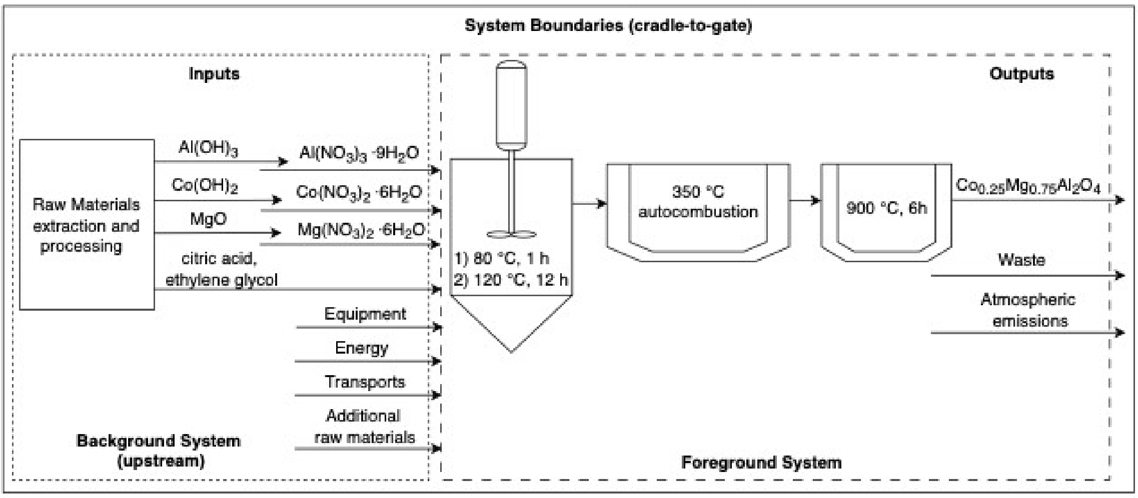

Figure S8 Flowchart for the preparation of $Co_{0.25}Mg_{0.75}Al_2O_4$ through sol-gel autoignition method (pigment E).

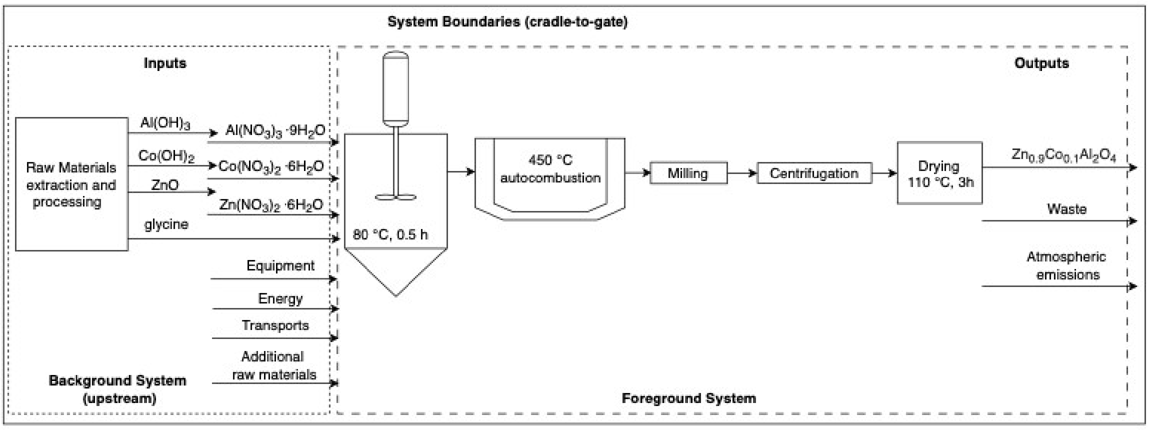

Figure S9 Flowchart for the preparation of $Zn_{0.9}Co_{0.1}Al_2O_4$ through sol-gel autoignition method (pigment F).

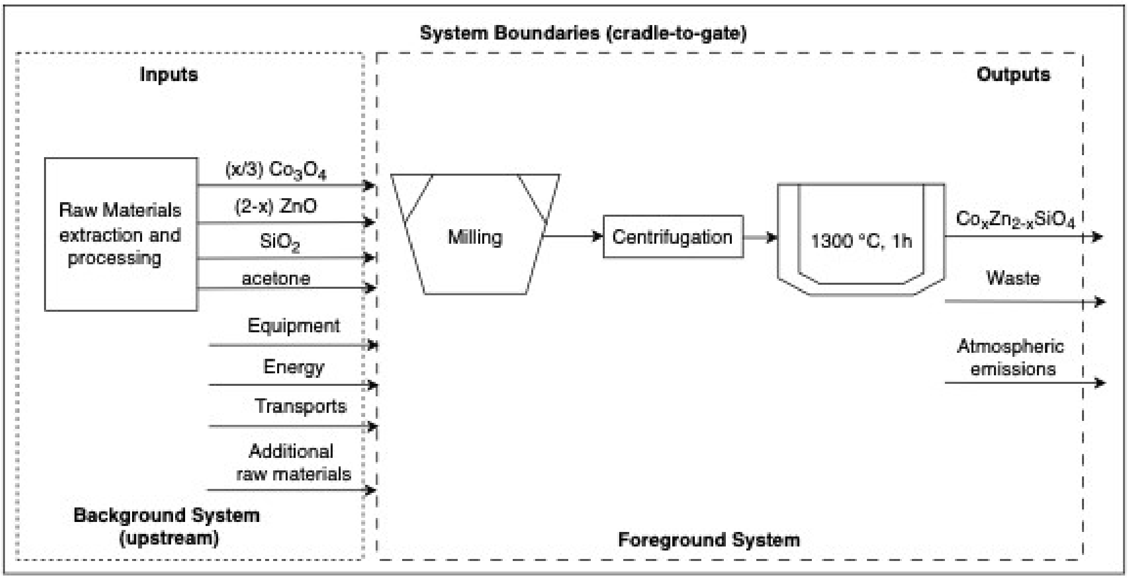

Figure S10 Flowchart for the preparation of $Co_xZn_{2-x}SiO_4$, where x = 0, 0.5 and 0.05 through solid-state reaction (pigments G, H, and I).

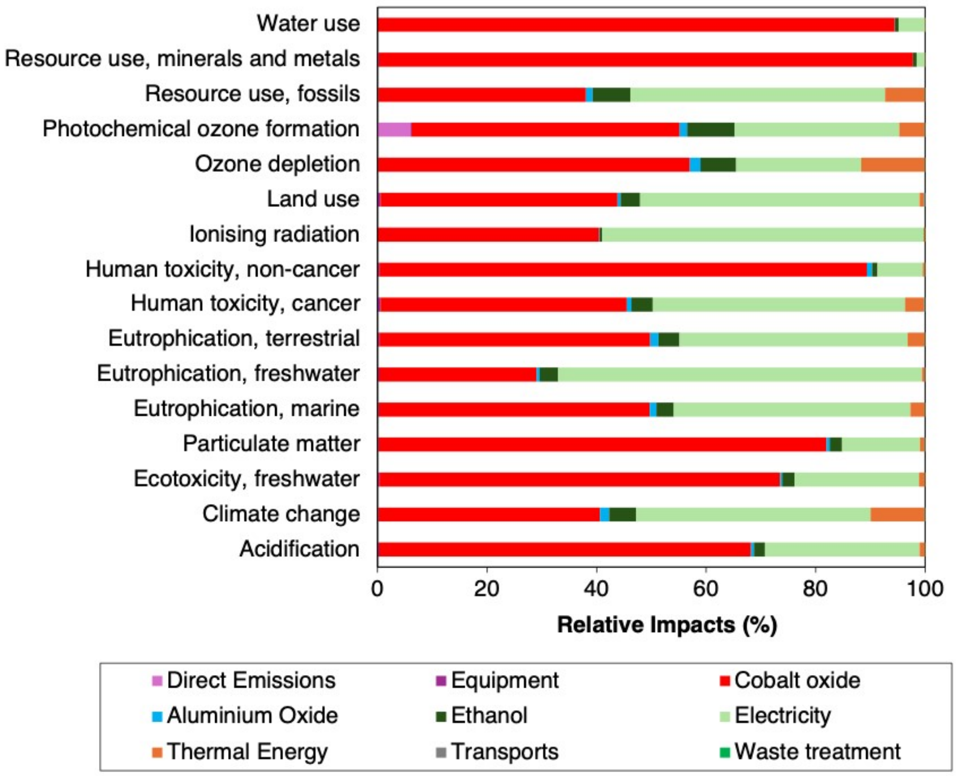

Figure S11 Relative impacts, calculated at midpoint level (EF3.1) for the production of 1 kg of $CoAl_2O_4$ through solid-state reaction (A1).

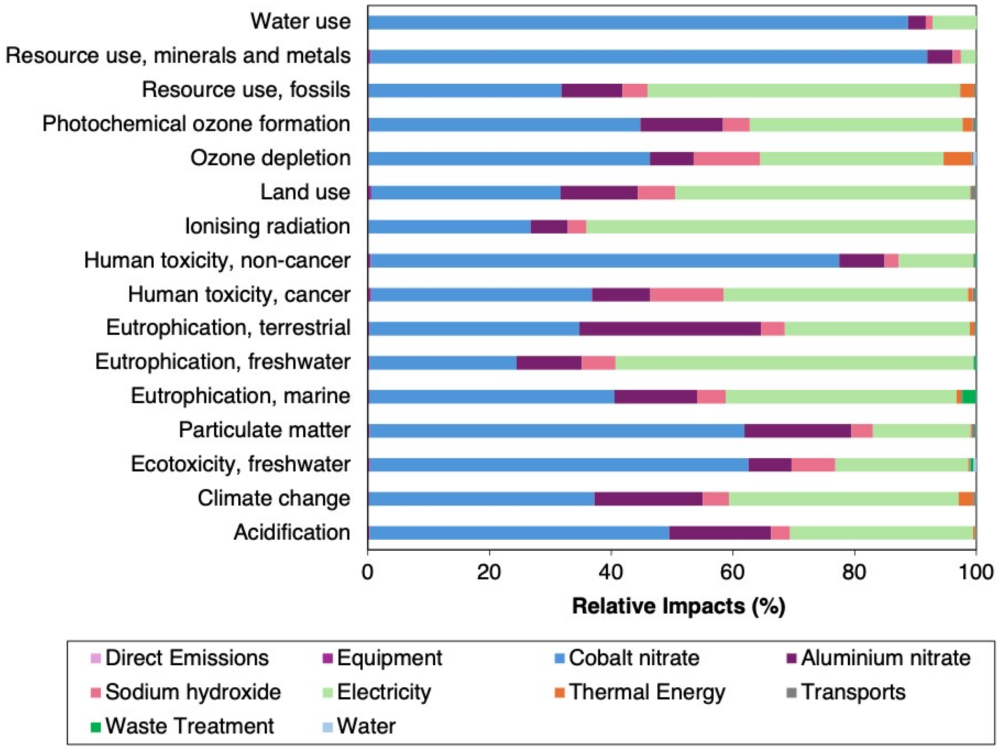

Figure S12 Relative impacts, calculated at midpoint level (EF3.1) for the production of 1 kg of $CoAl_2O_4$ through coprecipitation method (A2).

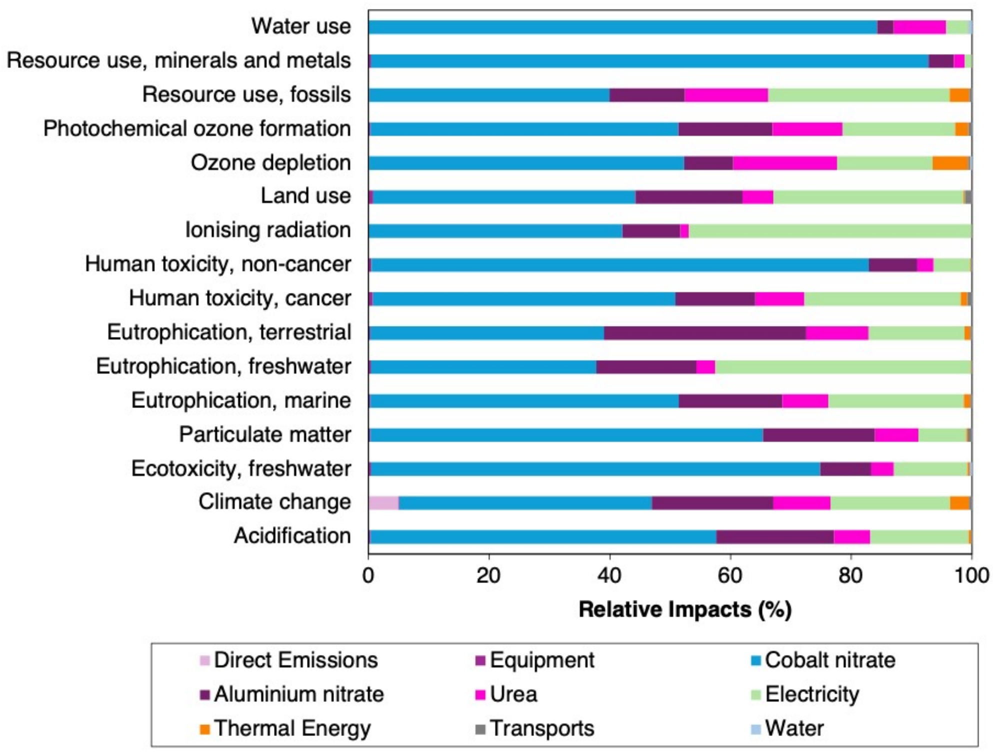

Figure S13 Relative impacts, calculated at midpoint level (EF3.1) for the production of 1 kg of $CoAl_2O_4$ through sol-gel autoignition method (A3).

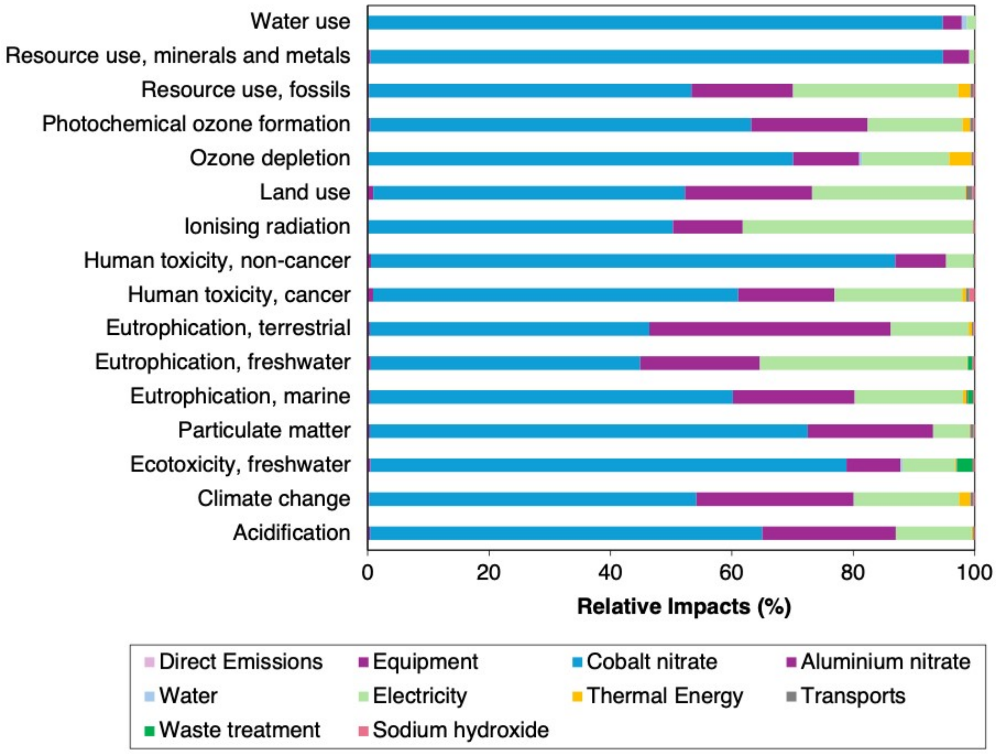

Figure S14 Relative impacts, calculated at midpoint level (EF3.1) for the production of 1 kg of $CoAl_2O_4$ prepared through microwave-assisted hydrothermal method (A4).

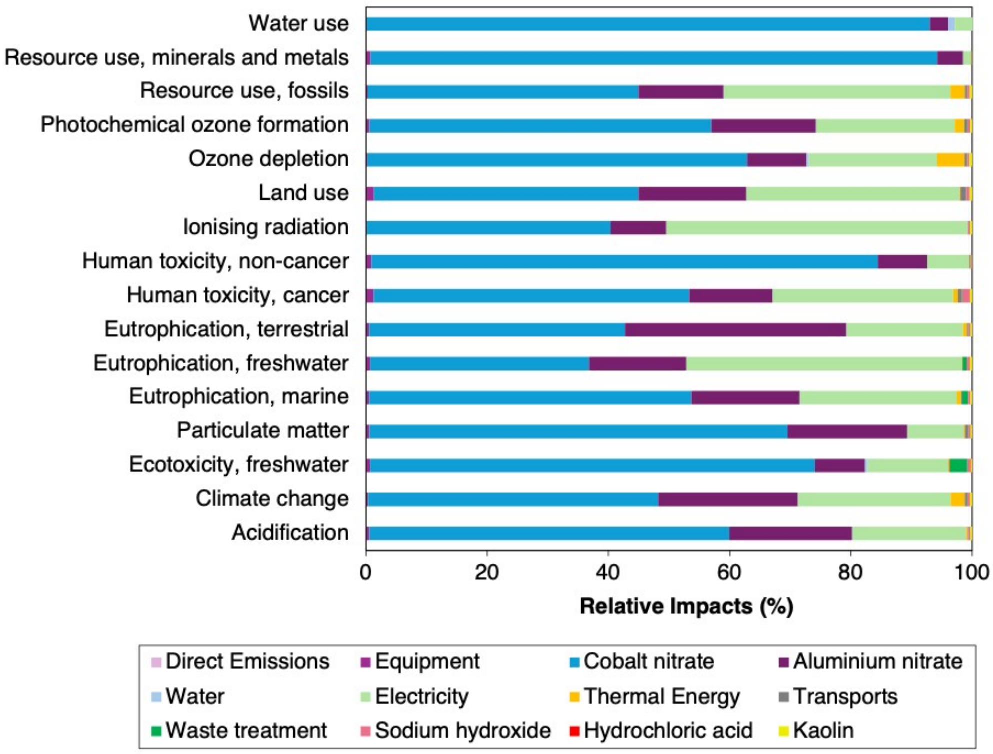

Figure S15 Relative impacts, calculated at midpoint level (EF3.1) for the production of 1 kg of hybrid pigment B ($CoAl_2O_4$/kaolin) through microwave-assisted hydrothermal method.

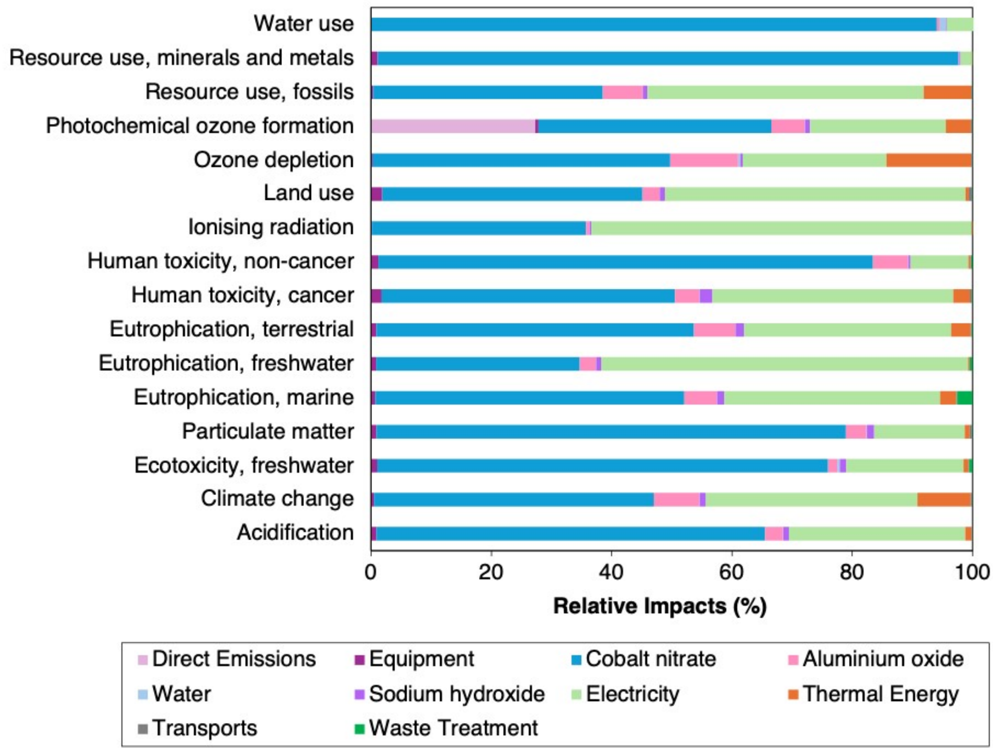

Figure S16 Relative impacts, calculated at midpoint level (EF3.1) for the production of 1 kg of hybrid pigment C ($CoAl_2O_4/Al_2O_3$) through heterogeneous precipitation method.

