Precious metal recovery from nanowaste for sustainable nanotechnology: Current challenges and life cycle considerations

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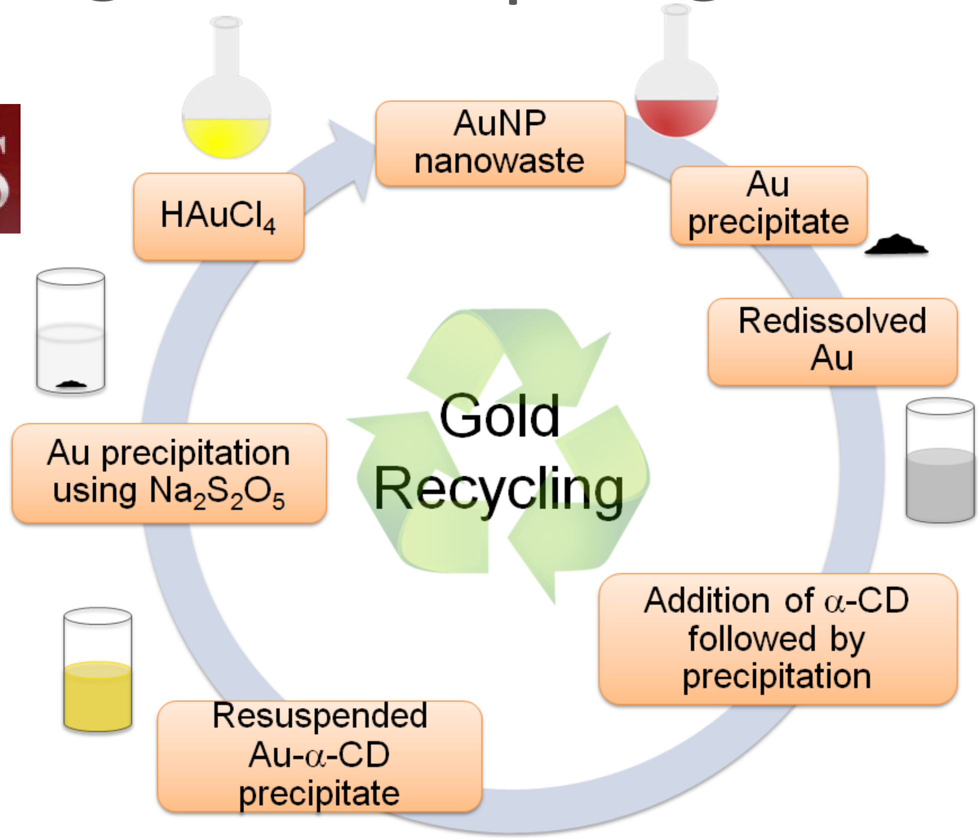
VTSuN ICTAS

VirginiaTech Invent the Future

CEINT Center for the Environmental Implications of NanoTechnology



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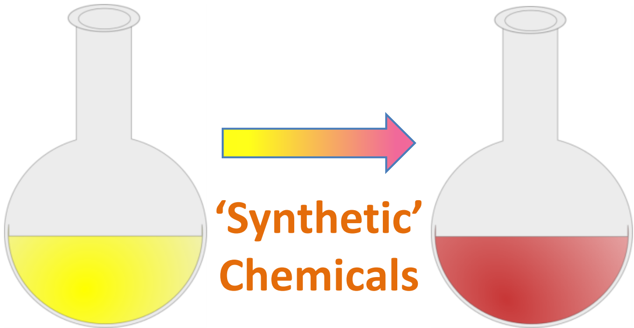
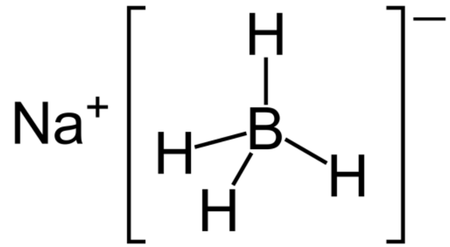
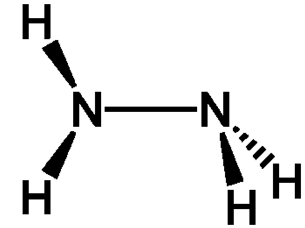
Conference 2015