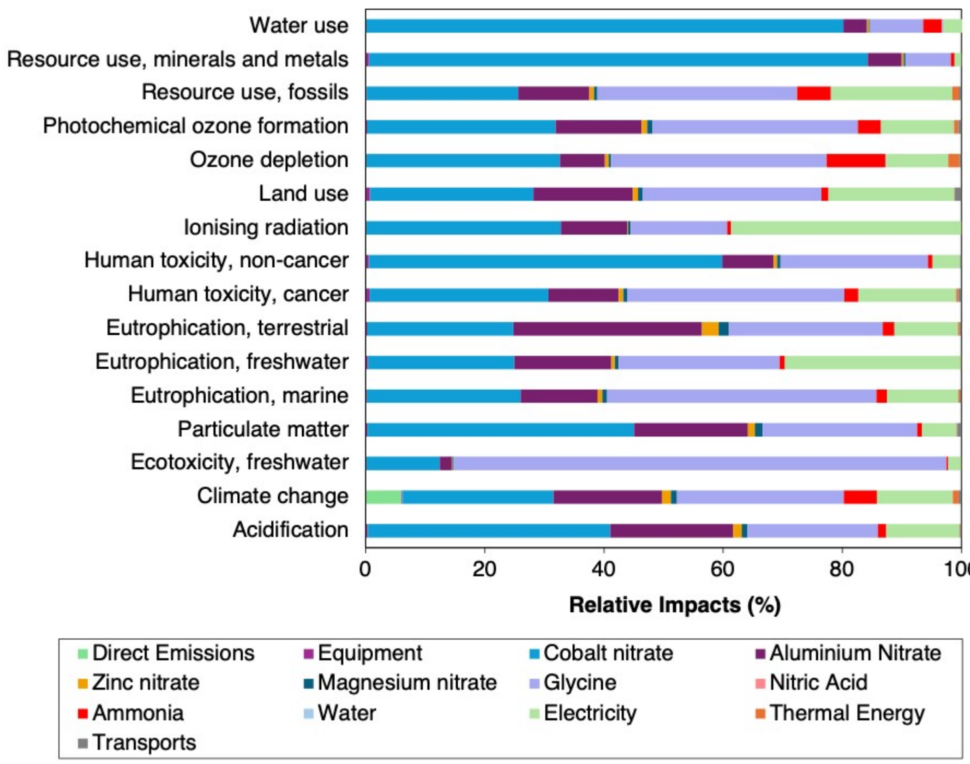

Figure S17 Relative impacts, calculated at midpoint level (EF3.1) for the production of 1 kg of pigment D ($Co_{0.67}Mg_{0.16}Zn_{0.16}Al_2O_4$) through sol-gel autoignition method.

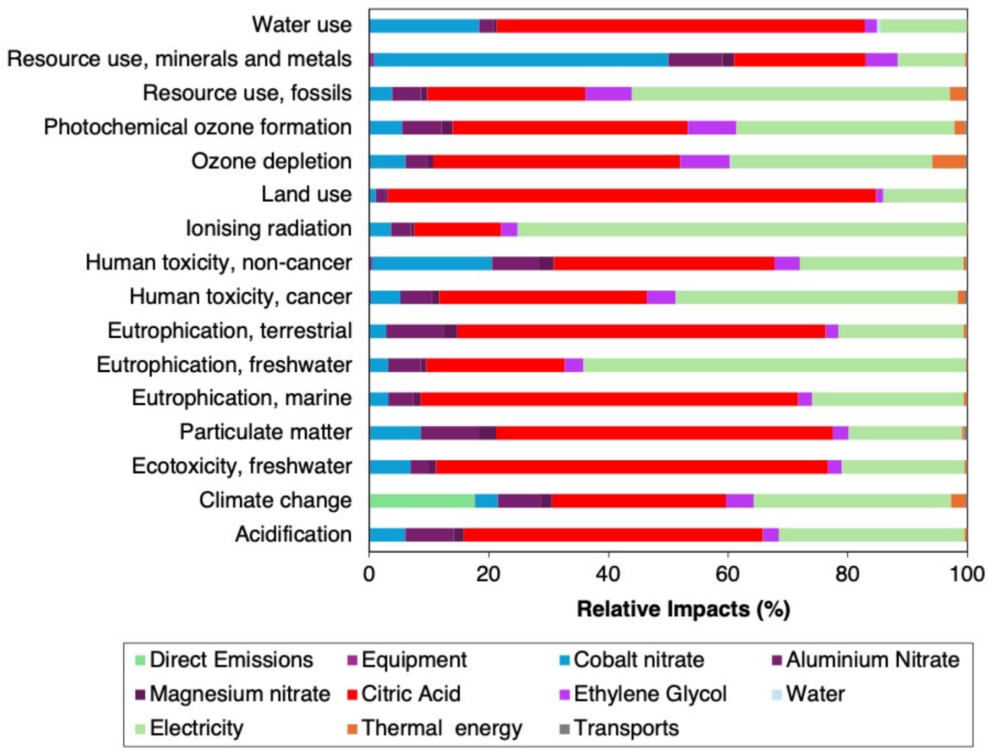

Figure S18 Relative impacts, calculated at midpoint level (EF3.1) for the production of 1 kg of pigment E ($Co_{0.25}Mg_{0.75}Al_2O_4$) through sol-gel autoignition method.

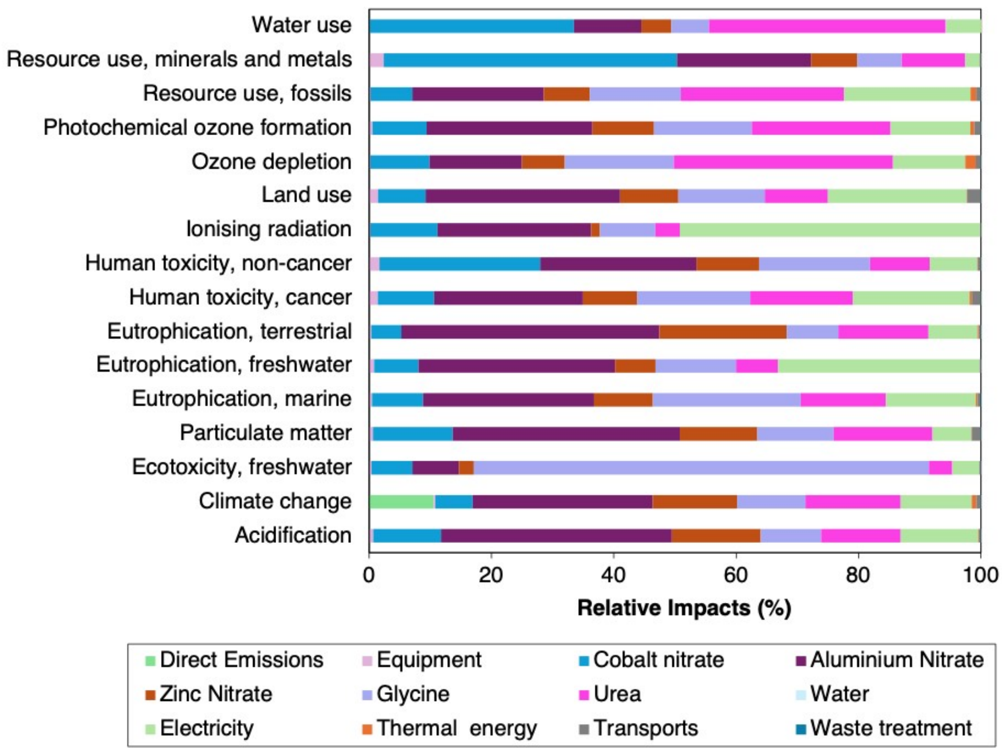

Figure S19 Relative impacts, calculated at midpoint level (EF3.1) for the production of 1 kg of pigment F ($Zn_{0.9}Co_{0.1}Al_2O_4$) through sol-gel autoignition method.

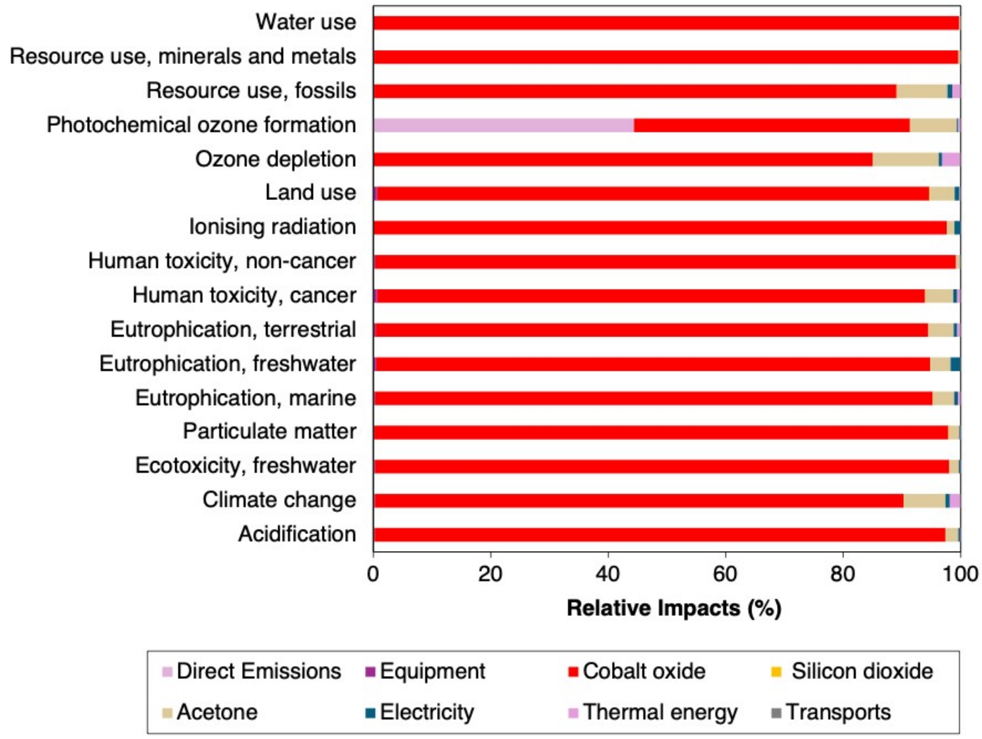

Figure S20 Relative impacts, calculated at midpoint level (EF3.1) for the production of 1 kg of pigment G (Co_2SiO_4) through solid-state reaction.

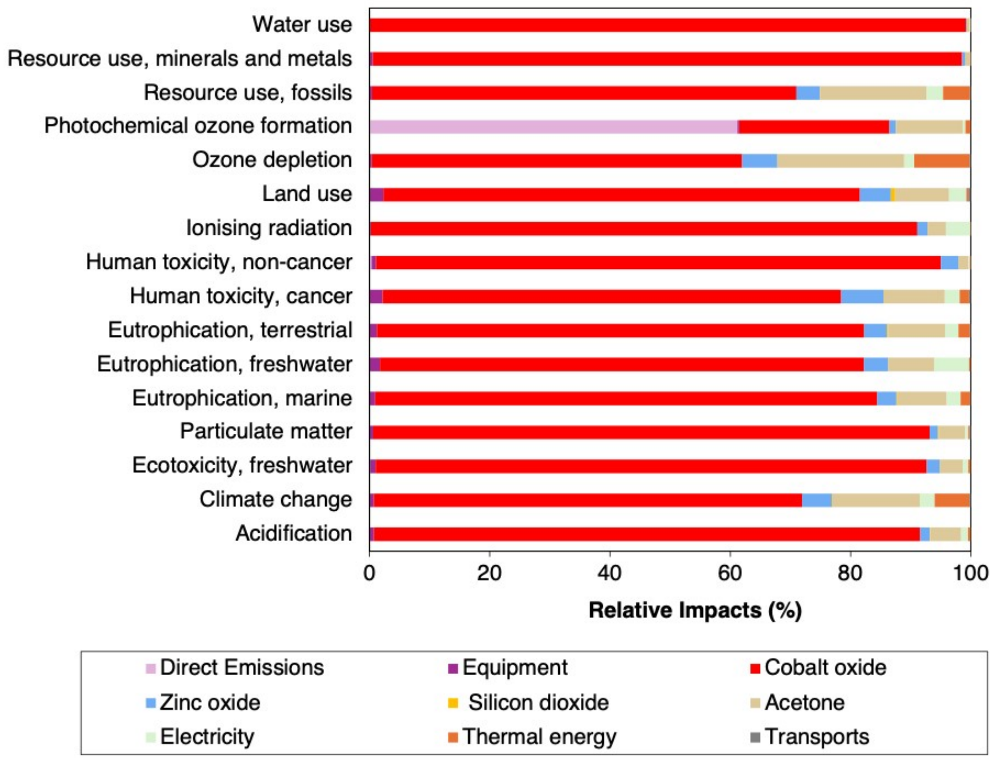

Figure S21 Relative impacts, calculated at midpoint level (EF3.1) for the production of 1 kg of pigment H ($Co_{0.5}Zn_{1.5}$ SiO_4) through solid-state reaction.

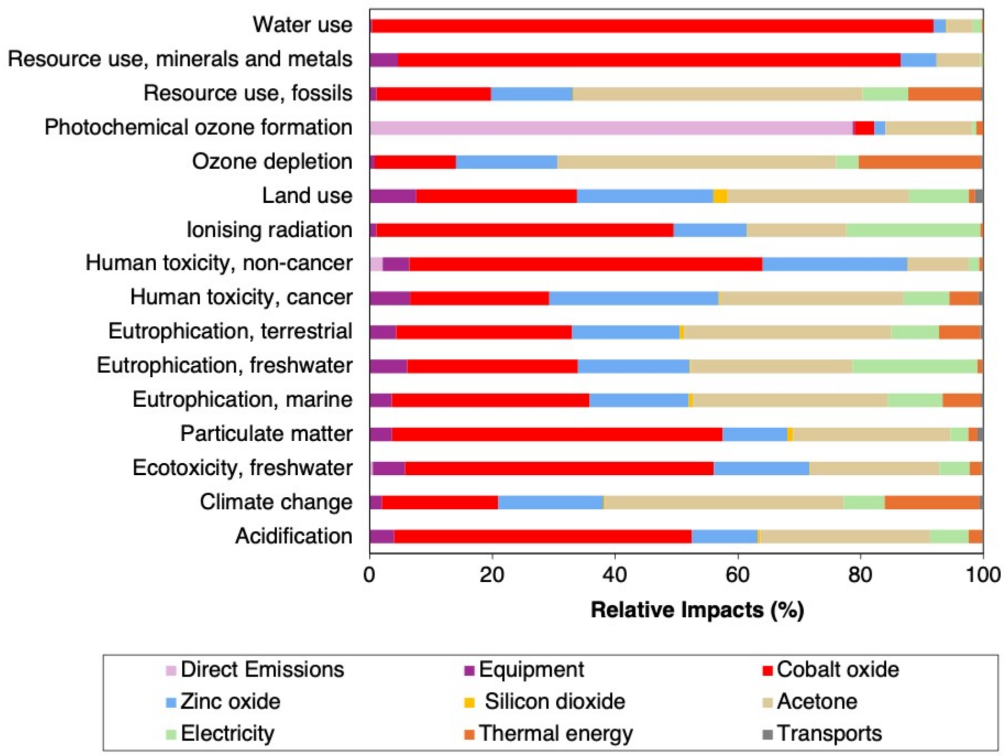

Figure S22 Relative impacts, calculated at midpoint level (EF3.1) for the production of 1 kg of pigment I ($Co_{0.05}Zn_{1.95}SiO_4$) through solid-state reaction.

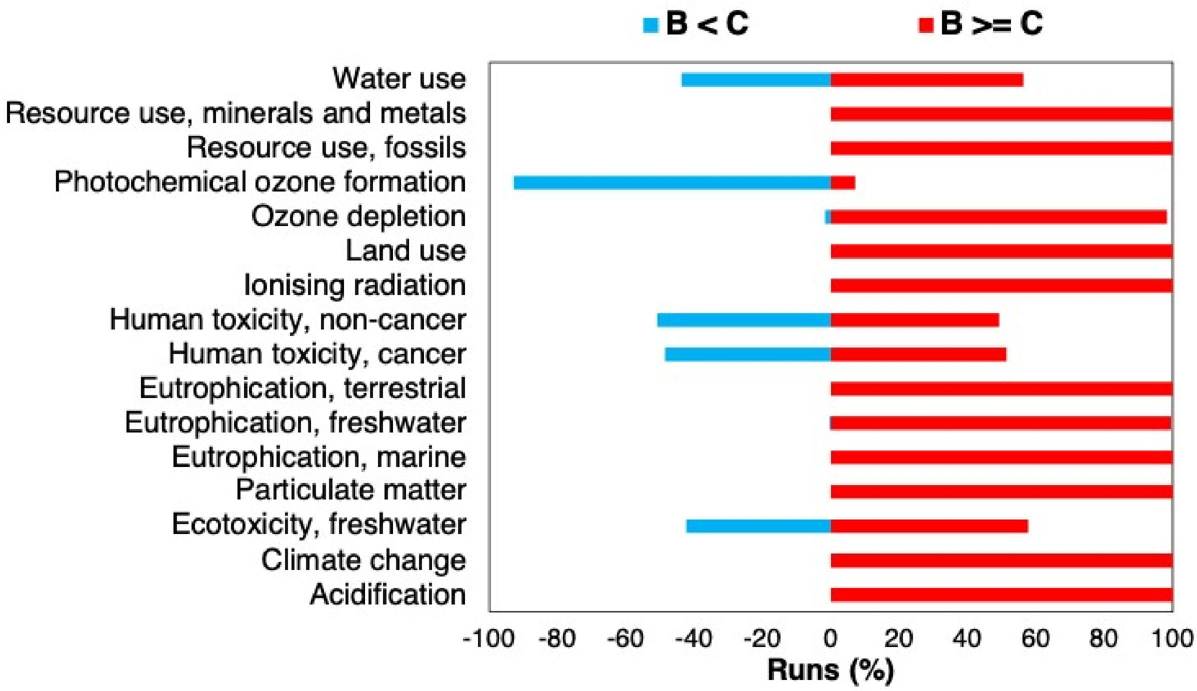

Figure S23 Monte Carlo simulation, performed at midpoint level (EF.3.1 impact assessment method), with 1000 runs in a 95% significance threshold for the comparative environmental impacts of B vs C.

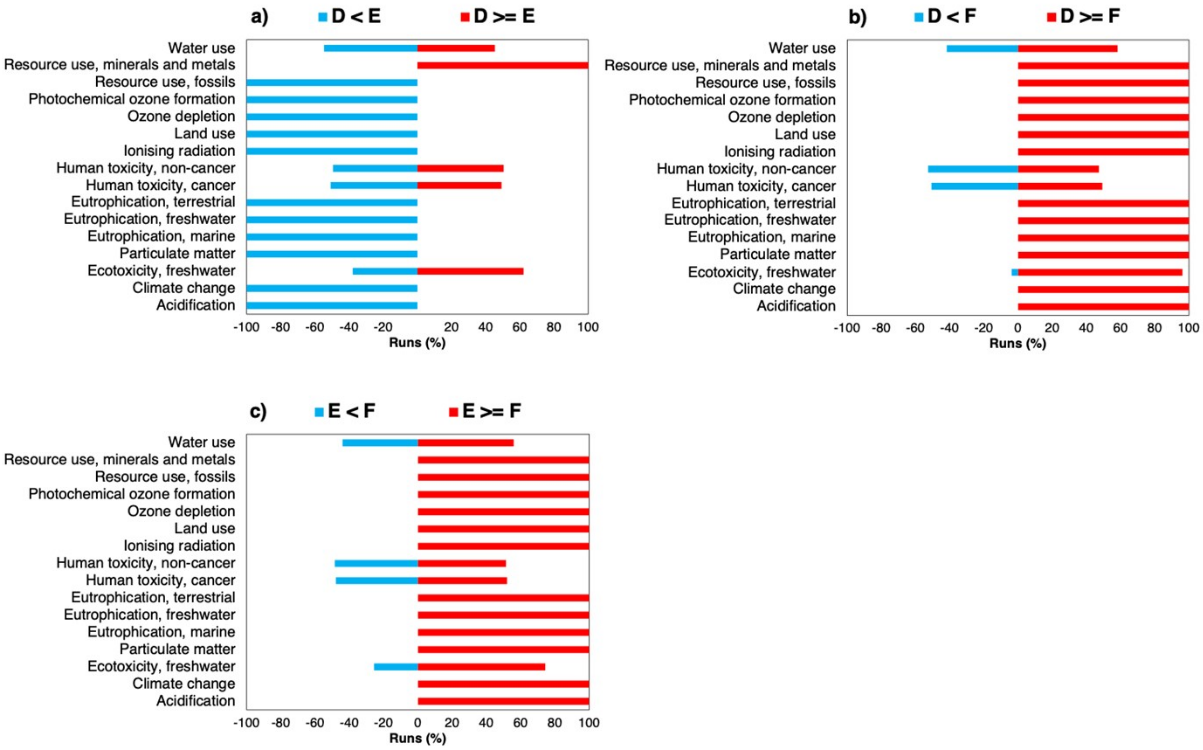

Figure S24 Monte Carlo simulation, performed at midpoint level (EF.3.1 impact assessment method), with 1000 runs in a 95% significance threshold, for the comparative environmental impacts of a) D vs E; b) D vs F; c) E vs F.