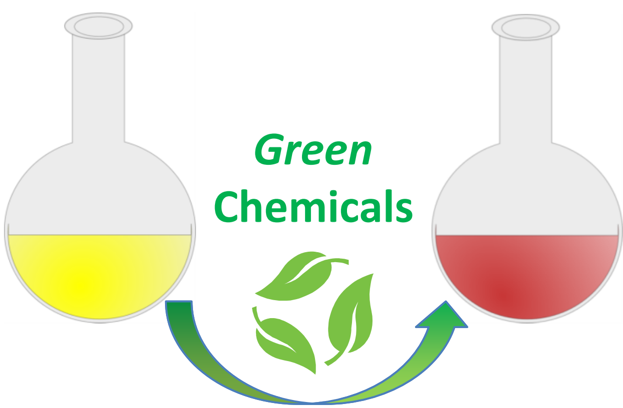




sodium borohydride



hydrazine



cinnamon

grape pomace

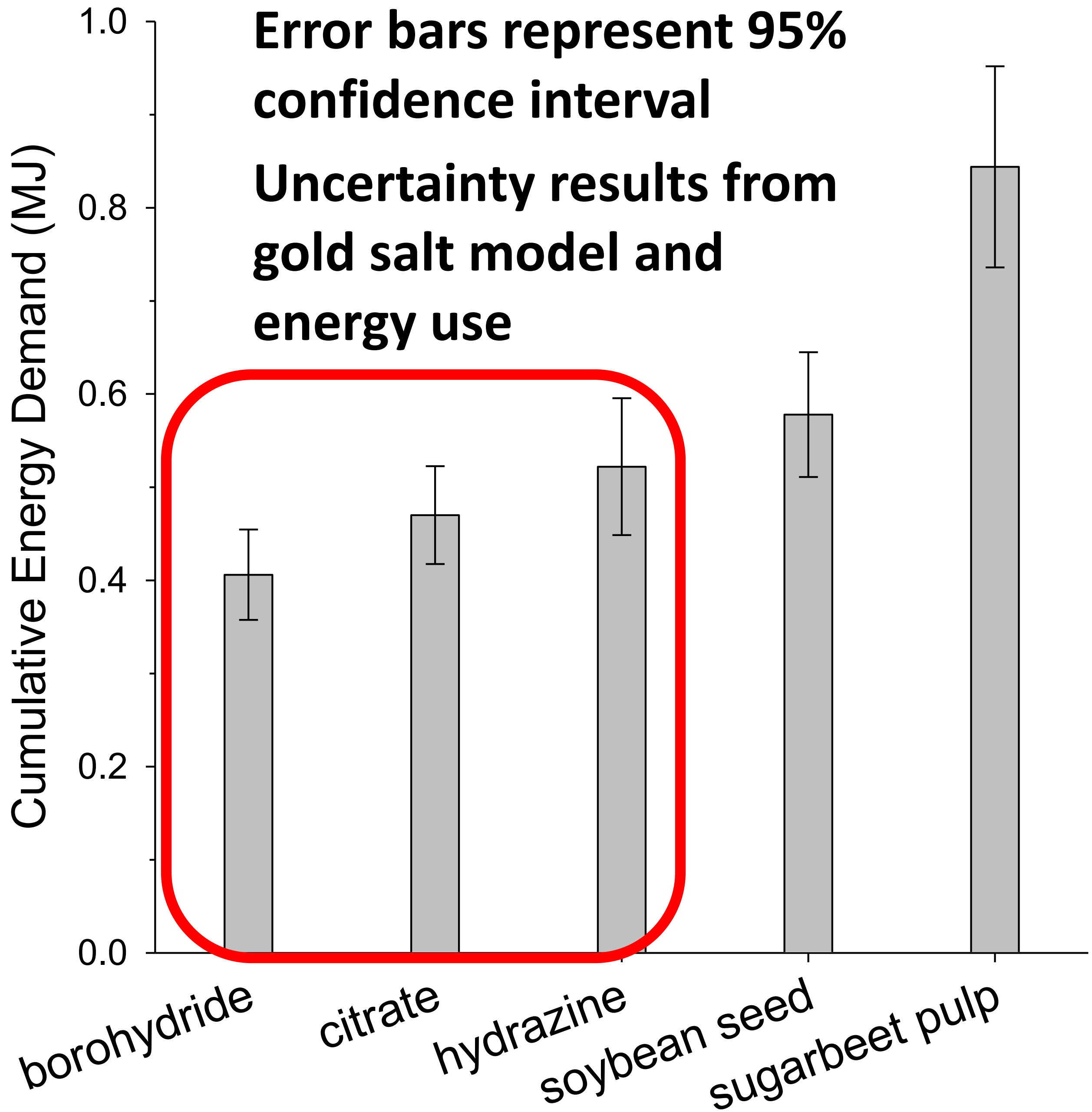
cypress leaves

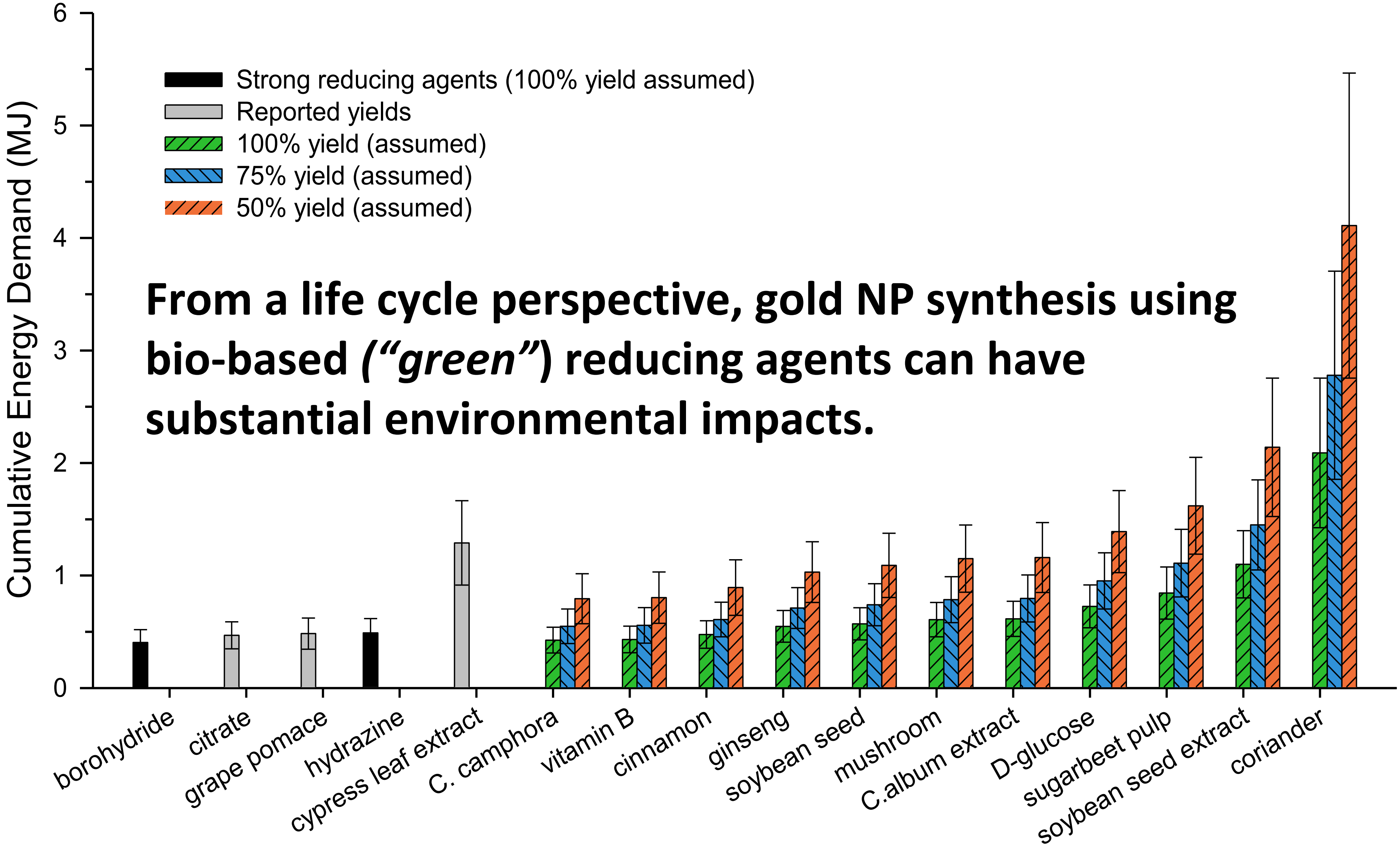
coriander leaves

soybean

Error bars represent 95% confidence interval

Uncertainty results from gold salt model and energy use

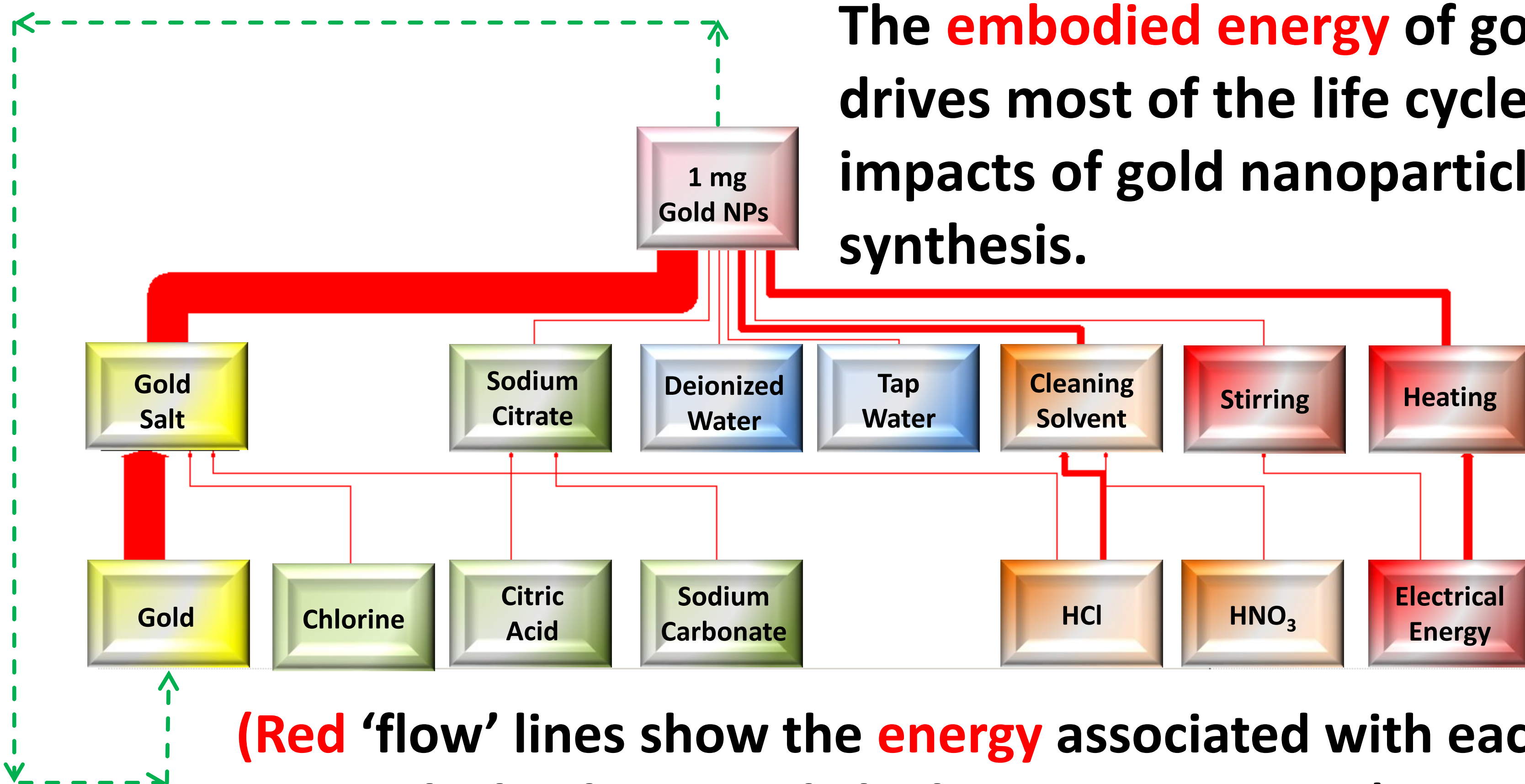




From a life cycle perspective, gold NP synthesis using bio-based (*"green"*) reducing agents can have substantial environmental impacts.