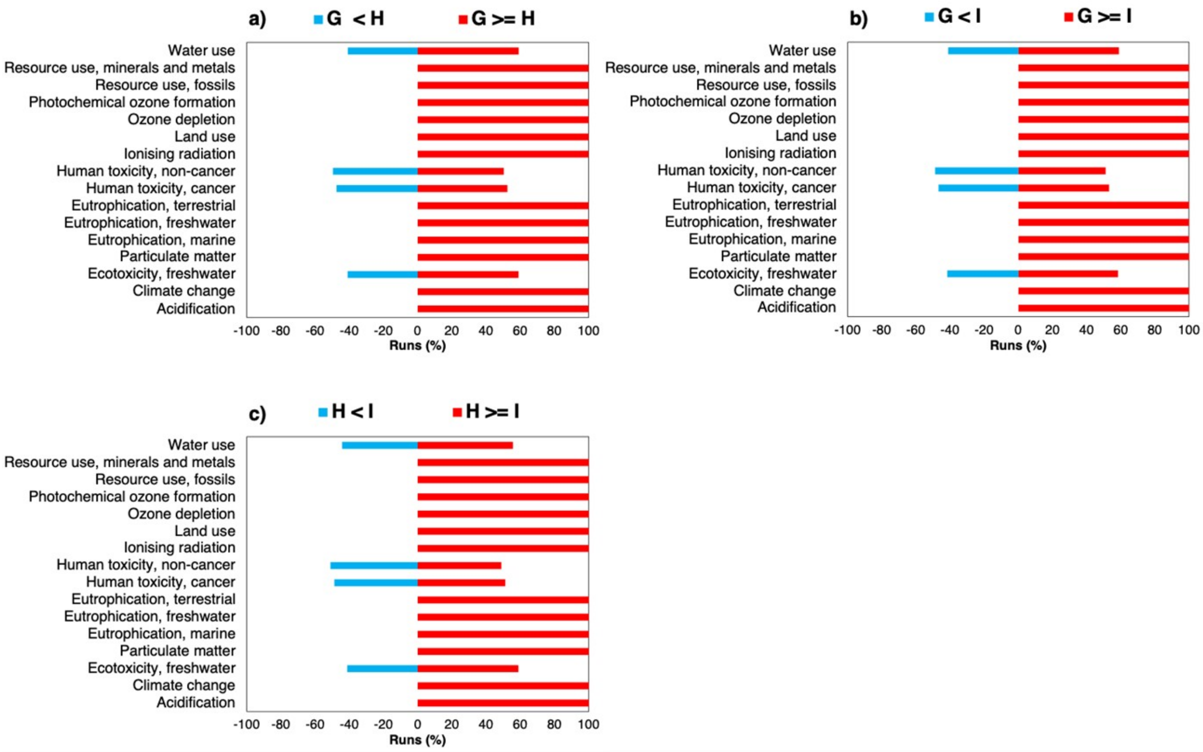

Figure S25 Monte Carlo simulation, performed at midpoint level (EF.3.1 impact assessment method), with 1000 runs in a 95% significance threshold, for the comparative environmental impacts of a) G vs H; b) G vs I; c) H vs I.

Tables

Table S1

Contributions to LCI for the production of 1 kg of cobalt oxide (CoO), modelled according to the procedure described by Mayer et al.[1]

Process	Description	Amount	Data Source
Output	CoO	1 kg	
	Materials		
Chemicals	Co_3O_4	1.07 kg	ecoinvent v. 3.10[1]
	Argon	0.57 kg	ecoinvent v. 3.10[2]
	Equipment and land use		
Chemical Factory		4E-10 p	ecoinvent v. 3.10[3]
	Energy		
Electricity		52 kWh	ecoinvent v. 3.10[4]
Thermal Energy		51.5 MJ	ecoinvent v. 3.10[5]
	Transports		
	Raw materials	0.107 tkm	ecoinvent v. 3.10[6]
	Atmospheric emissions		
	oxygen	0.0712 kg	SimaPro airborne emission substance list

[1]The EID dataset was: “Cobalt oxide {GLO}| cobalt production | APOS, U”.

[2]The EID dataset was: “Argon, crude, liquid {GLO}| market for argon, crude, liquid | APOS, U”

[3]The EID dataset was: “Chemical factory, organics {GLO}| market for | APOS, U”.

[4]The EID dataset was: “Electricity, medium voltage {RER}| market group for electricity, medium voltage | APOS, U”. The value was calculated by multiplying the power consumption of the equipment by the duration of its use.

[5]The EID dataset was: “Heat, central or small-scale, natural gas {RER}| market group for heat, central or small-scale, natural gas | APOS, U”. The dataset describes the thermal energy necessary for the process. To calculate the energy necessary to heat the reaction, the formula, $Q = m \cdot Cp \cdot \Delta T$, where m is the weight of the reaction mixture, Cp is the heat capacity of the reaction mixture and ΔT is the difference between the reaction temperature and ambient temperature. For the energy necessary to maintain the reaction at a certain temperature, the formula $Q = U_{oven} \cdot A_{oven} \cdot \Delta T \cdot t_r \cdot 0.036$, where U_{oven} is the heat transfer coefficient of the oven, A_{oven} is the surface of the oven and t_r is the reaction time. For the energy released or absorbed by the reaction at the temperature T, the formula $Q_r = n_{product} \cdot \Delta_r H^T$, where $\Delta_r H^T$ is the enthalpy of reaction at temperature T.

[6]The EID dataset was “Transport, freight, lorry 16-32 metric ton, EURO6 {RoW}| transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U”. The average distance was 100 km.

Table S2

Contributions to LCI for the production of 1 kg of A1, modelled according to the scaled-up procedure described by Ding et al., 2021[2] and Kim et al., 2019[3].

Process	Description	Amount	Data Source
Output	$CoAl_2O_4$	1 kg	
	Materials		
Chemicals	CoO	0.42 kg	ecoinvent v. 3.10[1]
	Al_2O_3	0.57 kg	ecoinvent v. 3.10[2]
	Ethanol	1.33 kg	ecoinvent v. 3.10[3]
	Equipment and land use		

Chemical Factory		4E-10 p	ecoinvent v. 3.10[4]
	Energy		
Electricity		52 kWh	ecoinvent v. 3.10[5]
Thermal Energy		51.5 MJ	ecoinvent v. 3.10[6]
	Transports		
	Raw materials	0.23 tkm	ecoinvent v. 3.10[7]
	Atmospheric emissions		
	Ethanol	0.0133 kg	SimaPro airborne emission substance list
	Waste treatment		
	Waste solvent	0.00132 kg	ecoinvent v. 3.10[8]

[1]Modelled as described in **Table S1**.

[2]The EID dataset was: “Aluminium oxide, non-metallurgical {IAI Area, EU27 & EFTA}| aluminium oxide production | APOS, U”.

[3]The EID dataset was: “Ethanol, without water, in 99.7% solution state, from ethylene {RoW}| ethylene hydration | APOS, U”.

[4]The EID dataset was: “Chemical factory, organics {GLO}| market for | APOS, U”.

[5]The EID dataset was: “Electricity, medium voltage {RER}| market group for electricity, medium voltage | APOS, U”. The value was calculated by multiplying the power consumption of the equipment by the duration of its use.

[6]The EID dataset was: “Heat, central or small-scale, natural gas {RER}| market group for heat, central or small-scale, natural gas | APOS, U”. The dataset describes the thermal energy necessary for the process. To calculate the energy necessary to heat the reaction, the formula, $Q = m \cdot Cp \cdot \Delta T$, where m is the weight of the reaction mixture, Cp is the heat capacity of the reaction mixture and ΔT is the difference between the reaction temperature and ambient temperature. For the energy necessary to maintain the reaction at a certain temperature, the formula $Q = U_{oven} \cdot A_{oven} \cdot \Delta T \cdot t_r \cdot 0.036$, where U_{oven} is the heat transfer coefficient of the oven, A_{oven} is the surface of the oven and t_r is the reaction time. For the energy released or absorbed by the reaction at the temperature T, the formula $Q_r = n_{product} \cdot \Delta_r H^T$, where $\Delta_r H^T$ is the enthalpy of reaction at temperature T.

[7]The EID dataset was “Transport, freight, lorry 16-32 metric ton, EURO6 {RoW}| transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U”. The average distance was 100 km.

[8]The EID dataset was “Wastewater, average {RoW}| treatment of wastewater, average, wastewater treatment | APOS, U”., and it describes the treatment of the waste solvent

Table S3

Contributions to LCI for the production of 1 kg of A2, modelled according to the scaled-up procedure described by Zhang et al., 2019[4].

Process	Description	Amount	Data Source
Output	$CoAl_2O_4$	1 kg	
	Materials		
Cobalt Nitrate	$Co(NO_3)_2 \cdot 6H_2O$	1.65 kg	Modelled from ecoinvent v. 3.10[1]
Aluminium Nitrate	$Al(NO_3)_3 \cdot 9H_2O$	4.22 kg	Modelled from ecoinvent v. 3.10[2]
Sodium Hydroxide	NaOH	1.81 kg	ecoinvent v. 3.10[3]
Water (deionized)	H_2O	36.30 kg	ecoinvent v. 3.10[4]
	Equipment and land use		
Chemical Factory		4E-10 p	ecoinvent v. 3.10[5]
	Energy		
Electricity		42.80 kWh	ecoinvent v. 3.10[6]

Thermal Energy		16.40 MJ	ecoinvent v. 3.10[7]
	Transports		
	Raw materials	0.77 tkm	ecoinvent v. 3.10[8]
	Atmospheric emissions		
In air	water	4.22E-02 kg	SimaPro airborne emission substance list
	Waste treatment		
	Waste solvent	0.0429 m^3	ecoinvent v. 3.10[9]

[1]Cobalt nitrate hexahydrate ($Co(NO_3)_2{\cdot}6H_2O$)was modelled from the EID dataset "Cobalt sulfate {RoW}| cobalt sulfate production | APOS, U", considering the reaction of cobalt hydroxide with an aqueous solution of nitric acid (50 wt.%). The input of sulfuric acid was replaced with a stoichiometric amount of nitric acid and the corresponding amounts of inputs and outputs were corrected for the content of cobalt.

[2]Aluminium nitrate ($Al(NO_3)_3{\cdot}9H_2O$) was modelled from the EID dataset "Aluminium sulfate, powder {RER}| production | APOS, U", considering the reaction of aluminium hydroxide with an aqueous solution of nitric acid (50 wt.%). The inputs of sulfuric acid were replaced with a stoichiometric amount of nitric acid and the corresponding amount of waste solvent was corrected for the mass balance.

[3]The EID dataset was: "Sodium hydroxide, without water, in 50% solution state {RER}| chlor-alkali electrolysis, diaphragm cell | APOS, U".

[4]The EID dataset was: "Water, deionised {RoW}| water production, deionised | APOS, U". and it describes the total amount of water necessary for the process (i.e., reaction, precipitate washing, solution preparation)

[5]The EID dataset was: "Chemical factory, organics {GLO}| market for | APOS, U".

[6]The EID dataset was: "Electricity, medium voltage {RER}| market group for electricity, medium voltage | APOS, U". The value was calculated by multiplying the power consumption of the equipment by the duration of its use.

[7]The EID dataset was: "Heat, central or small-scale, natural gas {RER}| market group for heat, central or small-scale, natural gas | APOS, U". The dataset describes the thermal energy necessary for the process. To calculate the energy necessary to heat the reaction, the formula, $Q = m{\cdot}Cp{\cdot}\Delta T$, where m is the weight of the reaction mixture, Cp is the heat capacity of the reaction mixture and ΔT is the difference between the reaction temperature and ambient temperature. For the energy necessary to maintain the reaction at a certain temperature, the formula $Q = U_{oven}{\cdot}A_{oven}{\cdot}\Delta T{\cdot}t_r{\cdot}0.036$, where U_{oven} is the heat transfer coefficient of the oven, A_{oven} is the surface of the oven and t_r is the reaction time. For the energy released or absorbed by the reaction at the temperature T, the formula $Q_r = n_{product}{\cdot}\Delta_r H^T$, where $\Delta_r H^T$ is the enthalpy of reaction at temperature T.

[8]The EID dataset was "Transport, freight, lorry 16-32 metric ton, EURO6 {RoW}| transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U". The average distance was 100 km.

[9]The EID dataset was "Wastewater, average {RoW}| treatment of wastewater, average, wastewater treatment | APOS, U"., and it describes the treatment of the waste solvent.

Table S4

Contributions to LCI for the production of 1 kg of A3, modelled according to the scaled-up procedure described by Tong et al., 2016[5].

Process	Description	Amount	Data Source
Output	$CoAl_2O_4$	1 kg	
	Materials		
Cobalt Nitrate	$Co(NO_3)_2{\cdot}6H_2O$	1.65 kg	Modelled from ecoinvent v. 3.10[1]
Aluminium Nitrate	$Al(NO_3)_3{\cdot}9H_2O$	4.22 kg	Modelled from ecoinvent v. 3.10[2]

Urea	CH_4N_2O	2.26 kg	ecoinvent v. 3.10[3]
Water (deionized)	H_2O	17.00 kg	ecoinvent v. 3.10[4]
	Equipment and land use		
Chemical Factory		4E-10 p	ecoinvent v. 3.10[5]
	Energy		
Electricity		19.9 kWh	ecoinvent v. 3.10[6]
Thermal Energy		18.7 MJ	ecoinvent v. 3.10[7]
	Transports		
	Raw materials	0.813 tkm	ecoinvent v. 3.10[8]
	Atmospheric emissions		
In air	water	4.22E-02 kg	SimaPro airborne emission substance list
	CO_2	1.66 kg	SimaPro airborne emission substance list
	N_2	1.69 kg	SimaPro airborne emission substance list

[1]Cobalt nitrate hexahydrate ($Co(NO_3)_2{\cdot}6H_2O$)was modelled from the EID dataset "Cobalt sulfate {RoW}| cobalt sulfate production | APOS, U", considering the reaction of cobalt hydroxide with an aqueous solution of nitric acid (50 wt.%). The input of sulfuric acid was replaced with a stoichiometric amount of nitric acid and the corresponding amounts of inputs and outputs were corrected for the content of cobalt.

[2]Aluminium nitrate ($Al(NO_3)_3{\cdot}9H_2O$) was modelled from the EID dataset "Aluminium sulfate, powder {RER}| production | APOS, U", considering the reaction of aluminium hydroxide with an aqueous solution of nitric acid (50 wt.%). The inputs of sulfuric acid were replaced with a stoichiometric amount of nitric acid and the corresponding amount of waste solvent was corrected for the mass balance.

[3]The EID dataset was: "Urea {RER}| urea production | APOS, U"

[4]The EID dataset was: "Water, deionised {RoW}| water production, deionised | APOS, U".

[5]The EID dataset was: "Chemical factory, organics {GLO}| market for | APOS, U".

[6]The EID dataset was: "Electricity, medium voltage {RER}| market group for electricity, medium voltage | APOS, U". The value was calculated by multiplying the power consumption of the equipment by the duration of its use.

[7]The EID dataset was: "Heat, central or small-scale, natural gas {RER}| market group for heat, central or small-scale, natural gas | APOS, U". The dataset describes the thermal energy necessary for the process. To calculate the energy necessary to heat the reaction, the formula, $Q = m{\cdot}Cp{\cdot}\Delta T$, where m is the weight of the reaction mixture, Cp is the heat capacity of the reaction mixture and ΔT is the difference between the reaction temperature and ambient temperature. For the energy necessary to maintain the reaction at a certain temperature, the formula $Q = U_{oven}{\cdot}A_{oven}{\cdot}\Delta T{\cdot}t_r{\cdot}0.036$, where U_{oven} is the heat transfer coefficient of the oven, A_{oven} is the surface of the oven and t_r is the reaction time. For the energy released or absorbed by the reaction at the temperature T, the formula $Q_r = n_{product}{\cdot}\Delta_r H^T$, where $\Delta_r H^T$ is the enthalpy of reaction at temperature T.

[8]The EID dataset was "Transport, freight, lorry 16-32 metric ton, EURO6 {RoW}| transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U". The average distance was 100 km.

Table S5

Contributions to LCI for the production of 1 kg of A4, modelled according to the scaled-up procedure described by Zhang et al., 2019[6].

Process	Description	Amount	Data Source
Output	$CoAl_2O_4$	1 kg	
	Materials		
Cobalt Nitrate	$Co(NO_3)_2{\cdot}6H_2O$	1.65 kg	Modelled from ecoinvent v.

			3.10[1]
Aluminium Nitrate	$Al(NO_3)_3·9H_2O$	4.22 kg	Modelled from ecoinvent v. 3.10[2]
Sodium hydroxide	NaOH	0.068 kg	ecoinvent v. 3.10[3]
Water (deionized)	H_2O	22 kg	ecoinvent v. 3.10[4]
	Equipment and land use		
Chemical Factory		4E-10 p	ecoinvent v. 3.10[5]
	Energy		
Electricity		13.5 kWh	ecoinvent v. 3.10[6]
Thermal Energy		8.71 MJ	ecoinvent v. 3.10[10]
	Transports		
	Raw materials	0.593 tkm	ecoinvent v. 3.10[7]
	Atmospheric emissions		
In air	water	0.22 kg	SimaPro airborne emission substance list
	Waste treatment		
	Waste solvent	0.0267 m^3	ecoinvent v. 3.10[8]

[1]Cobalt nitrate hexahydrate ($Co(NO_3)_2·6H_2O$)was modelled from the EID dataset "Cobalt sulfate {RoW}| cobalt sulfate production | APOS, U", considering the reaction of cobalt hydroxide with an aqueous solution of nitric acid (50 wt.%). The input of sulfuric acid was replaced with a stoichiometric amount of nitric acid and the corresponding amounts of inputs and outputs were corrected for the content of cobalt.

[2]Aluminium nitrate ($Al(NO_3)_3·9H_2O$) was modelled from the EID dataset "Aluminium sulfate, powder {RER}| production | APOS, U", considering the reaction of aluminium hydroxide with an aqueous solution of nitric acid (50 wt.%). The inputs of sulfuric acid were replaced with a stoichiometric amount of nitric acid and the corresponding amount of waste solvent was corrected for the mass balance.

[3]The EID dataset was: "Sodium hydroxide, without water, in 50% solution state {RER}| chlor-alkali electrolysis, diaphragm cell | APOS, U"."

[4]The EID dataset was: "Water, deionised {RoW}| water production, deionised | APOS, U".

[5]The EID dataset was: "Chemical factory, organics {GLO}| market for | APOS, U".

[6]The EID dataset was: "Electricity, medium voltage {RER}| market group for electricity, medium voltage | APOS, U". The value was calculated by multiplying the power consumption of the equipment by the duration of its use.

[7]The EID dataset was: "Heat, central or small-scale, natural gas {RER}| market group for heat, central or small-scale, natural gas | APOS, U". The dataset describes the thermal energy necessary for the process. To calculate the energy necessary to heat the reaction, the formula, $Q = m·Cp·\Delta T$, where m is the weight of the reaction mixture, Cp is the heat capacity of the reaction mixture and ΔT is the difference between the reaction temperature and ambient temperature. For the energy necessary to maintain the reaction at a certain temperature, the formula $Q = U_{oven}·A_{oven}·\Delta T·t_r·0.036$, where U_{oven} is the heat transfer coefficient of the oven, A_{oven} is the surface of the oven and t_r is the reaction time. For the energy released or absorbed by the reaction at the temperature T, the formula $Q_r = n_{product}·\Delta_r H^T$, where $\Delta_r H^T$ is the enthalpy of reaction at temperature T.

[8]The EID dataset was "Transport, freight, lorry 16-32 metric ton, EURO6 {RoW}| transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U". The average distance was 100 km.

[9]The EID dataset was "Wastewater, average {RoW}| treatment of wastewater, average, wastewater treatment | APOS, U"., and it describes the treatment of the waste solvent.

Table S6

Contributions to LCI for the production of 1 kg of B ($CoAl_2O_4$/kaolin), modelled according to the scaled-up procedure described by Zhang et al., 2019[6].

Process	Description	Amount	Data Source
Output	$CoAl_2O_4$/kaoline	1 kg	
	Materials		
Cobalt Nitrate	$Co(NO_3)_2{\cdot}6H_2O$	1.987 kg	Modelled from ecoinvent v. 3.10[1]
Aluminium Nitrate	$Al(NO_3)_3{\cdot}9H_2O$	2.53 kg	Modelled from ecoinvent v. 3.10[2]
Kaolin		0.4 kg	ecoinvent v. 3.10[3]
Sodium hydroxide	NaOH	0.068 kg	ecoinvent v. 3.10[4]
Hydrochloric acid	HCl	0.0185	ecoinvent v. 3.10[5]
Water (deionized)	H_2O	16.1 kg	ecoinvent v. 3.10[6]
	Equipment and land use		
Chemical Factory		4E-10 p	ecoinvent v. 3.10[7]
	Energy		
Electricity		13.3 kWh	ecoinvent v. 3.10[8]
Thermal Energy		7.28 MJ	ecoinvent v. 3.10[9]
	Transports		
	Raw materials	0.593 tkm	ecoinvent v. 3.10[10]
	Atmospheric emissions		
In air	water	0.22 kg	SimaPro airborne emission substance list
	Waste treatment		
	Waste solvent	0.0189 m^3	ecoinvent v. 3.10[11]

[1]Cobalt nitrate hexahydrate ($Co(NO_3)_2{\cdot}6H_2O$)was modelled from the EID dataset "Cobalt sulfate {RoW}| cobalt sulfate production | APOS, U", considering the reaction of cobalt hydroxide with an aqueous solution of nitric acid (50 wt.%). The input of sulfuric acid was replaced with a stoichiometric amount of nitric acid and the corresponding amounts of inputs and outputs were corrected for the content of cobalt.