"Life Cycle Assessment of "Green" Nanoparticle Synthesis Methods", *Environmental Engineering Science* ***(2014).*** Paramjeet Pati, Sean McGinnis and Peter J. Vikesland.

If gold is the key driver of life cycle impacts, can we reduce impacts by recovering/recycling gold?



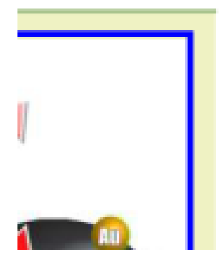
The embodied energy of gold drives most of the life cycle impacts of gold nanoparticle synthesis.

(Red 'flow' lines show the energy associated with each input. Thicker lines imply higher energy inputs.)

ACS Sustainable Chemistry & Engineering
Research Article
pubs.acs.org/journal/ascecg

Recovery of Gold from Incinerated Sewage Sludge Ash by Chlorination

Junichi Kakumazaki, Takahiro Kato, and Katsuyasu Sugawara*
Prefecture, Japan



Environmental Science & Technology
Article
pubs.acs.org/est

Recycling Potential of Neodymium: The Case of Computer Hard Disk Drives

Benjamin Sprecher,*[,†,§] Rene Kleijn,[†] and (
[†]Institute of Environmental Sciences Leiden (CML), I
[§]Materials Innovation Institute (M2i), P.O. Box 5008,

Supporting Information

ABSTRACT: Neodymium, one of the more critica metals, is often used in sustainable technologies. investigate the potential contribution of neodymium r scarcity in supply, with a case study on comput (HDDs). We first review the literature on neodymi recycling potential. From this review, we find that re HDDs is currently the most feasible pathway toward of neodymium, even though HDDs do not re application of neodymium. We then use a comb modeling and empirical experiments to conclud application of NdFeB magnets for HDDs, the poten

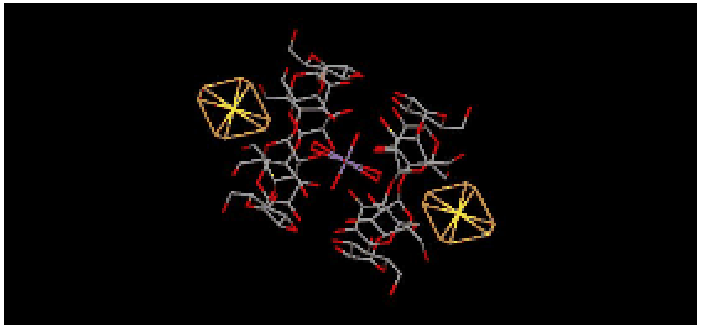
Environmental Science & Technology
Article
pubs.acs.org/est