[2]Aluminium nitrate ($Al(NO_3)_3{\cdot}9H_2O$) was modelled from the EID dataset "Aluminium sulfate, powder {RER}| production | APOS, U", considering the reaction of aluminium hydroxide with an aqueous solution of nitric acid (50 wt.%). The inputs of sulfuric acid were replaced with a stoichiometric amount of nitric acid and the corresponding amount of waste solvent was corrected for the mass balance.

[3]The EID dataset was "Kaolin {RER}| kaolin production | APOS, U".

[4]The EID dataset was: "Sodium hydroxide, without water, in 50% solution state {RER}| chlor-alkali electrolysis, diaphragm cell | APOS, U"."

[5]The EID dataset was: "Hydrochloric acid, without water, in 30% solution state {RER}| hydrochloric acid production, Mannheim process | APOS, U"

[6]The EID dataset was: "Water, deionised {RoW}| water production, deionised | APOS, U".

[7]The EID dataset was: "Chemical factory, organics {GLO}| market for | APOS, U".

[8]The EID dataset was: "Electricity, medium voltage {RER}| market group for electricity, medium voltage | APOS, U". The value was calculated by multiplying the power consumption of the equipment by the duration of its use.

[9]The EID dataset was: "Heat, central or small-scale, natural gas {RER}| market group for heat, central or small-scale, natural gas | APOS, U". The dataset describes the thermal energy necessary for the process. To calculate the energy necessary to heat the reaction, the formula, $Q = m{\cdot}Cp{\cdot}\Delta T$, where m is the weight of the reaction mixture, Cp is the heat capacity of the reaction mixture and ΔT is the difference between the reaction temperature and ambient temperature. For the energy necessary to maintain the reaction at a certain temperature, the formula

$Q = U_{oven} \cdot A_{oven} \cdot \Delta T \cdot t_r \cdot 0.036$, where U_{oven} is the heat transfer coefficient of the oven, A_{oven} is the surface of the oven and t_r is the reaction time. For the energy released or absorbed by the reaction at the temperature T, the formula $Q_r = n_{product} \cdot \Delta_r H^T$, where $\Delta_r H^T$ is the enthalpy of reaction at temperature T.

[10]The EID dataset was "Transport, freight, lorry 16-32 metric ton, EURO6 {RoW}| transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U". The average distance was 100 km.

[11]The EID dataset was "Wastewater, average {RoW}| treatment of wastewater, average, wastewater treatment | APOS, U"., and it describes the treatment of the waste solvent.

Table S7

Contributions to LCI for the production of 1 kg of pigment C ($CoAl_2O_4/Al_2O_3$), modelled according to the scaled-up procedure described by He et al., 2020[7].

Process	Description	Amount	Data Source
Output	$CoAl_2O_4/Al_2O_3$	1 kg	
		Materials	
Cobalt Nitrate	$Co(NO_3)_2 \cdot 6H_2O$	0.702 kg	Modelled from ecoinvent v. 3.10[1]
Aluminium Oxide	Al_2O_3	0.819 kg	Modelled from ecoinvent v. 3.10[2]
Sodium Hydroxide	NaOH	0.0964 kg	ecoinvent v. 3.10[3]
Water (deionized)	H_2O	11.7 kg	ecoinvent v. 3.10[4]
		Equipment and land use	
Chemical Factory		4E-10 p	Modelled from ecoinvent v. 3.10[5]
		Energy	
Electricity		13.5 kWh	ecoinvent v. 3.10[6]
Thermal Energy		20.2 MJ	ecoinvent v. 3.10[7]
		Transports	
	Raw materials	0.162 tkm	ecoinvent v. 3.10[8]
		Atmospheric emissions	
In air	water	0.137 kg	SimaPro airborne emission substance list
	ethanol	2.09E-04	SimaPro airborne emission substance list
		Waste treatment	
	Solvent	0.0163 m^3	ecoinvent v. 3.10[9]

[1]Cobalt nitrate hexahydrate ($Co(NO_3)_2 \cdot 6H_2O$)was modelled from the EID dataset "Cobalt sulfate {RoW}| cobalt sulfate production | APOS, U", considering the reaction of cobalt hydroxide with an aqueous solution of nitric acid (50 wt.%). The input of sulfuric acid was replaced with a stoichiometric amount of nitric acid and the corresponding amounts of inputs and outputs were corrected for the content of cobalt.

[2]Aluminium nitrate ($Al(NO_3)_3 \cdot 9H_2O$) was modelled from the EID dataset "Aluminium sulfate, powder {RER}| production | APOS, U", considering the reaction of aluminium hydroxide with an aqueous solution of nitric acid (50 wt.%). The inputs of sulfuric acid were replaced with a stoichiometric amount of nitric acid and the corresponding amount of waste solvent was corrected for the mass balance.

[3]The EID dataset was: "Sodium hydroxide, without water, in 50% solution state {RER}| chlor-alkali electrolysis, diaphragm cell | APOS, U".

[4]The EID dataset was: "Water, deionised {RoW}| water production, deionised | APOS, U". and it describes the total amount of water necessary for the process (i.e., reaction, precipitate washing, solution preparation)

[5]The EID dataset was: "Chemical factory, organics {GLO}| market for | APOS, U".

[6]The EID dataset was: "Electricity, medium voltage {RER}| market group for electricity, medium voltage | APOS, U". The value was calculated by multiplying the power consumption of the equipment by the duration of its use.

[7]The EID dataset was: "Heat, central or small-scale, natural gas {RER}| market group for heat, central or small-scale, natural gas | APOS, U". The dataset describes the thermal energy necessary for the process. To calculate the energy necessary to heat the reaction, the formula, $Q = m \cdot Cp \cdot \Delta T$, where m is the weight of the reaction mixture, Cp is the heat capacity of the reaction mixture and ΔT is the difference between the reaction temperature and ambient temperature. For the energy necessary to maintain the reaction at a certain temperature, the formula $Q = U_{oven} \cdot A_{oven} \cdot \Delta T \cdot t_r \cdot 0.036$, where U_{oven} is the heat transfer coefficient of the oven, A_{oven} is the surface of the oven and t_r is the reaction time. For the energy released or absorbed by the reaction at the temperature T, the formula $Q_r = n_{product} \cdot \Delta_r H^T$, where $\Delta_r H^T$ is the enthalpy of reaction at temperature T.

[8]The EID dataset was "Transport, freight, lorry 16-32 metric ton, EURO6 {RoW}| transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U". The average distance was 100 km.

[9]The EID dataset was "Wastewater, average {RoW}| treatment of wastewater, average, wastewater treatment | APOS, U"., and it describes the treatment of the waste solvent.

Table S8

Contributions to LCI for the production of 1 kg of pigment D ($Co_{0.67}Mg_{0.16}Zn_{0.16}Al_2O_4$), modelled according to the scaled-up procedure described by Mokhatri and Salem, 2017[8].

Process	Description	Amount	Data Source
Output	$Co_{0.67}Mg_{0.16}Zn_{0.16}Al_2O_4$	1 kg	
	Materials		
Cobalt nitrate	$Co(NO_3)_2 \cdot 6H_2O$	1.13 kg	Modelled from ecoinvent v. 3.10[1]
Aluminium nitrate	$Al(NO_3)_3 \cdot 9H_2O$	4.34 kg	Modelled from ecoinvent v. 3.10[2]
Zinc nitrate	$Zn(NO_3)_2 \cdot 6H_2O$	0.277 kg	Modelled from ecoinvent v. 3.10[3]
Magnesium nitrate	$Mg(NO_3)_2 \cdot 6H_2O$	0.247 kg	Modelled from ecoinvent v. 3.10[4]
Glycine	$C_2H_5NO_2$	1.97 kg	ecoinvent v. 3.8[5]
Ammonia	NH_3	0.792 kg	ecoinvent v. 3.8[6]
Water (deionized)	H_2O	5.76 kg	ecoinvent v. 3.10[7]
	Equipment and land use		
Chemical Factory		4E-10 p	ecoinvent v. 3.10[8]
	Energy		
Electricity		14.6 kWh	ecoinvent v. 3.10[9]
Thermal Energy		6.8 MJ	ecoinvent v. 3.10[10]
	Transports		
	Raw materials	0.876 tkm	ecoinvent v. 3.10[11]
	Atmospheric emissions		
In air	water	9.55 kg	SimaPro airborne emission substance list
	CO_2	2.31 kg	SimaPro airborne emission substance list
	N_2	1.67 kg	SimaPro airborne emission substance list

[1]Cobalt nitrate hexahydrate ($Co(NO_3)_2 \cdot 6H_2O$)was modelled from the EID dataset "Cobalt sulfate {RoW}| cobalt sulfate production | APOS, U", considering the reaction of cobalt hydroxide with an aqueous solution of nitric acid (50 wt.%). The input of sulfuric acid was replaced with a stoichiometric amount of nitric acid and the corresponding amounts of inputs and outputs were corrected for the content of cobalt.

[2]Aluminium nitrate ($Al(NO_3)_3 \cdot 9H_2O$) was modelled from the EID dataset "Aluminium sulfate, powder {RER}| production | APOS, U", considering the reaction of aluminium hydroxide with an aqueous solution of nitric acid (50 wt.%). The inputs of sulfuric acid were replaced with a stoichiometric amount of nitric acid and the corresponding amount of waste solvent was corrected for the mass balance.

[3]Zinc nitrate hexahydrate ($Zn(NO_3)_2 \cdot 6H_2O$) was modelled from the EID dataset "Zinc monosulfate {RoW}| production | APOS, U". It was considered the reaction of zinc oxide (ZnO) with an aqueous solution of nitric acid (50 wt.%): $ZnO+2HNO_3 = Zn(NO_3)_2 + H_2O$. The inputs of sulfuric acid were replaced with the stoichiometric amounts of nitric acid.

[4]Magnesium nitrate hexahydrate ($Mg(NO_3)_2 \cdot 6H_2O$) was modelled from ecoinvent v. 3.8, considering the reaction of magnesium oxide with nitric acid: $MgO+2HNO_3 = Mg(NO_3)_2 + H_2O$. The EID dataset for MgO was "Magnesium oxide {GLO}| market for | APOS, U" and for nitric acid was "Nitric acid, without water, in 50% solution state {RoW}| market for nitric acid, without water, in 50% solution state | APOS, U". It was assumed an excess of 0.5 mol HNO_3. The corresponding atmospheric emissions of NO_2 associated with the decomposition of excess nitric acid were also included (8.6E-04 kg). The energy inputs associated with the production of 1 kg of chemical substances at an industrial scale were also included in the inventory (0.56 kWh electrical, 2.15 MJ heat and 0.173 MJ steam).

[5]The EID dataset was: "Glycine {RER}| glycine production | APOS, U" .

[6]The EID dataset was: "Ammonia, anhydrous, liquid {RER w/o RU}| ammonia production, steam reforming, liquid | APOS, U".

[7]The EID dataset was: "Water, deionised {RoW}| water production, deionised | APOS, U".

[8]The EID dataset was: "Chemical factory, organics {GLO}| market for | APOS, U".

[9]The EID dataset was: "Electricity, medium voltage {RER}| market group for electricity, medium voltage | APOS, U". The value was calculated by multiplying the power consumption of the equipment by the duration of its use.

[10]The EID dataset was: "Heat, central or small-scale, natural gas {RER}| market group for heat, central or small-scale, natural gas | APOS, U". The dataset describes the thermal energy necessary for the process. To calculate the energy necessary to heat the reaction, the formula, $Q = m \cdot Cp \cdot \Delta T$, where m is the weight of the reaction mixture, Cp is the heat capacity of the reaction mixture and ΔT is the difference between the reaction temperature and ambient temperature. For the energy necessary to maintain the reaction at a certain temperature, the formula $Q = U_{oven} \cdot A_{oven} \cdot \Delta T \cdot t_r \cdot 0.036$, where U_{oven} is the heat transfer coefficient of the oven, A_{oven} is the surface of the oven and t_r is the reaction time. For the energy released or absorbed by the reaction at the temperature T, the formula $Q_r = n_{product} \cdot \Delta_r H^T$, where $\Delta_r H^T$ is the enthalpy of reaction at temperature T.

[11]The EID dataset was "Transport, freight, lorry 16-32 metric ton, EURO6 {RoW}| transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U". The average distance was 100 km.

Table S9

Contributions to LCI for the production of 1 kg of pigment E ($Co_{0.25}Mg_{0.75}Al_2O_4$), modelled according to the scaled-up procedure described by Wei et al., 2022[9].

Process	Description	Amount	Data Source
Output	$Co_{0.25}Mg_{0.75}Al_2O_4$	1 kg	
	Materials		
Cobalt nitrate	$Co(NO_3)_2 \cdot 6H_2O$	0.482 kg	Modelled from ecoinvent v. 3.10[1]
Aluminium nitrate	$Al(NO_3)_3 \cdot 9H_2O$	4.94 kg	Modelled from ecoinvent v. 3.10[2]
Magnesium nitrate	$Mg(NO_3)_2 \cdot 6H_2O$	1.27 kg	Modelled from ecoinvent v.

			3.13[3]
Citric acid	$C_8H_8O_6$	11.5 kg	ecoinvent v. 3.8[4]
Ethylene Glycol	$C_2H_6O_2$	2.47 kg	ecoinvent v. 3.8[5]
Water (deionized)	H_2O	19.9 kg	ecoinvent v. 3.10[6]
	Equipment and land use		
Chemical Factory		4E-10 p	ecoinvent v. 3.10[7]
	Energy		
Electricity		108 kWh	ecoinvent v. 3.10[8]
Thermal Energy		34.7 MJ	ecoinvent v. 3.10[9]
	Transports		
	Raw materials	1.44 tkm	ecoinvent v. 3.10[10]
	Atmospheric emissions		
In air	water	26.3 kg	SimaPro airborne emission substance list
	CO_2	19.2 kg	SimaPro airborne emission substance list
	N_2	0.742 kg	SimaPro airborne emission substance list

[1]Cobalt nitrate hexahydrate ($Co(NO_3)_2 \cdot 6H_2O$)was modelled from the EID dataset "Cobalt sulfate {RoW}| cobalt sulfate production | APOS, U", considering the reaction of cobalt hydroxide with an aqueous solution of nitric acid (50 wt.%). The input of sulfuric acid was replaced with a stoichiometric amount of nitric acid and the corresponding amounts of inputs and outputs were corrected for the content of cobalt.

[2]Aluminium nitrate ($Al(NO_3)_3 \cdot 9H_2O$) was modelled from the EID dataset "Aluminium sulfate, powder {RER}| production | APOS, U", considering the reaction of aluminium hydroxide with an aqueous solution of nitric acid (50 wt.%). The inputs of sulfuric acid were replaced with a stoichiometric amount of nitric acid and the corresponding amount of waste solvent was corrected for the mass balance.

[3]Magnesium nitrate hexahydrate ($Mg(NO_3)_2 \cdot 6H_2O$) was modelled from ecoinvent v. 3.8, considering the reaction of magnesium oxide with nitric acid: $MgO+2HNO_3 = Mg(NO_3)_2 + H_2O$. The EID dataset for MgO was "Magnesium oxide {GLO}| market for | APOS, U" and for nitric acid was "Nitric acid, without water, in 50% solution state {RoW}| market for nitric acid, without water, in 50% solution state | APOS, U". It was assumed an excess of 0.5 mol HNO_3. The corresponding atmospheric emissions of NO_2 associated with the decomposition of excess nitric acid were also included (8.6E-04 kg). The energy inputs associated with the production of 1 kg of chemical substances at an industrial scale were also included in the inventory (0.56 kWh electrical, 2.15 MJ heat and 0.173 MJ steam).

[4]The EID dataset was: "Citric acid {RER}| citric acid production | APOS, U"

[5]The EID dataset was: "Ethylene glycol {RER}| ethylene glycols production, thermal hydrolysis of ethylene oxide | APOS, U"

[6]The EID dataset was: "Water, deionised {RoW}| water production, deionised | APOS, U".

[7]The EID dataset was: "Chemical factory, organics {GLO}| market for | APOS, U".

[8]The EID dataset was: "Electricity, medium voltage {RER}| market group for electricity, medium voltage | APOS, U". The value was calculated by multiplying the power consumption of the equipment by the duration of its use.

[9]The EID dataset was: "Heat, central or small-scale, natural gas {RER}| market group for heat, central or small-scale, natural gas | APOS, U". The dataset describes the thermal energy necessary for the process. To calculate the energy necessary to heat the reaction, the formula, $Q = m \cdot Cp \cdot \Delta T$, where m is the weight of the reaction mixture, Cp is the heat capacity of the reaction mixture and ΔT is the difference between the reaction temperature and ambient temperature. For the energy necessary to maintain the reaction at a certain temperature, the formula $Q = U_{oven} \cdot A_{oven} \cdot \Delta T \cdot t_r \cdot 0.036$, where U_{oven} is the heat transfer coefficient of the oven, A_{oven} is the surface of the oven

and t_r is the reaction time. For the energy released or absorbed by the reaction at the temperature T, the formula $Q_r = n_{product} \cdot \Delta_r H^T$, where $\Delta_r H^T$ is the enthalpy of reaction at temperature T.

[10]The EID dataset was "Transport, freight, lorry 16-32 metric ton, EURO6 {RoW}| transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U". The average distance was 100 km.

Table S10

Contributions to LCI for the production of 1 kg of pigment F ($Zn_{0.9}Co_{0.1}Al_2O_4$), modelled according to the scaled-up procedure described by Ianos et al., 2017[10].

Process	Description	Amount	Data Source
Output	$Zn_{0.9}Co_{0.1}Al_2O_4$	1 kg	
	Materials		
Cobalt nitrate	$Co(NO_3)_2 \cdot 6H_2O$	0.159 kg	Modelled from ecoinvent v. 3.10[1]
Aluminium nitrate	$Al(NO_3)_3 \cdot 9H_2O$	4.08 kg	Modelled from ecoinvent v. 3.10[2]
Zinc nitrate	$Zn(NO_3)_2 \cdot 6H_2O$	1.47 kg	Modelled from ecoinvent v. 3.10[3]
glycine	C_4N_2O	0.457 kg	ecoinvent v. 3.8[4]
urea	$C_2H_6O_2$	2.47 kg	ecoinvent v. 3.8[5]
Water (deionized)	H_2O	0.667 kg	ecoinvent v. 3.10[6]
	Equipment and land use		
Chemical Factory		4E-10 p	ecoinvent v. 3.10[7]
	Energy		
Electricity		7.73 kWh	ecoinvent v. 3.10[8]
Thermal Energy		2.91 MJ	ecoinvent v. 3.10[9]
	Transports		
	Raw materials	0.863 tkm	ecoinvent v. 3.10[10]
	Atmospheric emissions		
In air	water	4.12 kg	SimaPro airborne emission substance list
	CO_2	2.34 kg	SimaPro airborne emission substance list
	N_2	1.85 kg	SimaPro airborne emission substance list
	Waste treatment		
	water	6.67E-04 m^3	ecoinvent v. 3.10[11]

[1]Cobalt nitrate hexahydrate ($Co(NO_3)_2 \cdot 6H_2O$) was modelled from the EID dataset "Cobalt sulfate {RoW}| cobalt sulfate production | APOS, U", considering the reaction of cobalt hydroxide with an aqueous solution of nitric acid (50 wt.%). The input of sulfuric acid was replaced with a stoichiometric amount of nitric acid and the corresponding amounts of inputs and outputs were corrected for the content of cobalt.

[2]Aluminium nitrate ($Al(NO_3)_3 \cdot 9H_2O$) was modelled from the EID dataset "Aluminium sulfate, powder {RER}| production | APOS, U", considering the reaction of aluminium hydroxide with an aqueous solution of nitric acid (50 wt.%). The inputs of sulfuric acid were replaced with a stoichiometric amount of nitric acid and the corresponding amount of waste solvent was corrected for the mass balance.

[3]Zinc nitrate hexahydrate ($Zn(NO_3)_2 \cdot 6H_2O$) was modelled from the EID dataset "Zinc monosulfate {RoW}| production | APOS, U". It was considered the reaction of zinc oxide (ZnO) with an aqueous solution of nitric acid (50 wt.%): $ZnO + 2HNO_3 = Zn(NO_3)_2 + H_2O$. The inputs of sulfuric acid were replaced with the stoichiometric amounts of nitric acid.

[4]The EID dataset was: "Glycine {RER}| glycine production | APOS, U".

[5]The EID dataset was "Urea {RER}| urea production | APOS, U".

[6]The EID dataset was: "Water, deionised {RoW}| water production, deionised | APOS, U".

[7]The EID dataset was: "Chemical factory, organics {GLO}| market for | APOS, U".

[8]The EID dataset was: "Electricity, medium voltage {RER}| market group for electricity, medium voltage | APOS, U". The value was calculated by multiplying the power consumption of the equipment by the duration of its use.