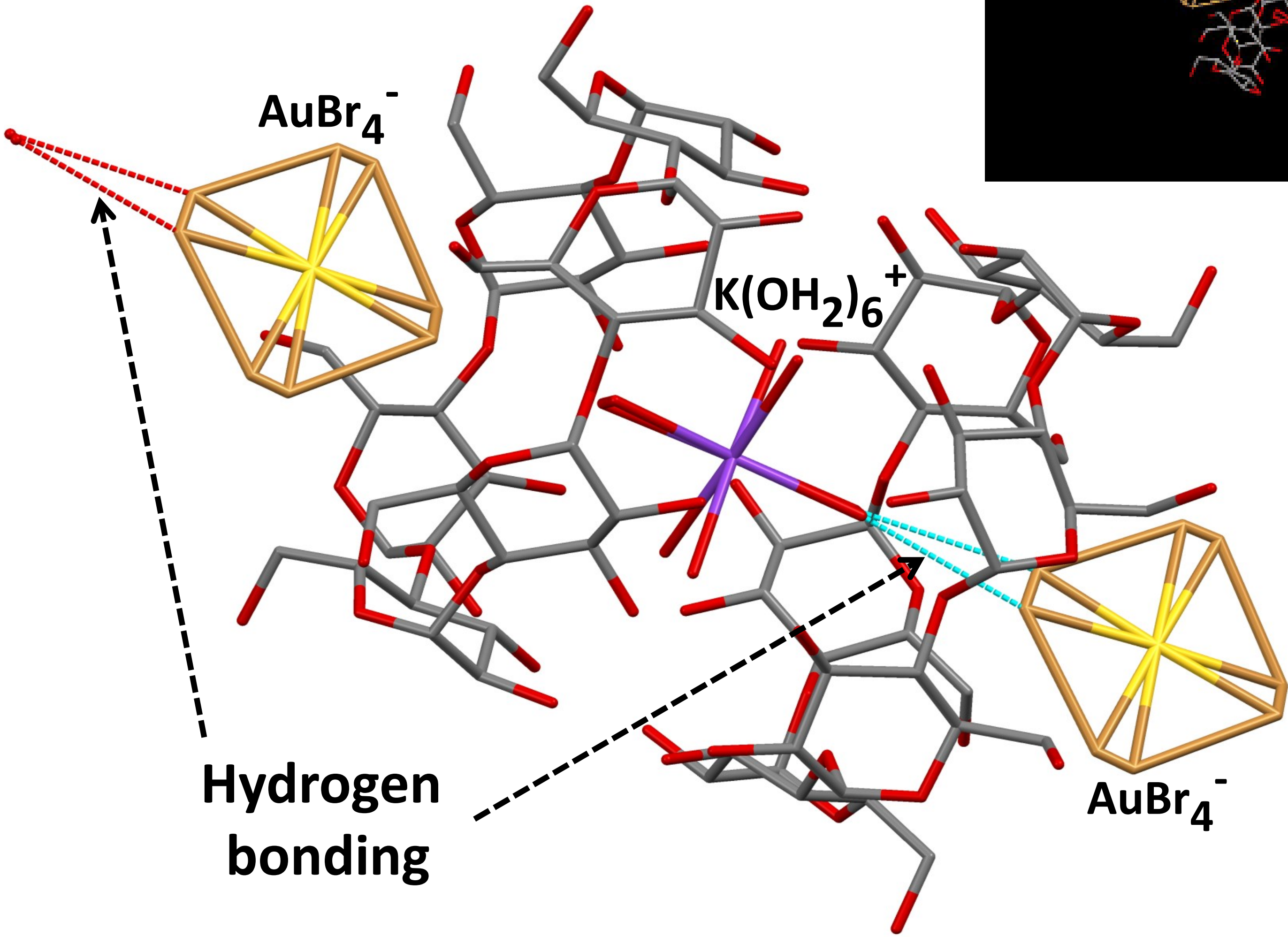
Recycling of Indium From CIGS Photovoltaic Cells: Potential of Combining Acid-Resistant Nanofiltration with Liquid–Liquid Extraction

Yannick-Serge Zimmermann,[†,‡] Claudia Niewersch,[†] Markus Lenz,*[,†,§] Zöhre Zohra Kül,[†] Philippe F.-X. Corvini,[†,∥] Andreas Schäffer,[‡,∥] and Thomas Wintgens[†]
[†]Institute for Ecopreneurship, School of Life Sciences, University of Applied Sciences and Arts Northwestern Switzerland, Gründenstrasse 40, CH-4132 Muttenz, Switzerland
[‡]Institute for Environmental Research (Biology V), RWTH Aachen University, 52074 Aachen, Germany
[§]Department of Environmental Technology, Wageningen University, 6708 WG Wageningen, The Netherlands