[9]The EID dataset was: "Heat, central or small-scale, natural gas {RER}| market group for heat, central or small-scale, natural gas | APOS, U". The dataset describes the thermal energy necessary for the process. To calculate the energy necessary to heat the reaction, the formula, $Q = m \cdot Cp \cdot \Delta T$, where m is the weight of the reaction mixture, Cp is the heat capacity of the reaction mixture and ΔT is the difference between the reaction temperature and ambient temperature. For the energy necessary to maintain the reaction at a certain temperature, the formula $Q = U_{oven} \cdot A_{oven} \cdot \Delta T \cdot t_r \cdot 0.036$, where U_{oven} is the heat transfer coefficient of the oven, A_{oven} is the surface of the oven and t_r is the reaction time. For the energy released or absorbed by the reaction at the temperature T, the formula $Q_r = n_{product} \cdot \Delta_r H^T$, where $\Delta_r H^T$ is the enthalpy of reaction at temperature T.

[10]The EID dataset was "Transport, freight, lorry 16-32 metric ton, EURO6 {RoW}| transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U". The average distance was 100 km.

[11]The EID dataset was "Wastewater, average {RoW}| treatment of wastewater, average, wastewater treatment | APOS, U", and it describes the treatment of the waste solvent.

Table S11

Contributions to LCI for the production of 1 kg of pigment G (Co_2SiO_4), modelled according to the scaled-up procedure described by Forés et al., 2000[11].

Process	Description	Amount	Data Source
Output	Co_2SiO_4	1 kg	
	Materials		
Chemicals	Co_3O_4	0.765 kg	ecoinvent v. 3.10[1]
	SiO_2	0.286 kg	ecoinvent v. 3.10[2]
	Acetone	0.434kg	ecoinvent v. 3.10[3]
	Equipment and land use		
Chemical Factory		4E-10 p	ecoinvent v. 3.10[4]
	Energy		
Electricity		0.64 kWh	ecoinvent v. 3.10[5]
Thermal Energy		9.08 MJ	ecoinvent v. 3.10[6]
	Transports		
	Raw materials	0.105 tkm	ecoinvent v. 3.10[7]
	Atmospheric emissions		
	Acetone	0.45 kg	SimaPro airborne emission substance list
	Oxygen	0.0508 kg	SimaPro airborne emission substance list

[1]The EID dataset was: "Cobalt oxide {GLO}| cobalt production | APOS, U".

[2]The EID dataset was: "Silica sand {RoW}| silica sand production | APOS, U".

[3]The EID dataset was: "Acetone, liquid {RER}| acetone production, from isopropanol | APOS, U

[4]The EID dataset was: "Chemical factory, organics {GLO}| market for | APOS, U".

[5]The EID dataset was: "Electricity, medium voltage {RER}| market group for electricity, medium voltage | APOS, U". The value was calculated by multiplying the power consumption of the equipment by the duration of its use.

[6]The EID dataset was: "Heat, central or small-scale, natural gas {RER}| market group for heat, central or small-scale, natural gas | APOS, U". The dataset describes the thermal energy necessary for the process. To calculate the energy necessary to heat the reaction, the formula, $Q = m \cdot Cp \cdot \Delta T$, where m is the weight of the reaction mixture, Cp is the heat capacity of the reaction mixture and ΔT is the difference between the reaction temperature and ambient temperature. For the energy necessary to maintain the reaction at a certain temperature, the formula $Q = U_{oven} \cdot A_{oven} \cdot \Delta T \cdot t_r \cdot 0.036$, where U_{oven} is the heat transfer coefficient of the oven, A_{oven} is the surface of the oven and t_r is the reaction time. For the energy released or absorbed by the reaction at the temperature T, the formula $Q_r = n_{product} \cdot \Delta_r H^T$, where $\Delta_r H^T$ is the enthalpy of reaction at temperature T.

[7]The EID dataset was "Transport, freight, lorry 16-32 metric ton, EURO6 {RoW}| transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U". The average distance was 100 km.

Table S12

Contributions to LCI for the production of 1 kg of pigment H ($Co_{0.5}Zn_{1.5}SiO_4$), modelled according to the scaled-up procedure described by Forés et al., 2000[11].

Process	Description	Amount	Data Source
Output	$Co_{0.5}Zn_{1.5}SiO_4$	1 kg	
	Materials		
Chemicals			
	Co_3O_4	0.183 kg	ecoinvent v. 3.10[1]
	SiO_2	0.274 kg	ecoinvent v. 3.10[2]
	ZnO	0.556	ecoinvent v. 3.10[3]
	Acetone	0.434 kg	ecoinvent v. 3.10[4]
	Equipment and land use		
Chemical Factory		4E-10 p	ecoinvent v. 3.10[5]
	Energy		
Electricity		0.64 kWh	ecoinvent v. 3.10[6]
Thermal Energy		8.86 MJ	ecoinvent v. 3.10[7]
	Transports		
	Raw materials	0.101 tkm	ecoinvent v. 3.10[8]
	Atmospheric emissions		
	Acetone	0.434 kg	SimaPro airborne emission substance list
	Oxygen	0.0121	SimaPro airborne emission substance list

[1]The EID dataset was: "Cobalt oxide {GLO}| cobalt production | APOS, U".

[2]The EID dataset was: "Silica sand {RoW}| silica sand production | APOS, U".

[3] The EID dataset was: "Zinc oxide {RER}| zinc oxide production | APOS, U".

[4]The EID dataset was: "Acetone, liquid {RER}| acetone production, from isopropanol | APOS, U

[5]The EID dataset was: "Chemical factory, organics {GLO}| market for | APOS, U".

[6]The EID dataset was: "Electricity, medium voltage {RER}| market group for electricity, medium voltage | APOS, U". The value was calculated by multiplying the power consumption of the equipment by the duration of its use.

[7]The EID dataset was: "Heat, central or small-scale, natural gas {RER}| market group for heat, central or small-scale, natural gas | APOS, U". The dataset describes the thermal energy necessary for the process. To calculate the energy necessary to heat the reaction, the formula, $Q = m \cdot Cp \cdot \Delta T$, where m is the weight of the reaction mixture, Cp is the heat capacity of the reaction mixture and ΔT is the difference between the reaction temperature and ambient temperature. For the energy necessary to maintain the reaction at a certain temperature, the formula $Q = U_{oven} \cdot A_{oven} \cdot \Delta T \cdot t_r \cdot 0.036$, where U_{oven} is the heat transfer coefficient of the oven, A_{oven} is the surface of the oven

and t_r is the reaction time. For the energy released or absorbed by the reaction at the temperature T, the formula $Q_r = n_{product} \cdot \Delta_r H^T$, where $\Delta_r H^T$ is the enthalpy of reaction at temperature T.

[8]The EID dataset was "Transport, freight, lorry 16-32 metric ton, EURO6 {RoW}| transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U". The average distance was 100 km.

Table S13

Contributions to LCI for the production of 1 kg of pigment I ($Co_{0.05}Zn_{1.95}SiO_4$), modelled according to the scaled-up procedure described by Forés et al., 2000[11].

Process	Description	Amount	Data Source
Output	$Co_{0.05}Zn_{1.95}SiO_4$	1 kg	
Materials			
Chemicals			
	Co_3O_4	0.018 kg	ecoinvent v. 3.10[1]
	SiO_2	0.27 kg	ecoinvent v. 3.10[2]
	ZnO	0.713	ecoinvent v. 3.10[3]
	Acetone	0.434 kg	ecoinvent v. 3.10[4]
Equipment and land use			
Chemical Factory		4E-10 p	ecoinvent v. 3.10[5]
Energy			
Electricity		0.64 kWh	ecoinvent v. 3.10[6]
Thermal Energy		8.86 MJ	ecoinvent v. 3.10[7]
Transports			
	Raw materials	0.10 tkm	ecoinvent v. 3.10[8]
Atmospheric emissions			
	Acetone	4.29E-08 kg	SimaPro airborne emission substance list
	Oxygen	0.0036	SimaPro airborne emission substance list

[1]The EID dataset was: "Cobalt oxide {GLO}| cobalt production | APOS, U".

[2]The EID dataset was: "Silica sand {RoW}| silica sand production | APOS, U".

[3] The EID dataset was: "Zinc oxide {RER}| zinc oxide production | APOS, U".

[4]The EID dataset was: "Acetone, liquid {RER}| acetone production, from isopropanol | APOS, U

[5]The EID dataset was: "Chemical factory, organics {GLO}| market for | APOS, U".

[6]The EID dataset was: "Electricity, medium voltage {RER}| market group for electricity, medium voltage | APOS, U". The value was calculated by multiplying the power consumption of the equipment by the duration of its use.

[7]The EID dataset was: "Heat, central or small-scale, natural gas {RER}| market group for heat, central or small-scale, natural gas | APOS, U". The dataset describes the thermal energy necessary for the process. To calculate the energy necessary to heat the reaction, the formula, $Q = m \cdot Cp \cdot \Delta T$, where m is the weight of the reaction mixture, Cp is the heat capacity of the reaction mixture and ΔT is the difference between the reaction temperature and ambient temperature. For the energy necessary to maintain the reaction at a certain temperature, the formula $Q = U_{oven} \cdot A_{oven} \cdot \Delta T \cdot t_r \cdot 0.036$, where U_{oven} is the heat transfer coefficient of the oven, A_{oven} is the surface of the oven and t_r is the reaction time. For the energy released or absorbed by the reaction at the temperature T, the formula $Q_r = n_{product} \cdot \Delta_r H^T$, where $\Delta_r H^T$ is the enthalpy of reaction at temperature T.

[8]The EID dataset was "Transport, freight, lorry 16-32 metric ton, EURO6 {RoW}| transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U". The average distance was 100 km.

Table S14

Potential environmental impacts, calculated at midpoint level (EF 3.1), for the production of 1 kg of hybrid ceramic pigments B ($CoAl_2O_4$/kaoline) and C ($CoAl_2O_4/Al_2O_3$).

Impact category	Unit	B	C
Acidification	kg CO_2 eq	1.21E-01	7.91E-02
Climate change	CTUe	1.76E+01	1.28E+01
Ecotoxicity, freshwater	disease inc.	1.56E+02	1.09E+02
Particulate matter	kg N eq	9.40E-07	5.91E-07
Eutrophication, marine	kg P eq	1.63E-02	1.20E-02
Eutrophication, freshwater	mol N eq	8.90E-03	6.76E-03
Eutrophication, terrestrial	CTUh	1.83E-01	1.04E-01
Human toxicity, cancer	CTUh	7.82E-08	5.93E-08
Human toxicity, non-cancer	kBq U-235 eq	5.47E-07	3.95E-07
Ionising radiation	Pt	5.72E+00	4.59E+00
Land use	kg CFC11 eq	6.88E+01	4.93E+01
Ozone depletion	kg NMVOC eq	3.78E-07	3.40E-07
Photochemical ozone formation	MJ	4.97E-02	5.15E-02
Resource use, fossils	kg CO2 eq	2.75E+02	2.28E+02
Resource use, minerals and metals	kg Sb eq	1.02E-03	6.99E-04
Water use	m^3 depriv.	4.47E+01	3.15E+01

Table S15

Potential environmental impacts, calculated at midpoint level (EF3.0) associated with the preparation of 1 kg of D ($Co_{0.67}Mg_{0.16}Zn_{0.16}Al_2O_4$), $CoAl_2O_4$ doped with Mg^{2+}, E ($Co_{0.25}Mg_{0.75}Al_2O_4$), and $ZnAl_2O_4$ doped with Co^{2+}, F ($Zn_{0.9}Co_{0.1}Al_2O_4$).

Impact category	Unit	D	E	F
Acidification	mol H^+ eq	2.03E-01	5.94E-01	1.05E-01
Climate change	kg CO_2 eq	3.82E+01	1.09E+02	2.22E+01
Ecotoxicity, freshwater	CTUe	1.07E+03	8.24E+02	2.76E+02
Particulate matter	disease inc.	1.67E-06	3.75E-06	8.06E-07
Eutrophication, marine	kg N eq	3.86E-02	1.35E-01	1.68E-02
Eutrophication, freshwater	kg P eq	1.51E-02	5.14E-02	7.17E-03
Eutrophication, terrestrial	mol N eq	3.63E-01	1.37E+00	2.56E-01
Human toxicity, cancer	CTUh	1.56E-07	4.02E-07	7.13E-08
Human toxicity, non-cancer	CTUh	8.86E-07	1.11E-06	2.80E-07
Ionising radiation	kBq U-235 eq	8.10E+00	3.08E+01	3.38E+00
Land use	Pt	1.26E+02	1.42E+03	6.22E+01
Ozone depletion	kg CFC11 eq	8.38E-07	1.92E-06	3.95E-07
Photochemical ozone formation	kg NMVOC eq	1.02E-01	2.54E-01	5.10E-02
Resource use, fossils	MJ	5.54E+02	1.57E+03	2.90E+02
Resource use, minerals and metals	kg Sb eq	1.30E-03	9.43E-04	3.20E-04
Water use	m^3 depriv.	5.97E+01	1.11E+02	2.01E+01

Table S16

Potential environmental impacts, calculated at midpoint level (EF3.0) associated with the preparation of 1 kg of olivine and Co-doped willemite, G (Co_2SiO_4), H ($Co_{0.5}Zn_{1.5}SiO_4$) and respectively, I ($Co_{0.5}Zn_{1.5}SiO_4$).

Impact category	Unit	G	H	I
Acidification	mol H^+ eq	3.65E-01	9.41E-02	1.74E-02
Climate change	kg CO_2 eq	2.79E+01	8.65E+00	3.20E+00
Ecotoxicity, freshwater	CTUe	4.44E+02	1.14E+02	2.05E+01
Particulate matter	disease inc.	3.33E-06	8.47E-07	1.43E-07

Eutrophication, marine	kg N eq	3.22E-02	8.87E-03	2.27E-03
Eutrophication, freshwater	kg P eq	1.19E-02	3.36E-03	9.59E-04
Eutrophication, terrestrial	mol N eq	2.80E-01	7.88E-02	2.20E-02
Human toxicity, cancer	CTUh	1.53E-07	4.56E-08	1.51E-08
Human toxicity, non-cancer	CTUh	2.67E-06	6.75E-07	1.09E-07
Ionising radiation	kBq U-235 eq	1.32E+01	3.40E+00	6.29E-01
Land use	Pt	1.40E+02	4.02E+01	1.20E+01
Ozone depletion	kg CFC11 eq	6.64E-07	2.28E-07	1.05E-07
Photochemical ozone formation	kg NMVOC eq	2.04E-01	1.13E-01	8.67E-02
Resource use, fossils	MJ	5.74E+02	1.78E+02	6.65E+01
Resource use, minerals and metals	kg Sb eq	5.79E-03	1.41E-03	1.66E-04
Water use	m^3 depriv.	2.54E+02	6.11E+01	6.53E+00

Table S17

Monte Carlo simulation, performed at midpoint level (EF.3.1 impact assessment method), with 1000 runs in a 95% significance threshold, for the comparative environmental impacts of A1 vs A2.

Impact category	Unit	A1 >= A2 (%)	Mean	Median	SD	CV (%)	2,5%	97,5%	SEM
Acidification	mol H^+ eq	100	7.23E-02	7.17E-02	1.28E-02	17.73	4.88E-02	1.00E-01	4.05E-04
Climate change	kg CO_2 eq	99	2.71E+00	2.73E+00	1.09E+00	40.10	3.74E-01	4.81E+00	3.44E-02
Ecotoxicity, freshwater	CTUe	54.4	5.44E+01	4.41E+01	3.57E+02	655.32	-6.74E+02	7.85E+02	1.13E+01
Eutrophication, freshwater	kg P eq	95.4	1.61E-03	1.66E-03	9.90E-04	61.39	-4.93E-04	3.60E-03	3.13E-05
Eutrophication, marine	kg N eq	96.9	2.38E-03	2.47E-03	1.23E-03	51.83	-2.39E-04	4.50E-03	3.90E-05
Eutrophication, terrestrial	mol N eq	1.2	-4.20E-02	-3.95E-02	2.16E-02	-51.38	-8.93E-02	-3.97E-03	6.83E-04
Human toxicity, cancer	CTUh	52	2.17E-08	1.81E-08	4.00E-07	1846.12	-8.05E-07	8.28E-07	1.27E-08
Human toxicity, non-cancer	CTUh	51.9	2.13E-06	2.66E-06	5.26E-05	2473.07	-1.02E-04	1.09E-04	1.66E-06
Ionising radiation	kBq U-235 eq	100	4.70E+00	3.71E+00	3.98E+00	84.59	1.63E+00	1.43E+01	1.26E-01
Land use	Pt	99.1	2.45E+01	2.44E+01	8.59E+00	35.11	6.41E+00	4.17E+01	2.72E-01
Ozone depletion	kg CFC11 eq	99.9	5.31E-07	5.04E-07	1.91E-07	36.03	2.51E-07	9.67E-07	6.05E-09
Particulate matter	disease inc.	99.9	6.44E-07	6.30E-07	1.87E-07	29.03	3.18E-07	1.08E-06	5.91E-09
Photochemical ozone formation	kg NMVOC eq	100	4.41E-02	4.35E-02	6.62E-03	15.03	3.36E-02	5.96E-02	2.09E-04
Resource use, fossils	MJ	100	2.22E+02	2.19E+02	2.68E+01	12.09	1.77E+02	2.84E+02	8.48E-01
Resource use, minerals and metals	kg Sb eq	100	1.79E-03	1.79E-03	8.86E-05	4.95	1.59E-03	1.96E-03	2.80E-06
Water use	m^3 depriv.	59.8	1.15E+02	2.20E+02	8.90E+02	771.89	-1.92E+03	1.66E+03	2.81E+01

Table S18

Monte Carlo simulation, performed at midpoint level (EF.3.1 impact assessment method), with 1000 runs in a 95% significance threshold, for the comparative environmental impacts of A1 vs A3.

Impact category	Unit	A1 >= A3 (%)	Mean	Median	SD	CV (%)	2,5%	97,5%	SEM
Acidification	mol H^+ eq	100	1.06E-01	1.06E-01	1.32E-02	12.40	8.36E-02	1.36E-01	4.17E-04
Climate change	kg CO_2 eq	100	7.03E+00	7.08E+00	1.36E+00	19.40	4.16E+00	9.65E+00	4.31E-02
Ecotoxicity, freshwater	CTUe	59	8.68E+01	9.54E+01	4.66E+02	536.06	-8.32E+02	9.70E+02	1.47E+01
Eutrophication, freshwater	kg P eq	100	9.46E-03	7.91E-03	6.02E-03	63.70	3.30E-03	2.50E-02	1.90E-04
Eutrophication, marine	kg N eq	100	9.94E-03	9.96E-03	1.36E-03	13.72	7.31E-03	1.27E-02	4.31E-05
Eutrophication, terrestrial	mol N eq	49.6	-1.49E-03	-1.53E-04	2.25E-02	-1515.53	-5.05E-02	4.08E-02	7.12E-04
Human toxicity, cancer	CTUh	49.7	2.98E-08	-4.49E-08	3.63E-06	12184.96	-7.34E-06	7.36E-06	1.15E-07

Human toxicity, non-cancer	CTUh	48.8	-3.68E-06	-1.35E-05	4.30E-04	-11661.08	-8.77E-04	8.77E-04	1.36E-05
Ionising radiation	kBq U-235 eq	100	9.65E+00	7.38E+00	8.02E+00	83.17	3.37E+00	3.18E+01	2.54E-01
Land use	Pt	100	7.07E+01	7.05E+01	1.05E+01	14.86	4.97E+01	9.30E+01	3.32E-01
Ozone depletion	kg CFC11 eq	100	6.23E-07	5.97E-07	1.84E-07	29.51	3.41E-07	1.01E-06	5.81E-09
Particulate matter	disease inc.	100	7.34E-07	7.21E-07	1.85E-07	25.21	3.97E-07	1.14E-06	5.85E-09
Photochemical ozone formation	kg NMVOC eq	100	5.71E-02	5.62E-02	6.61E-03	11.57	4.60E-02	7.20E-02	2.09E-04
Resource use, fossils	MJ	100	3.53E+02	3.49E+02	4.52E+01	12.80	2.76E+02	4.55E+02	1.43E+00
Resource use, minerals and metals	kg Sb eq	100	1.81E-03	1.82E-03	8.87E-05	4.89	1.62E-03	1.97E-03	2.80E-06
Water use	m^3 depriv.	56.5	8.46E+01	1.58E+02	1.06E+03	1252.36	-2.29E+03	1.86E+03	3.35E+01

Table S19

Monte Carlo simulation, performed at midpoint level (EF.3.1 impact assessment method), with 1000 runs in a 95% significance threshold, for the comparative environmental impacts of A1 vs A4.

Impact category	Unit	A1 >= A4 (%)	Mean	Median	SD	CV (%)	2,5%	97,5%	SEM
Acidification	mol H^+ eq	100	1.30E-01	1.30E-01	1.33E-02	10.26	1.06E-01	1.58E-01	4.22E-04
Climate change	kg CO_2 eq	100	1.46E+01	1.46E+01	1.20E+00	8.23	1.23E+01	1.70E+01	3.79E-02
Ecotoxicity, freshwater	CTUe	58.9	1.19E+02	1.20E+02	5.24E+02	440.03	-8.60E+02	1.19E+03	1.66E+01
Eutrophication, freshwater	kg P eq	100	1.21E-02	1.02E-02	6.96E-03	57.32	4.59E-03	3.03E-02	2.20E-04
Eutrophication, marine	kg N eq	100	1.41E-02	1.42E-02	1.39E-03	9.81	1.14E-02	1.69E-02	4.39E-05
Eutrophication, terrestrial	mol N eq	98.8	5.26E-02	5.36E-02	2.14E-02	40.56	8.43E-03	9.33E-02	6.75E-04
Human toxicity, cancer	CTUh	50.9	1.42E-07	9.58E-08	4.46E-06	3154.15	-8.84E-06	8.46E-06	1.41E-07
Human toxicity, non-cancer	CTUh	50.9	7.78E-06	7.24E-06	5.29E-04	6793.19	-1.06E-03	1.01E-03	1.67E-05
Ionising radiation	kBq U-235 eq	100	1.15E+01	8.41E+00	1.07E+01	92.74	3.93E+00	4.00E+01	3.37E-01
Land use	Pt	100	8.83E+01	8.73E+01	1.16E+01	13.19	6.67E+01	1.12E+02	3.68E-01
Ozone depletion	kg CFC11 eq	100	7.99E-07	7.76E-07	1.69E-07	21.16	5.28E-07	1.21E-06	5.35E-09
Particulate matter	disease inc.	100	8.95E-07	8.89E-07	1.82E-07	20.38	5.67E-07	1.29E-06	5.77E-09
Photochemical ozone formation	kg NMVOC eq	100	7.45E-02	7.35E-02	8.03E-03	10.78	6.17E-02	9.24E-02	2.54E-04
Resource use, fossils	MJ	100	4.84E+02	4.77E+02	5.02E+01	10.37	4.02E+02	6.00E+02	1.59E+00
Resource use, minerals and metals	kg Sb eq	100	1.84E-03	1.85E-03	8.61E-05	4.67	1.67E-03	2.00E-03	2.72E-06
Water use	m^3 depriv.	56.9	1.01E+02	1.42E+02	1.04E+03	1020.56	-2.23E+03	1.94E+03	3.28E+01

Table S20

Monte Carlo simulation, performed at midpoint level (EF.3.1 impact assessment method), with 1000 runs in a 95% significance threshold, for the comparative environmental impacts of A2 vs A3.

Impact category	Unit	A2 >= A3 (%)	Mean	Median	SD	CV (%)	2,5%	97,5%	SEM
Acidification	mol H^+ eq	100	3.43E-02	3.44E-02	2.41E-03	7.02	2.95E-02	3.90E-02	7.62E-05
Climate change	kg CO_2 eq	100	4.34E+00	4.43E+00	9.18E-01	21.17	2.26E+00	5.94E+00	2.90E-02
Ecotoxicity, freshwater	CTUe	55.9	4.17E+01	4.79E+01	2.52E+02	603.26	-4.64E+02	5.80E+02	7.96E+00
Eutrophication, freshwater	kg P eq	100	7.74E-03	6.42E-03	4.69E-03	60.63	2.69E-03	2.11E-02	1.48E-04
Eutrophication, marine	kg N eq	100	7.55E-03	7.49E-03	6.69E-04	8.86	6.37E-03	8.99E-03	2.11E-05
Eutrophication, terrestrial	mol N eq	100	4.07E-02	4.07E-02	6.96E-03	17.11	2.65E-02	5.43E-02	2.20E-04
Human toxicity, cancer	CTUh	51.7	8.05E-08	1.08E-07	3.24E-06	4022.57	-6.25E-06	6.52E-06	1.02E-07
Human toxicity, non-cancer	CTUh	50.9	2.98E-06	8.14E-06	3.84E-04	12898.74	-7.45E-04	7.64E-04	1.21E-05
Ionising radiation	kBq U-235 eq	100	5.23E+00	3.63E+00	5.09E+00	97.26	1.72E+00	1.91E+01	1.61E-01
Land use	Pt	100	4.55E+01	4.52E+01	6.21E+00	13.66	3.38E+01	5.84E+01	1.96E-01
Ozone depletion	kg CFC11 eq	99.3	9.80E-08	9.16E-08	4.90E-08	49.94	2.63E-08	2.19E-07	1.55E-09
Particulate matter	disease inc.	99.9	9.33E-08	9.14E-08	2.83E-08	30.39	3.82E-08	1.54E-07	8.96E-10
Photochemical ozone formation	kg NMVOC eq	100	1.34E-02	1.35E-02	2.23E-03	16.63	8.70E-03	1.77E-02	7.05E-05
Resource use, fossils	MJ	100	1.31E+02	1.27E+02	3.22E+01	24.64	7.82E+01	2.02E+02	1.02E+00
Resource use, minerals and metals	kg Sb eq	88.1	1.68E-05	1.85E-05	1.74E-05	103.90	-2.17E-05	4.77E-05	5.51E-07
Water use	m^3 depriv.	50.5	-9.30E+00	4.29E+00	3.14E+02	-3369.76	-6.75E+02	5.85E+02	9.91E+00

Table S21

Monte Carlo simulation, performed at midpoint level (EF.3.1 impact assessment method), with 1000 runs in a 95% significance threshold, for the comparative environmental impacts of A2 vs A4.

Impact category	Unit	A2 >= A4 (%)	Mean	Median	SD	CV (%)	2,5%	97,5%	SEM
Acidification	mol H^+ eq	100	5.79E-02	5.77E-02	2.12E-03	3.66	5.43E-02	6.24E-02	6.69E-05
Climate change	kg CO_2 eq	100	1.18E+01	1.18E+01	3.45E-01	2.92	1.12E+01	1.25E+01	1.09E-02
Ecotoxicity, freshwater	CTUe	58.7	5.41E+01	5.35E+01	3.10E+02	573.82	-6.17E+02	6.71E+02	9.81E+00
Eutrophication, freshwater	kg P eq	100	1.03E-02	8.39E-03	7.50E-03	73.05	3.45E-03	2.77E-02	2.37E-04
Eutrophication, marine	kg N eq	100	1.16E-02	1.16E-02	7.11E-04	6.11	1.04E-02	1.33E-02	2.25E-05
Eutrophication, terrestrial	mol N eq	100	9.34E-02	9.27E-02	6.33E-03	6.78	8.30E-02	1.08E-01	2.00E-04
Human toxicity, cancer	CTUh	51.1	2.86E-07	5.98E-08	3.99E-06	1397.17	-7.63E-06	8.53E-06	1.26E-07
Human toxicity, non-cancer	CTUh	50.4	2.48E-05	2.17E-06	4.74E-04	1907.25	-9.25E-04	9.98E-04	1.50E-05

Ionising radiation	kBq U-235 eq	100	6.85E+00	4.52E+00	7.30E+00	106.47	2.14E+00	2.85E+01	2.31E-01
Land use	Pt	100	6.35E+01	6.29E+01	7.86E+00	12.38	4.85E+01	8.06E+01	2.49E-01
Ozone depletion	kg CFC11 eq	100	2.91E-07	2.83E-07	4.75E-08	16.30	2.24E-07	4.13E-07	1.50E-09
Particulate matter	disease inc.	100	2.55E-07	2.50E-07	2.85E-08	11.16	2.14E-07	3.25E-07	9.01E-10
Photochemical ozone formation	kg NMVOC eq	100	3.06E-02	3.03E-02	2.65E-03	8.65	2.63E-02	3.75E-02	8.37E-05
Resource use, fossils	MJ	100	2.58E+02	2.54E+02	3.32E+01	12.85	2.03E+02	3.29E+02	1.05E+00
Resource use, minerals and metals	kg Sb eq	100	5.25E-05	4.88E-05	1.46E-05	27.84	3.50E-05	8.91E-05	4.62E-07
Water use	m^3 depriv.	53.1	-1.81E+00	3.43E+01	4.10E+02	-22702.91	-9.37E+02	7.32E+02	1.30E+01

Table S22

Monte Carlo simulation, performed at midpoint level (EF.3.1 impact assessment method), with 1000 runs in a 95% significance threshold, for the comparative environmental impacts of A3 vs A4.

Impact category	**Unit**	**A3 >= A4 (%)**	**Mean**	**Median**	**SD**	**CV (%)**	**2,5%**	**97,5%**	**SEM**
Acidification	mol H^+ eq	100	2.37E-02	2.34E-02	2.44E-03	10.29	2.00E-02	2.94E-02	7.71E-05
Climate change	kg CO_2 eq	100	7.55E+00	7.46E+00	9.21E-01	12.20	6.02E+00	9.62E+00	2.91E-02
Ecotoxicity, freshwater	CTUe	58.9	1.28E+01	1.29E+01	6.36E+01	498.10	-1.14E+02	1.44E+02	2.01E+00
Eutrophication, freshwater	kg P eq	100	2.36E-03	1.92E-03	1.67E-03	70.65	7.62E-04	6.44E-03	5.27E-05
Eutrophication, marine	kg N eq	100	4.12E-03	4.10E-03	3.74E-04	9.07	3.45E-03	4.92E-03	1.18E-05
Eutrophication, terrestrial	mol N eq	100	5.30E-02	5.27E-02	5.99E-03	11.30	4.28E-02	6.61E-02	1.90E-04
Human toxicity, cancer	CTUh	48.3	-1.28E-08	-2.53E-08	8.49E-07	-6655.14	-1.71E-06	1.72E-06	2.69E-08
Human toxicity, non-cancer	CTUh	47.4	-4.18E-06	-6.48E-06	1.01E-04	-2404.23	-2.04E-04	1.99E-04	3.18E-06
Ionising radiation	kBq U-235 eq	100	1.50E+00	1.02E+00	1.62E+00	108.09	4.72E-01	6.04E+00	5.14E-02
Land use	Pt	100	1.78E+01	1.74E+01	2.92E+00	16.39	1.29E+01	2.47E+01	9.24E-02
Ozone depletion	kg CFC11 eq	100	1.93E-07	1.90E-07	3.09E-08	16.04	1.43E-07	2.65E-07	9.79E-10
Particulate matter	disease inc.	100	1.65E-07	1.62E-07	2.50E-08	15.15	1.25E-07	2.19E-07	7.90E-10
Photochemical ozone formation	kg NMVOC eq	100	1.73E-02	1.69E-02	3.26E-03	18.81	1.23E-02	2.48E-02	1.03E-04
Resource use, fossils	MJ	100	1.30E+02	1.28E+02	1.57E+01	12.09	1.02E+02	1.63E+02	4.96E-01
Resource use, minerals and metals	kg Sb eq	100	3.67E-05	3.14E-05	2.04E-05	55.50	1.58E-05	9.05E-05	6.44E-07
Water use	m^3 depriv.	51.6	3.35E+00	3.11E+00	9.66E+01	2884.84	-2.02E+02	1.86E+02	3.05E+00

Table S23

Monte Carlo simulation, performed at midpoint level (EF.3.1 impact assessment method), with 1000 runs in a 95% significance threshold, for the comparative environmental impacts of B vs C.

Impact category	Unit	B >= C (%)	Mean	Median	SD	CV (%)	2,5%	97,5%	SEM
Acidification	mol H^+ eq	100	4.18E-02	4.15E-02	3.57E-03	8.52	3.59E-02	4.94E-02	1.13E-04
Climate change	kg CO_2 eq	100	4.68E+00	4.65E+00	4.84E-01	10.33	3.82E+00	5.71E+00	1.53E-02
Ecotoxicity, freshwater	CTUe	57.7	4.46E+01	4.07E+01	2.29E+02	513.46	-4.09E+02	4.96E+02	7.24E+00
Eutrophication, freshwater	kg P eq	99.6	2.10E-03	1.97E-03	8.29E-04	39.39	9.13E-04	4.20E-03	2.62E-05
Eutrophication, marine	kg N eq	100	4.27E-03	4.24E-03	3.50E-04	8.19	3.69E-03	5.06E-03	1.11E-05
Eutrophication, terrestrial	mol N eq	100	7.85E-02	7.74E-02	1.07E-02	13.64	6.10E-02	1.03E-01	3.39E-04
Human toxicity, cancer	CTUh	51.4	-6.63E-10	1.79E-08	4.41E-07	-66545.10	-8.97E-07	8.51E-07	1.40E-08
Human toxicity, non-cancer	CTUh	49.2	-2.08E-06	-1.49E-06	5.37E-05	-2585.31	-1.14E-04	1.03E-04	1.70E-06
Ionising radiation	kBq U-235 eq	100	1.07E+00	8.73E-01	8.38E-01	78.40	3.86E-01	3.22E+00	2.65E-02
Land use	Pt	100	1.93E+01	1.89E+01	3.13E+00	16.24	1.46E+01	2.68E+01	9.90E-02
Ozone depletion	kg CFC11 eq	98.3	3.74E-08	3.77E-08	1.71E-08	45.72	3.74E-09	7.28E-08	5.41E-10
Particulate matter	disease inc.	100	3.50E-07	3.42E-07	5.14E-08	14.67	2.84E-07	4.67E-07	1.62E-09
Photochemical ozone formation	kg NMVOC eq	7.1	-1.87E-03	-1.97E-03	1.25E-03	-66.70	-3.99E-03	7.18E-04	3.94E-05
Resource use, fossils	MJ	100	4.63E+01	4.62E+01	6.83E+00	14.75	3.30E+01	5.97E+01	2.16E-01
Resource use, minerals and metals	kg Sb eq	100	3.15E-04	3.11E-04	2.12E-05	6.74	2.86E-04	3.71E-04	6.71E-07
Water use	m^3 depriv.	56.3	8.64E+00	2.14E+01	1.58E+02	1824.17	-3.42E+02	2.88E+02	4.99E+00

Table S24

Monte Carlo simulation, performed at midpoint level (EF.3.1 impact assessment method), with 1000 runs in a 95% significance threshold, for the comparative environmental impacts of D vs E.

Impact category	Unit	D >= E (%)	Mean	Median	SD	CV (%)	2,5%	97,5%	SEM
Acidification	mol H^+ eq	0	-3.91E-01	-3.92E-01	1.20E-02	-3.08	-4.12E-01	-3.63E-01	3.81E-04
Climate change	kg CO_2 eq	0	-7.08E+01	-7.11E+01	2.67E+00	-3.77	-7.53E+01	-6.47E+01	8.43E-02
Ecotoxicity, freshwater	CTUe	62.1	2.56E+02	2.49E+02	8.18E+02	320.12	-1.34E+03	2.03E+03	2.59E+01
Eutrophication, freshwater	kg P eq	0	-3.72E-02	-3.27E-02	1.89E-02	-50.78	-8.39E-02	-1.89E-02	5.98E-04
Eutrophication, marine	kg N eq	0	-9.66E-02	-9.72E-02	4.95E-03	-5.12	-1.05E-01	-8.55E-02	1.57E-04
Eutrophication, terrestrial	mol N eq	0	-1.00E+00	-1.00E+00	2.65E-02	-2.63	-1.06E+00	-9.49E-01	8.37E-04
Human toxicity, cancer	CTUh	49.2	-4.21E-07	-1.17E-07	1.06E-05	-2513.61	-2.03E-05	2.00E-05	3.34E-07
Human toxicity, non-cancer	CTUh	50.5	-2.16E-05	8.91E-06	1.25E-03	-5791.63	-2.36E-03	2.38E-03	3.96E-05
Ionising radiation	kBq U-235 eq	0	-2.27E+01	-1.64E+01	1.95E+01	-86.15	-7.53E+01	-1.00E+01	6.17E-01

Land use	Pt	0	-1.29E+03	-1.29E+03	2.52E+01	-1.95	-1.34E+03	-1.25E+03	7.95E-01
Ozone depletion	kg CFC11 eq	0	-1.09E-06	-1.10E-06	1.04E-07	-9.57	-1.28E-06	-8.53E-07	3.30E-09
Particulate matter	disease inc.	0	-2.09E-06	-2.12E-06	1.87E-07	-8.96	-2.36E-06	-1.64E-06	5.92E-09
Photochemical ozone formation	kg NMVOC eq	0	-1.53E-01	-1.53E-01	1.12E-02	-7.31	-1.74E-01	-1.30E-01	3.53E-04
Resource use, fossils	MJ	0	-1.02E+03	-1.01E+03	1.17E+02	-11.46	-1.30E+03	-8.20E+02	3.71E+00
Resource use, minerals and metals	kg Sb eq	100	3.62E-04	3.55E-04	3.91E-05	10.82	3.06E-04	4.67E-04	1.24E-06
Water use	m^3 depriv.	45.3	-7.18E+01	-1.17E+02	1.18E+03	-1647.92	-2.32E+03	2.47E+03	3.74E+01

Table S25

Monte Carlo simulation, performed at midpoint level (EF.3.1 impact assessment method), with 1000 runs in a 95% significance threshold, for the comparative environmental impacts of D vs F.

Impact category	**Unit**	**D >= F (%)**	**Mean**	**Median**	**SD**	**CV (%)**	**2,5%**	**97,5%**	**SEM**
Acidification	mol H^+ eq	100	9.79E-02	9.69E-02	9.97E-03	10.19	8.18E-02	1.19E-01	3.15E-04
Climate change	kg CO_2 eq	100	1.58E+01	1.57E+01	2.08E+00	13.13	1.24E+01	2.03E+01	6.58E-02
Ecotoxicity, freshwater	CTUe	96.2	7.77E+02	7.50E+02	4.68E+02	60.21	-7.48E+01	1.77E+03	1.48E+01
Eutrophication, freshwater	kg P eq	100	7.69E-03	6.93E-03	3.23E-03	41.95	3.84E-03	1.66E-02	1.02E-04
Eutrophication, marine	kg N eq	100	2.19E-02	2.14E-02	3.62E-03	16.54	1.65E-02	3.00E-02	1.14E-04
Eutrophication, terrestrial	mol N eq	100	1.06E-01	1.05E-01	1.79E-02	16.96	7.49E-02	1.49E-01	5.68E-04
Human toxicity, cancer	CTUh	49.3	2.88E-08	-4.49E-08	2.06E-06	7155.38	-3.97E-06	4.19E-06	6.52E-08
Human toxicity, non-cancer	CTUh	47.3	-6.28E-06	-1.11E-05	2.46E-04	-3913.37	-4.81E-04	4.82E-04	7.77E-06
Ionising radiation	kBq U-235 eq	100	4.58E+00	3.42E+00	4.07E+00	88.89	1.60E+00	1.52E+01	1.29E-01
Land use	Pt	100	6.32E+01	6.21E+01	1.03E+01	16.29	4.71E+01	8.65E+01	3.25E-01
Ozone depletion	kg CFC11 eq	100	4.36E-07	4.26E-07	7.84E-08	17.98	3.02E-07	6.17E-07	2.48E-09
Particulate matter	disease inc.	100	8.62E-07	8.21E-07	2.03E-07	23.57	6.09E-07	1.39E-06	6.42E-09
Photochemical ozone formation	kg NMVOC eq	100	5.06E-02	4.95E-02	8.02E-03	15.84	3.83E-02	7.08E-02	2.54E-04
Resource use, fossils	MJ	100	2.61E+02	2.56E+02	4.18E+01	15.98	1.94E+02	3.61E+02	1.32E+00
Resource use, minerals and metals	kg Sb eq	100	9.85E-04	9.81E-04	4.25E-05	4.32	9.17E-04	1.08E-03	1.35E-06
Water use	m^3 depriv.	58.2	7.65E+01	1.07E+02	5.64E+02	736.87	-1.10E+03	1.08E+03	1.78E+01

Table S26

Monte Carlo simulation, performed at midpoint level (EF.3.1 impact assessment method), with 1000 runs in a 95% significance threshold, for the comparative environmental impacts of E vs F.

Impact category	Unit	E >= F (%)	Mean	Median	SD	CV (%)	2,5%	97,5%	SEM
Acidification	mol H^+ eq	100	4.90E-01	4.89E-01	6.69E-03	1.37	4.77E-01	5.04E-01	2.12E-04
Climate change	kg CO_2 eq	100	8.67E+01	8.68E+01	1.69E+00	1.95	8.35E+01	9.00E+01	5.34E-02
Ecotoxicity, freshwater	CTUe	74.4	5.71E+02	5.77E+02	9.59E+02	167.93	-1.47E+03	2.48E+03	3.03E+01
Eutrophication, freshwater	kg P eq	100	4.46E-02	3.87E-02	2.06E-02	46.24	2.31E-02	9.93E-02	6.52E-04
Eutrophication, marine	kg N eq	100	1.18E-01	1.18E-01	2.51E-03	2.12	1.14E-01	1.23E-01	7.93E-05
Eutrophication, terrestrial	mol N eq	100	1.11E+00	1.11E+00	2.15E-02	1.93	1.07E+00	1.16E+00	6.80E-04
Human toxicity, cancer	CTUh	52.1	3.42E-07	8.12E-07	1.27E-05	3705.75	-2.54E-05	2.51E-05	4.01E-07
Human toxicity, non-cancer	CTUh	51.4	2.57E-06	7.37E-05	1.50E-03	58273.79	-3.03E-03	2.90E-03	4.74E-05
Ionising radiation	kBq U-235 eq	100	2.69E+01	1.96E+01	2.35E+01	87.56	1.18E+01	8.21E+01	7.44E-01
Land use	Pt	100	1.36E+03	1.35E+03	2.39E+01	1.77	1.31E+03	1.41E+03	7.57E-01
Ozone depletion	kg CFC11 eq	100	1.53E-06	1.52E-06	7.46E-08	4.88	1.39E-06	1.68E-06	2.36E-09
Particulate matter	disease inc.	100	2.95E-06	2.94E-06	9.28E-08	3.15	2.80E-06	3.16E-06	2.94E-09
Photochemical ozone formation	kg NMVOC eq	100	2.04E-01	2.03E-01	1.04E-02	5.10	1.88E-01	2.28E-01	3.29E-04
Resource use, fossils	MJ	100	1.28E+03	1.27E+03	1.20E+02	9.33	1.09E+03	1.58E+03	3.78E+00
Resource use, minerals and metals	kg Sb eq	100	6.22E-04	6.21E-04	2.62E-05	4.21	5.76E-04	6.80E-04	8.29E-07
Water use	m^3 depriv.	55.9	1.56E+02	2.14E+02	1.34E+03	855.81	-2.85E+03	2.55E+03	4.23E+01

Table S27

Monte Carlo simulation, performed at midpoint level (EF.3.1 impact assessment method), with 1000 runs in a 95% significance threshold, for the comparative environmental impacts of G vs H.

Impact category	Unit	G >= H (%)	Mean	Median	SD	CV (%)	2,5%	97,5%	SEM
Acidification	mol H^+ eq	100	2.71E-01	2.67E-01	2.61E-02	9.64	2.33E-01	3.29E-01	8.25E-04
Climate change	kg CO_2 eq	100	1.92E+01	1.91E+01	1.04E+00	5.40	1.73E+01	2.15E+01	3.28E-02
Ecotoxicity, freshwater	CTUe	59	3.35E+02	3.35E+02	1.48E+03	442.51	-2.70E+03	3.19E+03	4.69E+01
Eutrophication, freshwater	kg P eq	100	8.44E-03	8.08E-03	1.94E-03	23.02	5.71E-03	1.29E-02	6.14E-05
Eutrophication, marine	kg N eq	100	2.34E-02	2.33E-02	1.87E-03	7.99	2.01E-02	2.75E-02	5.92E-05
Eutrophication, terrestrial	mol N eq	100	2.01E-01	2.00E-01	1.73E-02	8.59	1.71E-01	2.39E-01	5.47E-04
Human toxicity, cancer	CTUh	52.5	8.83E-08	1.20E-07	1.38E-06	1564.87	-2.59E-06	2.85E-06	4.37E-08
Human toxicity, non-cancer	CTUh	50.4	-5.29E-07	2.38E-06	1.88E-04	-35534.50	-3.73E-04	3.76E-04	5.94E-06
Ionising radiation	kBq U-235 eq	100	9.77E+00	7.82E+00	7.36E+00	75.37	3.43E+00	2.90E+01	2.33E-01

Land use	Pt	100	9.91E+01	9.78E+01	1.53E+01	15.40	7.04E+01	1.31E+02	4.82E-01
Ozone depletion	kg CFC11 eq	100	4.34E-07	4.26E-07	4.65E-08	10.71	3.63E-07	5.40E-07	1.47E-09
Particulate matter	disease inc.	100	2.50E-06	2.46E-06	2.76E-07	11.04	2.06E-06	3.16E-06	8.72E-09
Photochemical ozone formation	kg NMVOC eq	100	9.18E-02	9.07E-02	8.28E-03	9.02	7.81E-02	1.10E-01	2.62E-04
Resource use, fossils	MJ	100	3.96E+02	3.91E+02	4.11E+01	10.37	3.28E+02	4.96E+02	1.30E+00
Resource use, minerals and metals	kg Sb eq	100	4.38E-03	4.38E-03	9.62E-05	2.20	4.19E-03	4.57E-03	3.04E-06
Water use	m^3 depriv.	59.1	1.90E+02	4.32E+02	2.23E+03	1169.54	-4.81E+03	4.06E+03	7.04E+01

Table S28

Monte Carlo simulation, performed at midpoint level (EF.3.1 impact assessment method), with 1000 runs in a 95% significance threshold, for the comparative environmental impacts of G vs I.

Impact category	Unit	G >= I (%)	Mean	Median	SD	CV (%)	2,5%	97,5%	SEM
Acidification	mol H^+ eq	100	3.46E-01	3.41E-01	3.21E-02	9.27	2.97E-01	4.20E-01	1.01E-03
Climate change	kg CO_2 eq	100	2.47E+01	2.47E+01	1.33E+00	5.37	2.23E+01	2.75E+01	4.20E-02
Ecotoxicity, freshwater	CTUe	58.4	4.33E+02	5.01E+02	1.89E+03	435.00	-3.46E+03	3.84E+03	5.96E+01
Eutrophication, freshwater	kg P eq	100	1.09E-02	1.03E-02	2.69E-03	24.72	7.28E-03	1.72E-02	8.50E-05
Eutrophication, marine	kg N eq	100	3.00E-02	2.97E-02	2.41E-03	8.03	2.60E-02	3.53E-02	7.61E-05
Eutrophication, terrestrial	mol N eq	100	2.58E-01	2.57E-01	2.22E-02	8.60	2.21E-01	3.09E-01	7.02E-04
Human toxicity, cancer	CTUh	53.2	1.15E-07	1.11E-07	1.72E-06	1491.08	-3.32E-06	3.58E-06	5.44E-08
Human toxicity, non-cancer	CTUh	51.2	5.98E-07	3.64E-06	2.39E-04	39957.51	-4.56E-04	4.80E-04	7.56E-06
Ionising radiation	kBq U-235 eq	100	1.28E+01	1.03E+01	9.03E+00	70.67	4.45E+00	3.73E+01	2.85E-01
Land use	Pt	100	1.28E+02	1.26E+02	2.11E+01	16.55	9.14E+01	1.76E+02	6.69E-01
Ozone depletion	kg CFC11 eq	100	5.59E-07	5.49E-07	6.16E-08	11.01	4.65E-07	7.05E-07	1.95E-09
Particulate matter	disease inc.	100	3.18E-06	3.13E-06	3.54E-07	11.11	2.60E-06	3.97E-06	1.12E-08
Photochemical ozone formation	kg NMVOC eq	100	1.18E-01	1.16E-01	1.12E-02	9.50	9.94E-02	1.43E-01	3.54E-04
Resource use, fossils	MJ	100	5.09E+02	5.01E+02	5.40E+01	10.61	4.29E+02	6.39E+02	1.71E+00
Resource use, minerals and metals	kg Sb eq	100	5.62E-03	5.61E-03	1.15E-04	2.05	5.40E-03	5.86E-03	3.65E-06
Water use	m^3 depriv.	58.9	2.93E+02	6.74E+02	2.84E+03	968.16	-5.93E+03	5.11E+03	8.98E+01

Table S29

Monte Carlo simulation, performed at midpoint level (EF.3.1 impact assessment method), with 1000 runs in a 95% significance threshold, for the comparative environmental impacts of H vs I.

Impact category	**Unit**	**H >= I (%)**	**Mean**	**Median**	**SD**	**CV (%)**	**2,5%**	**97,5%**	**SEM**
Acidification	mol H^+ eq	100	7.66E-02	7.54E-02	7.77E-03	10.15	6.57E-02	9.49E-02	2.46E-04
Climate change	kg CO_2 eq	100	5.44E+00	5.42E+00	2.89E-01	5.32	4.91E+00	6.04E+00	9.15E-03
Ecotoxicity, freshwater	CTUe	58.8	1.03E+02	1.03E+02	4.16E+02	402.34	-7.12E+02	9.06E+02	1.32E+01
Eutrophication, freshwater	kg P eq	100	2.40E-03	2.30E-03	5.83E-04	24.31	1.58E-03	3.95E-03	1.84E-05
Eutrophication, marine	kg N eq	100	6.57E-03	6.54E-03	5.03E-04	7.65	5.65E-03	7.71E-03	1.59E-05
Eutrophication, terrestrial	mol N eq	100	5.67E-02	5.62E-02	4.68E-03	8.25	4.86E-02	6.66E-02	1.48E-04
Human toxicity, cancer	CTUh	51.2	1.10E-08	9.72E-09	3.71E-07	3369.39	-7.17E-07	7.31E-07	1.17E-08
Human toxicity, non-cancer	CTUh	48.9	-1.03E-06	-1.42E-06	5.10E-05	-4938.37	-1.04E-04	9.91E-05	1.61E-06
Ionising radiation	kBq U-235 eq	100	2.82E+00	2.18E+00	2.38E+00	84.25	9.92E-01	8.19E+00	7.53E-02
Land use	Pt	100	2.81E+01	2.77E+01	4.63E+00	16.46	2.00E+01	3.83E+01	1.46E-01
Ozone depletion	kg CFC11 eq	100	1.24E-07	1.21E-07	1.52E-08	12.23	1.02E-07	1.64E-07	4.80E-10
Particulate matter	disease inc.	100	6.98E-07	6.89E-07	7.51E-08	10.76	5.79E-07	8.73E-07	2.37E-09
Photochemical ozone formation	kg NMVOC eq	100	2.58E-02	2.56E-02	2.46E-03	9.51	2.18E-02	3.17E-02	7.77E-05
Resource use, fossils	MJ	100	1.12E+02	1.10E+02	1.20E+01	10.74	9.43E+01	1.41E+02	3.81E-01
Resource use, minerals and metals	kg Sb eq	100	1.24E-03	1.24E-03	2.57E-05	2.07	1.19E-03	1.29E-03	8.13E-07
Water use	m^3 depriv.	55.7	4.70E+01	7.98E+01	6.35E+02	1350.82	-1.39E+03	1.17E+03	2.01E+01

Appendix A: Experimental

$CoAl_2O_4$ via solid-state reaction (A1)

The first synthesis of $CoAl_2O_4$ assessed by LCA in this work was SSR, as described by Ding et al.[2] and Kim et al.[3]. In those works, the pigment synthesis started with stoichiometric amounts of CoO and Al_2O_3 which were first ball milled together in ethanol for 12 h. After filtration, the mixture was calcined at 1200 °C for 3 h, then re-milled, pressed and calcined again at 1500 °C for 3 h to obtain $CoAl_2O_4$ pigment.

$CoAl_2O_4$ via coprecipitation method (A2)

The CPT method for preparing $CoAl_2O_4$ was assessed by LCA methodology, following the procedure described by Zhang et al.[4]. In that study, stoichiometric amounts of $Co(NO_3)_2{\cdot}6H_2O$ and $Al(NO_3)_3{\cdot}9H_2O$ were stirred together in deionized water and pH was adjusted to 10, with the slow addition of a 3 M solution of NaOH. After centrifuging and washing, the obtained precipitate was dried at 60 °C for 24 h and then calcined at 1200 °C for 2 h.

$CoAl_2O_4$ via sol-gel self-combustion method (A3)

The third method for the preparation of $CoAl_2O_4$ assessed by LCA was SGA, according to the procedure detailed by Tong et al.[5]. In this procedure, stoichiometric amounts of $Co(NO_3)_2{\cdot}6H_2O$, $Al(NO_3)_3{\cdot}9H_2O$ were added to an aqueous solution of urea (molar ratio Co:urea was 3:20) and stirred together. Upon evaporation, the gel precursor was then heated to 250 °C to undergo self-combustion. The obtained powders were calcined at 740 °C for 4 h.

$CoAl_2O_4$ via microwave-assisted hydrothermal method (A4)

The HT-MW route was assessed by LCA, considering the experimental procedure as described by Zhang et al.[6]**.** In that study, stoichiometric amounts of $Co(NO_3)_2{\cdot}6H_2O$, $Al(NO_3)_3{\cdot}9H_2O$ were dissolved in deionized water under magnetic stirring, then pH was adjusted to 10 with the addition of an aqueous solution of 3M NaOH. The precursor solution was added into a microwave hydrothermal reactor, then heated and kept at 240 °C for 6 h. The obtained precipitate was centrifuged and washed, then calcined at 1200 °C for 1 h.

$CoAl_2O_4$/kaolin hybrid via microwave assisted hydrothermal method (B)

The first hybrid pigment assessed in this study by LCA was $CoAl_2O_4$/kaolin (B).
In this procedure described by Zhang et al. [6], the hybrid pigment B was prepared in a similar way to A4. Kaolin was first purified with 4% HCl solution and added to the initial reaction mixture that followed the same pathway as A4. However, the obtained precipitate was calcined at 900 °C for 1 h.

$CoAl_2O_4/Al_2O_3$ hybrid via heterogeneous precipitation method (C)

The second hybrid pigment assessed by LCA methodology was $CoAl_2O_4/Al_2O_3$ (C), prepared by heterogeneous precipitation (HPT), according to the procedure reported by He et al.[7]. In that study, $Co(NO_3)_2·6H_2O$ was added to a suspension of Al_2O_3 in deionized water and stirred at room temperature for 30 min. pH was adjusted to 10 by the addition of a 2M aqueous solution of NaOH and the obtained mixture was stirred for 1 h. The precipitate was collected by centrifugation, washed with water and ethanol, dried at 60 °C for 8 h. The hybrid pigment was finally obtained after calcination at 1100 °C for 3 h.

$Co_{0.67}Mg_{0.16}Zn_{0.16}Al_2O_4$ via sol-gel autoignition method (D)

The Mg^{2+} and Zn^{2+} -doped $CoAl_2O_4$ prepared by SGA was assessed by LCA methodology considering the synthetic procedure described by Mokhatri and Salem[8]. In that work, $Al(NO_3)_3·9H_2O$, $Co(NO_3)_2·6H_2O$, $Mg(NO_3)_2·6H_2O$, $Zn(NO_3)_2·6H_2O$ in ratio 2:0.67:0.16 were stirred in deionized water at 60 °C for 15 min. A solution of glycine was then pumped dropwise (4.5 moles per mole of product), and then the pH was adjusted to 2.5 by mixing a few drops of ammonia and nitric acid. The excess water was evaporated and then the gel was heat-treated at 500 °C for 15 min. The obtained powder was calcined at 1000 °C for 1 h to yield the blue pigment.

$Co_{0.25}Mg_{0.75}Al_2O_4$ via sol-gel autoignition method (E)

The Mg^{2+}-doped $CoAl_2O_4$ pigment prepared by SGA was assessed by LCA methodology following the experimental section detailed by We et al.[9]. According to that study, $Co(NO_3)_2·6H_2O$, $Mg(NO_3)_2·6H_2O$ and $Al(NO_3)_3·9H_2O$ in ratio 0.25:0.75:2 were added to an aqueous solution of citric acid (CA), at 80 °C under continuous magnetic stirring. Ethylene glycol (EG) was subsequently added to the reaction mixture (the ratio CA:EG:metal was 3:2:1). The mixture was kept at 80 °C for 1 h, then at 120 °C for 12 h. The obtained powders were heated at 350 °C for 2 h to form the gel that was subsequently calcined at 900 °C for 6 h.

$Zn_{0.9}Co_{0.1}Al_2O_4$ via self-propagating combustion method (F)

The Co^{2+}-doped $ZnAl_2O_4$ pigment prepared by self-propagating combustion was assessed by LCA, considering the synthesis procedure described by Ianos et al.[10]. According to that work, $Co(NO_3)_2·6H_2O$, $Al(NO_3)_3·9H_2O$, $Zn(NO_3)_2·6H_2O$ and glycine were mixed in 0.9:0.1:2:1.1 ratio under magnetic stirring, then heated at 80 °C for 30 min. Subsequently, the gel was heated at 450 °C to initiate auto-ignition. The obtained powders were wet milled, then washed with deionised water and dried at 110 °C for 3 h.

Co_2SiO_4 (G), $Co_{0.5}Zn_{1.5}SiO_4$ (H) and $Co_{0.05}Zn_{1.95}SiO_4$ (I) via solid-state reaction method

The cobalt olivine-based pigments, prepared by SSR were assessed by LCA, utilizing the procedure detailed by Fores et al[11]. In that study, cobalt olivine and Co^{2+}-doped willemite ($Co_xZn_{2-x}SiO_4$, x = 0, 0.05 and 0.5) were prepared via solid-state method. The metal oxides (Co_3O_4, ZnO and SiO_2) were mixed in the ratio (x/3):(2-x):1 then ball milled in acetone. After filtration, the mixture was calcined at 1300 °C for 1 h to yield the ceramic pigment.

Appendix B: Detailed environmental impact analysis

Detailed Life Cycle Impact Assessment (LCIA) analysis for the production of 1 kg of $CoAl_2O_4$ prepared through solid-state reaction (A1)

The impacts on "**climate change**" equal 40.6 kg CO_2 eq, 86.1% (i.e., 34.9 kg CO_2 eq) of the impact is due to the emission of CO_2 of fossil source in air, 44.7% due to the consumption of electricity, 11.2% attributed to the EID dataset "Electricity, high voltage {DE}| electricity production, lignite | APOS, U", describing the production of electricity from lignite sources.

For "**acidification**" the impact equals 0.315 mol H^+ eq, 80.1% (0.25 mol H^+ eq) due to the emission of SO_2 in air, for 71.6% associated with the production of CoO, 39.5% attributed to the EID dataset "Cobalt oxide {GLO}| cobalt production | APOS, U", describing the production of Co_3O_4.

For "**photochemical ozone formation**" the impact equals 0.149 kg NMVOC eq, for 49.0% (i.e., 7.29E-02 kg NMVOC eq) due to the emission of nitrogen oxides in air, for 50.2% during the production of CoO, for 18.0% attributed to the EID dataset "Diesel, burned in building machine {GLO}| diesel, burned in building machine | APOS, U", describing the production of diesel associated with the extraction of cobalt oxide.

For "**ozone depletion**" the impacts equal 1.37E-06 kg CFC11 eq, for 48.9% (6.71E-07 kg CFC11 eq) due to the emissions of methane-, bromotrifluoro-, halon 1301 in air, for 37.3% during the production of CoO, 9.65% attributed to the EID dataset "Natural gas, high pressure {QA}| petroleum and gas production, offshore | APOS, U", describing the production of natural gas employed for the production of the electricity mix necessary during the synthesis of cobalt oxide.

For "**ionizing radiation**" the impact equals 19.0 kBq U-235 eq, for 60.2% due to the emission of Radon-222 in air, for 68.4% associated with the consumption of the electricity throughout the process, 97.3% attributed to the EID dataset "Tailing, from uranium milling {GLO}| treatment of tailing, from uranium milling | APOS, U", describing the treatment of the radioactive waste during the production of uranium hexafluoride necessary for the generation of nuclear-based electricity.

For "**human toxicity, cancer**" the impact equals 1.98E-07 CTUh, for 85.7% (1.7E-07 CTUh) due to the emissions of anthracene in air, for 51.5% attributed to the consumption of electricity, for 60.1% associated with the EID dataset "Coke {RoW}| coke production | APOS, U", describing the production of coke employed in the manufacturing of steel, necessary for the construction of the hydropower plant.

For "**human toxicity, non-cancer**" the impact equals 1.78E-06 CTUh, 37.3% (i.e., 6.65E-07 CTUh) due to the emission of Lead (II) in air, 95.3% due to the production of CoO, for 52.2% associated with the EID dataset "Copper cake {GLO}| treatment of copper cake | APOS, U" describing the waste treatment during the production of cobalt oxide.

For "**ecotoxicity, freshwater**" the impact equals 358 CTUe, for 34.3% (i.e., 123 CTUe) due to the emission of chlorine in water, for 97.9% during the production of CoO, for 53.6% associated with the EID dataset "Wastewater, average {RoW}| market for wastewater, average | APOS, U", describing the wastewaters treatment during the production of cobalt oxide.

The impact on "**particulate matter**" equals 2.41E-06 disease inc., 37.3% (i.e., 8.98E-07 disease inc.) attributed to the emission of fine particulate <2.5 μm in air, 71.1% during the production of CoO, for 22.5% associated with the EID dataset "Diesel, burned in building machine {GLO}| diesel, burned in building machine | APOS, U", describing the diesel consumption for the production of Co_3O_4, as the precursor for CoO.

For "**eutrophication, freshwater**" the impact equals 2.39E-02 kg P eq, 95.6% (i.e., 2.29E-02 kg P eq) attributed to the emission of phosphate in water, 68.7% due to the consumption of electricity, for 89.1% associated with EID dataset "Spoil from lignite mining {GLO}| treatment of spoil from lignite mining, in surface landfill | APOS, U", describing the waste treatment associated with lignite production for the generation of electricity.

For "**resource use, minerals and metals**" the impact equals 3.52E-03 kg Sb eq, 44.4% (i.e., 1.57E-03 kg Sb eq) attributed to the depletion of sulfur, 100% during the production of CoO, 99.95% attributed to the EID dataset "Cobalt oxide {GLO}| cobalt production | APOS, U", i.e., the production of Co_3O_4.

For "**resource use, fossils**" the impact equals 867 MJ, 36.5% (i.e., 316 MJ) due to the consumption of natural gas, 40.6% during the production of CoO, for 16.2% associated with the EID dataset "Natural gas, high pressure {US}| petroleum and gas production, onshore | APOS, U".

For "**water use**" the impact equals 159.47 m^3, for 95.4% associated with the consumption of water of RoW origins (i.e., the world minus the local geographies for which a process exists in the database).

Detailed Life Cycle Impact Assessment (LCIA) analysis for the production of 1 kg of $CoAl_2O_4$ prepared through microwave-assisted hydrothermal method (A4)

For "**climate change**", the impact equals 26.0 kg CO_2 eq, for 79.5% (i.e., 20.7 kg CO_2 eq) due to the emission of CO_2 of fossil source in air, 57.3% associated with the production of cobalt nitrate, for 6.38% attributed to the EID dataset "Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | APOS, U", which describes the generation of thermal energy used in the production of cobalt hydroxide and aluminium hydroxide precursors for cobalt nitrate and aluminium nitrate, respectively.

For "**acidification**", the impact equals 0.186 mol H^+ eq, for 70.22% (i.e., 0.124 mol H^+ eq) due to the emission of SO_2 in air, 72.4% during the production of cobalt nitrate, for 34.1% associated with the EID dataset "Cobalt hydroxide {GLO}| cobalt production | APOS, U", describing the production of cobalt hydroxide.

For “**photochemical ozone formation**”, the impact equals 7.45E-02 kg NMVOC eq, for 59.2% (i.e., 4.41E-02 kg NMVOC eq) due to the emission of nitrogen oxides in air, for 58.1% attributed to the production of cobalt nitrate, for 12.6% associated with the EID dataset “Diesel, burned in building machine {GLO}| diesel, burned in building machine | APOS, U”, describing the consumption of diesel for the production of cobalt hydroxide.

For “**ionizing radiation**”, the impact equals 7.64 kBq U-235 eq, for 58.7% (4.49 kBq U-235 eq) due to the emission of Radon-222 in air, for 45.4% attributed to the consumption of electricity, 97.3% associated with the same EID dataset as for **A1.**

For “**ozone depletion**”, the impact equals 5.65E-07 kg CFC11 eq, for 46.6% (2.63E-07 kg CFC11 eq) due to the emissions of methane-, bromotrifluoro-, halon 1301, 58.6% attributed to the production of cobalt nitrate, for 9.11% associated with the same EID dataset as for A1.

For “**human toxicity, cancer**”, the impact equals 1.13E-07 CTUh, for 77.5% (8.75E-08 CTUh) due to the emission of anthracene in air, 52.0% during the production of cobalt nitrate, 93.1% associated with the same EID dataset as for A1.

For “**human toxicity, non-cancer**”, the impact equals 8.82E-07 CTUh, for 36.8% (i.e., 3.25E-07 CTuh) associated with the emission of Lead (II) in air, 91.0% due to the production of cobalt nitrate, for 50.2% associated with the same EID dataset as for A1.

For “**ecotoxicity, freshwater**”, the impact equals 243 CTUe, for 26.7% (i.e., 64.9 CTUe) attributed to the emission of chlorine in water, for 89.7% during the production of cobalt nitrate, for 56.6% associated with the same EID dataset as for A1.

For “**particulate matter**” the impact equals 1.5E-06 disease inc., 41.1% (i.e., 6.34E-07 disease inc.) attributed to the emission of fine particulate <2.5 μm in air, for 65.9% during the production of cobalt nitrate, for 24.7% associated with the EID dataset “Electricity, high voltage, for internal use in coal mining {CN}| electricity production, hard coal, at coal mine power plant | APOS, U”, describing the consumption of the electricity for the production of cobalt hydroxide.

For “**eutrophication, freshwater**”, the impact equals 1.21E-02 kg P eq, 95.0% (i.e., 1.15E-02 kg P eq) attributed to the emission of phosphate in water, 42.4% during the production of cobalt nitrate, 24.8% associated with the same EID dataset as for A1.

For “**resource use, fossils**”, the impact equals 385 MJ, 34.1% (i.e., 131 MJ) due to the consumption of natural gas, 57.4% attributed to the production of cobalt nitrate, for 15.8% associated with the EID dataset “Natural gas, high pressure {RU}| petroleum and gas production, onshore | APOS, U”.

For “**resource use, minerals and metals**”, the impact equals 1.68E-03 kg Sb eq, 42.1% (i.e., 7.06E-04 kg Sb eq) attributed to the depletion of sulfur, 99.9% associated with the production of cobalt nitrate, for 100% attributed to the EID dataset “Cobalt hydroxide {GLO}| cobalt production | APOS, U”.

For **“water use**”, the impact equals 73.2 m^3, for 95.3% associated with the depletion of water of RoW origins.

Detailed Life Cycle Impact Assessment (LCIA) analysis for the production of 1 kg of hybrid pigment B ($CoAl_2O_4$/kaoline) prepared through microwave-assisted hydrothermal method.

For “**climate change**”, the impact equals 17.6 kg CO_2 eq, for 80.6% (i.e., 14.2 kg CO_2 eq) due to the emission of CO_2 of fossil source in air, 50.3% associated with the production of cobalt nitrate, for 6.38% attributed to the EID dataset “Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | APOS, U”, which describes the generation of thermal energy used in the production of cobalt hydroxide and aluminium hydroxide precursors for cobalt nitrate and aluminium nitrate, respectively.

For “**acidification**”, the impact equals 0.121 mol H^+ eq, for 70.4% (i.e., 0.0852 mol H^+ eq) due to the emission of SO_2 in air, 66.6% during the production of cobalt nitrate, for 34.1% associated with the EID dataset “Cobalt hydroxide {GLO}| cobalt production | APOS, U”, describing the production of cobalt hydroxide.

For “**photochemical ozone formation**”, the impact equals 4.97E-02 kg NMVOC eq, for 59.7% (i.e., 2.97E-02 kg NMVOC eq) due to the emission of nitrogen oxides in air, for 52.0% attributed to the production of cobalt nitrate, for 12.6% associated with the EID dataset “Diesel, burned in building machine {GLO}| diesel, burned in building machine | APOS, U”, describing the consumption of diesel for the production of cobalt hydroxide.

For “**ionizing radiation**”, the impact equals 5.72 kBq U-235 eq, for 60.9% (3.49 kBq U-235 eq) due to the emission of Radon-222 in air, for 57.3% attributed to the consumption of electricity, 97.3% associated with the same EID dataset as for **A1.**

For “**ozone depletion**”, the impact equals 3.78E-07 kg CFC11 eq, for 48.3% (1.83E-07 kg CFC11 eq) due to the emissions of methane-, bromotrifluoro-, halon 1301, 50.6% attributed to the production of cobalt nitrate, for 9.11% associated with the same EID dataset as for A1.

For “**human toxicity, cancer**”, the impact equals 7.28E-08 CTUh, for 79.6% (6.22E-08 CTUh) due to the emission of anthracene in air, 44.4% during the production of cobalt nitrate, 93.1% associated with the same EID dataset as for A1.

For “**human toxicity, non-cancer**”, the impact equals 5.47E-07 CTUh, for 36.2% (i.e., 1.98E-07 CTuh) associated with the emission of Lead (II) in air, 90.0% due to the production of cobalt nitrate, for 50.2% associated with the same EID dataset as for A1.

For “**ecotoxicity, freshwater**”, the impact equals 156 CTUe, for 25.7% (i.e., 40.1 CTUe) attributed to the emission of chlorine in water, for 84.1% during the production of cobalt nitrate, for 56.6% associated with the same EID dataset as for A1.

For “**particulate matter**” the impact equals 9.4E-07 disease inc., 42.7% (i.e., 4.01E-07 disease inc.) attributed to the emission of fine particulate <2.5 μm in air, for 62.5% during the production of cobalt nitrate, for 24.7% associated with the EID dataset "Electricity, high voltage, for internal use in coal mining {CN}| electricity production, hard coal, at coal mine power plant | APOS, U", describing the consumption of the electricity for the production of cobalt hydroxide.

For "**eutrophication, freshwater**", the impact equals 8.9E-03 kg P eq, 95.6% (i.e., 8.51E-03 kg P eq) attributed to the emission of phosphate in water, 47.1% associated with the electricity consumption, 80.1% attributed to the EID dataset "Spoil from lignite mining {GLO}| treatment of spoil from lignite mining, in surface landfill | APOS, U", describing the waste treatment from lignite mining.

For "**resource use, fossils**", the impact equals 275 MJ, 33.1% (i.e., 90.9 MJ) due to the consumption of natural gas, 49.8% attributed to the production of cobalt nitrate, for 15.8% associated with the EID dataset "Natural gas, high pressure {RU}| petroleum and gas production, onshore | APOS, U".

For "**resource use, minerals and metals**", the impact equals 1.02E-03 kg Sb eq, 41.8% (i.e., 4.25E-04 kg Sb eq) attributed to the depletion of copper, 97.5% associated with the production of cobalt nitrate, for 100% attributed to the EID dataset "Cobalt hydroxide {GLO}| cobalt production | APOS, U".

For **"water use**", the impact equals 44.7 m^3, for 94.5% associated with the depletion of water of RoW origins.

Detailed Life Cycle Impact Assessment (LCIA) analysis for the production of 1 kg of hybrid pigment C ($CoAl_2O_4/Al_2O_3$) prepared through heterogeneous precipitation method.

For "**climate change**", the impact equals 12.6 kg CO_2 eq, for 87.4% (i.e., 11.2 kg CO_2 eq) due to the emission of CO_2 of fossil source in air, 45.1% associated with the production of cobalt nitrate, for 6.38% attributed to the EID dataset "Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | APOS, U", which describes the generation of thermal energy used in the production of cobalt hydroxide and aluminium hydroxide precursors for cobalt nitrate and aluminium nitrate, respectively.

For "**acidification**", the impact equals 0.079 mol H^+ eq, for 75.3% (i.e., 0.059 mol H^+ eq) due to the emission of SO_2 in air, 67.8% during the production of cobalt nitrate, for 34.1% associated with the EID dataset "Cobalt hydroxide {GLO}| cobalt production | APOS, U", describing the production of cobalt hydroxide.

For "**photochemical ozone formation**", the impact equals 5.15E-02 kg NMVOC eq, for 42.0% (i.e., 2.17E-02 kg NMVOC eq) due to the emission of nitrogen oxides in air, for 50.6% attributed to the production of cobalt nitrate, for 12.6% associated with the EID dataset "Diesel, burned in building machine {GLO}| diesel, burned in building machine | APOS, U", describing the consumption of diesel for the production of cobalt hydroxide.

For "**ionizing radiation**", the impact equals 4.59 kBq U-235 eq, for 62% (2.85 kBq U-235 eq) due to the emission of Radon-222 in air, for 71.5% attributed to the consumption of electricity, 97.3% associated with the same EID dataset as for **A1.**

For "**ozone depletion**", the impact equals 3.4E-07 kg CFC11 eq, for 52.0% (1.77E-07 kg CFC11 eq) due to the emissions of methane-, bromotrifluoro-, halon 1301, 37.1% attributed to the production of cobalt nitrate, for 9.11% associated with the same EID dataset as for A1.

For "**human toxicity, cancer**", the impact equals 5.93E-08 CTUh, for 79.6% (6.22E-08 CTUh) due to the emission of anthracene in air, 41.6% during the production of cobalt nitrate, 93.1% associated with the same EID dataset as for A1.

For "**human toxicity, non-cancer**", the impact equals 3.95E-07 CTUh, for 34.0% (i.e., 1.32E-07 CTUh) associated with the emission of Lead (II) in air, 94.3% due to the production of cobalt nitrate, for 50.2% associated with the same EID dataset as for A1.

For "**ecotoxicity, freshwater**", the impact equals 109 CTUe, for 26.4% (i.e., 28.7 CTUe) attributed to the emission of chloride in water, for 83.6% during the production of cobalt nitrate, for 23.9% associated with the EID dataset "Hazardous waste, for incineration {RoW}| treatment of hazardous waste, hazardous waste incineration | APOS, U", describing the hazardous waste treatment generated during the production of cobalt nitrate.

For "**particulate matter**" the impact equals 5.91 E-07 disease inc., 43.0% (i.e., 2.54E-07 disease inc.) attributed to the emission of fine particulate <2.5 μm in air, for 70.1% during the production of cobalt nitrate, for 27.4% associated with the EID dataset "Electricity, high voltage, for internal use in coal mining {CN}| electricity production, hard coal, at coal mine power plant | APOS, U", describing the consumption of the electricity for the production of cobalt hydroxide.

For "**eutrophication, freshwater**", the impact equals 6.76E-03 kg P eq, 96.4% (i.e., 6.52E-03 kg P eq) attributed to the emission of phosphate in water, 62.7% associated with the electricity consumption, 80.1% attributed to the EID dataset "Spoil from lignite mining {GLO}| treatment of spoil from lignite mining, in surface landfill | APOS, U", describing the waste treatment from lignite mining.

For "**resource use, fossils**", the impact equals 228 MJ, 38.9% (i.e., 88.8 MJ) due to the consumption of natural gas, for 36.3% attributed to the production of cobalt nitrate, for 15.8% associated with the EID dataset "Natural gas, high pressure {RU}| petroleum and gas production, onshore | APOS, U".

For "**resource use, minerals and metals**", the impact equals 6.99E-04 kg Sb eq, 43.1% (i.e., 3.01E-04 kg Sb eq) attributed to the depletion of sulfur, 100% associated with the production of cobalt nitrate, for 100% attributed to the EID dataset "Cobalt hydroxide {GLO}| cobalt production | APOS, U".

For **"water use**", the impact equals 31.5 m^3, for 94.0% associated with the depletion of water of RoW origins.

Detailed Life Cycle Impact Assessment (LCIA) analysis for the production of 1 kg of pigment F ($Zn_{0.9}Co_{0.1}Al_2O_4$) prepared via sol-gel autoignition method.

For "**climate change**", the impact equals 22.2 kg CO_2 eq, for 75.4% (i.e., 16.8 kg CO_2 eq) due to the emission of CO_2 of fossil source in air, 23.4% associated with the production of aluminium nitrate, for 6.8% attributed to the EID dataset "Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | APOS, U", which describes the generation of thermal energy used in the production of aluminium hydroxide as the precursor for aluminium nitrate.

For "**acidification**", the impact equals 0.105 mol H^+ eq, for 50.9% (i.e., 0.0533 mol H^+ eq) due to the emission of SO_2 in air, 32.5% during the production of aluminium nitrate, for 27.2% associated with the EID dataset "Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | APOS, U"

For "**photochemical ozone formation**", the impact equals 5.1E-02 kg NMVOC eq, for 56.4% (i.e., 2.88E-02 kg NMVOC eq) due to the emission of nitrogen oxides in air, for 33.0% attributed to the production of aluminium nitrate, for 15.2% associated with the EID dataset "Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | APOS, U", describing the consumption of thermal energy for the production of aluminium hydroxide.

For "**ionizing radiation**", the impact equals 3.38 kBq U-235 eq, for 67.3% (2.28 kBq U-235 eq) due to the emission of Radon-222 in air, for 51.2% attributed to the consumption of electricity, 97.3% associated with the same EID dataset as for **A1.**

For "**ozone depletion**", the impact equals 3.95E-07 kg CFC11 eq, for 65.1% (2.58E-07 kg CFC11 eq) due to the emissions of methane-, bromotrifluoro-, halon 1301, 15.3% attributed to the production of aluminium nitrate, for 14.1% associated with the EID dataset "Natural gas, high pressure {QA}| petroleum and gas production, offshore | APOS, U".

For "**human toxicity, cancer**", the impact equals 7.13E-08 CTUh, for 85.6% (6.1E-08 CTUh) due to the emission of anthracene in air, 25.5% during the production of aluminium nitrate, 80.9% associated with the EID dataset "Coke {RoW}| coke production | APOS, U", describing the production of coke employed in the manufacturing of steel, necessary for the construction of the pipeline for the natural gas transportation.

For "**human toxicity, non-cancer**", the impact equals 2.8E-07 CTUh, for 26.9% (i.e., 7.55E-08 CTUh) associated with the emission of Lead (II) in air, 38.0% due to the production of cobalt nitrate, for 50.2% associated with the same EID dataset as for A1.

For "**ecotoxicity, freshwater**", the impact equals 276 CTUe, for 36.8% (i.e., 102.0 CTUe) attributed to the emission of chloroacetic acid in water, for 100% during the production of glycine, for 100% as direct emissions during the production of glycine, described by the EID dataset "Glycine {RER}| glycine production | APOS, U".

For "**particulate matter**" the impact equals 8.06E-07 disease inc., 47.0% (i.e., 3.79E-07 disease inc.) attributed to the emission of fine particulate <2.5 μm in air, for 37.7% during the production of aluminium nitrate, for 27.8% associated with the EID dataset "Electricity, high voltage, for internal use in coal mining {CN}| electricity production, hard coal, at coal mine power plant | APOS, U", describing the consumption of the electricity for the production of aluminium hydroxide.

For "**eutrophication, freshwater**", the impact equals 7.17E-03 kg P eq, 98.4% (i.e., 7.06E-03 kg P eq) attributed to the emission of phosphate in water, 33.1% associated with the electricity consumption, 80.1% attributed to the EID dataset "Spoil from lignite mining {GLO}| treatment of spoil from lignite mining, in surface landfill | APOS, U", describing the waste treatment from lignite mining.

For "**resource use, fossils**", the impact equals 290 MJ, 49.3% (i.e., 143 MJ) due to the consumption of natural gas, for 46.0% attributed to the production of urea, for 36.1% associated with the EID dataset "Natural gas, high pressure {RU}| petroleum and gas production, onshore | APOS, U", describing the natural gas consumption during the production of urea.

For "**resource use, minerals and metals**", the impact equals 3.2E-04 kg Sb eq, 27.0% (i.e., 8.64E-05 kg Sb eq) attributed to the depletion of copper, 78.0% associated with the production of cobalt nitrate, for 87.5% attributed to the EID dataset "Cobalt hydroxide {GLO}| cobalt production | APOS, U".

For **"water use**", the impact equals 20.1 m^3, for 53.45% associated with the depletion of water of RoW origins and 31.1% associated with the depletion of water of RER origins (i.e., Europe).

Detailed Life Cycle Impact Assessment (LCIA) analysis for the production of 1 kg of pigment I ($Co_{0.05}Zn_{1.95}SiO_4$) prepared via solid-state reaction.

The impacts on "**climate change**" equal 3.2 kg CO_2 eq, 85.0% (i.e., 2.72 kg CO_2 eq) of the impact is due to the emission of CO_2 of fossil source in air, 37.5% due to the consumption of acetone, 24.5% attributed to the EID dataset "Propylene {RER}| unsaturated hydrocarbons production, steam cracking operation, average | APOS, U", describing the production of propylene as a precursor for acetone.

For "**acidification**" the impact equals 0.0174 mol H^+ eq, 76.6% (0.0133 mol H^+ eq) due to the emission of SO_2 in air, for 53.8% associated with the production of Co_3O_4, 100% as direct emission during Co_3O_4 production, described by the EID dataset "Cobalt oxide {GLO}| cobalt production | APOS, U".

For "**photochemical ozone formation**" the impact equals 8.67E-02 kg NMVOC eq, for 78.8% (i.e., 6.83E-02 kg NMVOC eq) due to the emission of acetone in air, for 99.8% as direct emission of the process.

For “**ozone depletion**” the impacts equal 1.05E-07 kg CFC11 eq, for 75.8% (7.93E-08 kg CFC11 eq) due to the emissions of methane-, bromotrifluoro-, halon 1301 in air, for 52.0% during the production of acetone, 92.9% attributed to the EID dataset “Petroleum {NO}| petroleum and gas production, offshore | APOS, U”, describing the extraction of petroleum as a precursor for propylene.

For “**ionizing radiation**” the impact equals 0.629 kBq U-235 eq, for 57.9% (0.364 kBq U-235 eq) due to the emission of Radon-222 in air, for 38.0% associated with the production of cobalt oxide, 97.1% attributed to the EID dataset “Tailing, from uranium milling {GLO}| treatment of tailing, from uranium milling | APOS, U”

For “**human toxicity, cancer**” the impact equals 1.51E-08 CTUh, for 89.8% (1.36E-08 CTUh) due to the emissions of anthracene in air, for 31.4% attributed to the production of acetone, for 91.7% associated with the EID dataset “Coke {RoW}| coke production | APOS, U”, describing the production of coke employed in the manufacturing of steel, necessary for the construction of chemical factory.

For “**human toxicity, non-cancer**” the impact equals 1.09E-07 CTUh, 30.3% (i.e., 3.29E-08 CTUh) due to the emission of Lead (II) in air, 76.3% due to the production of Co_3O_4, for 52.4% associated with the EID dataset “Copper cake {GLO}| treatment of copper cake | APOS, U” describing the waste treatment during the production of cobalt oxide.

For “**ecotoxicity, freshwater**” the impact equals 20.5 CTUe, for 24.1% (i.e., 4.94 CTUe) due to the emission of chlorine in water, for 96.8% during the production of Co_3O_4, for 53.6% associated with the EID dataset “Wastewater, average {RoW}| market for wastewater, average | APOS, U”, describing the wastewaters treatment during the production of cobalt oxide.

The impact on “**particulate matter**” equals 1.43E-07 disease inc., 43.9% (i.e., 8.98E-07 disease inc.) attributed to the emission of fine particulate <2.5 μm in air, 39.5% during the production of Co_3O_4, for 22.8% associated with the EID dataset “Diesel, burned in building machine {GLO}| diesel, burned in building machine | APOS, U”, describing the diesel consumption for the production of Co_3O_4.

For “**eutrophication, freshwater**” the impact equals 9.59E-04 kg P eq, 95.4% (i.e., 9.15E-04 kg P eq) attributed to the emission of phosphate in water, 27.2% due to the consumption of acetone, for 48.8% associated with EID dataset “Spoil from lignite mining {GLO}| treatment of spoil from lignite mining, in surface landfill | APOS, U”.

For “**resource use, minerals and metals**” the impact equals 1.66E-04 kg Sb eq, 38.7% (i.e., 6.43E-05 kg Sb eq) attributed to the depletion of copper, 95.1% during the production of of Co_3O_4, 98.2% attributed to the EID dataset “Cobalt oxide {GLO}| cobalt production | APOS, U”, i.e., the production of Co_3O_4.

For “**resource use, fossils**” the impact equals 66.5 MJ, 47.5% (i.e., 31.6 MJ) due to the consumption of natural gas, 38.5% during the production of acetone, for 19.4% associated with the EID dataset “Natural gas, high pressure {US}| petroleum and gas production, onshore | APOS, U”.

For “**water use**” the impact equals 6.53 m^3, for 92.94% associated with the consumption of water of RoW origins (i.e., the world minus the local geographies for which a process exists in the database).

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