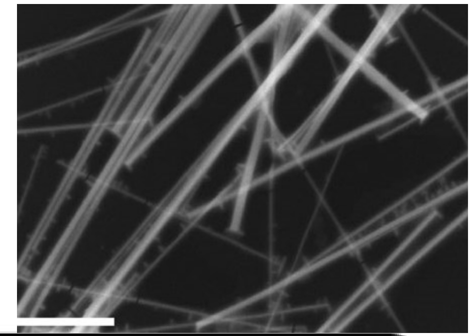
Recovering gold from nanowaste…

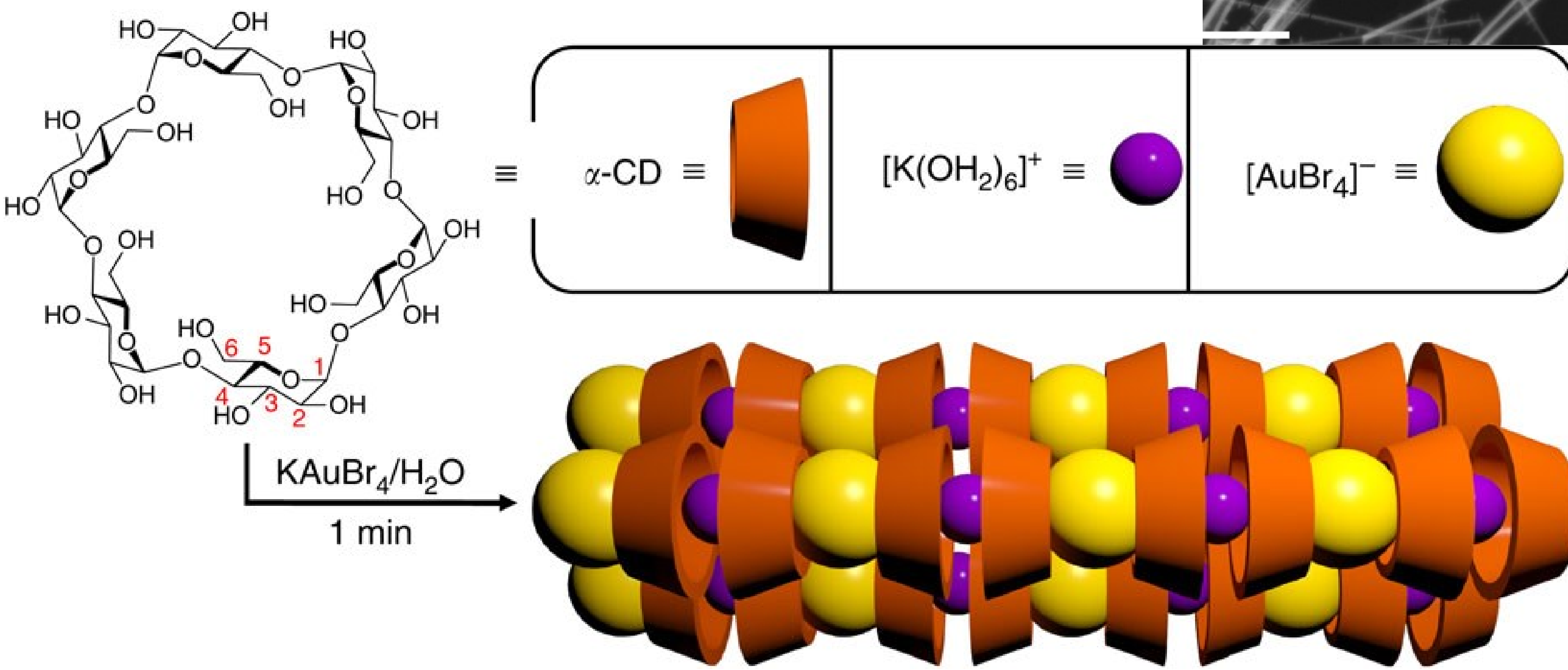
… using α-cyclodextrin



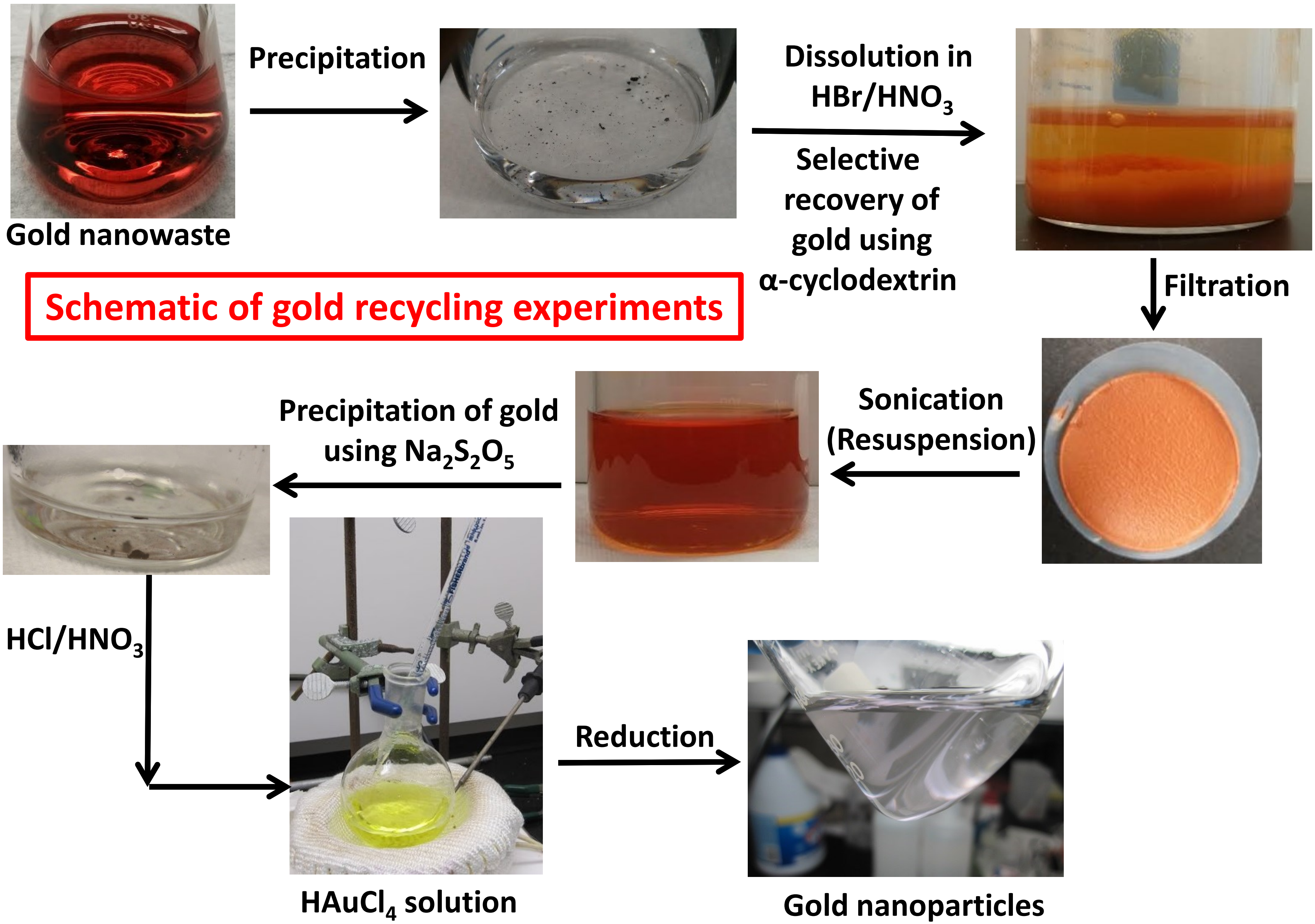


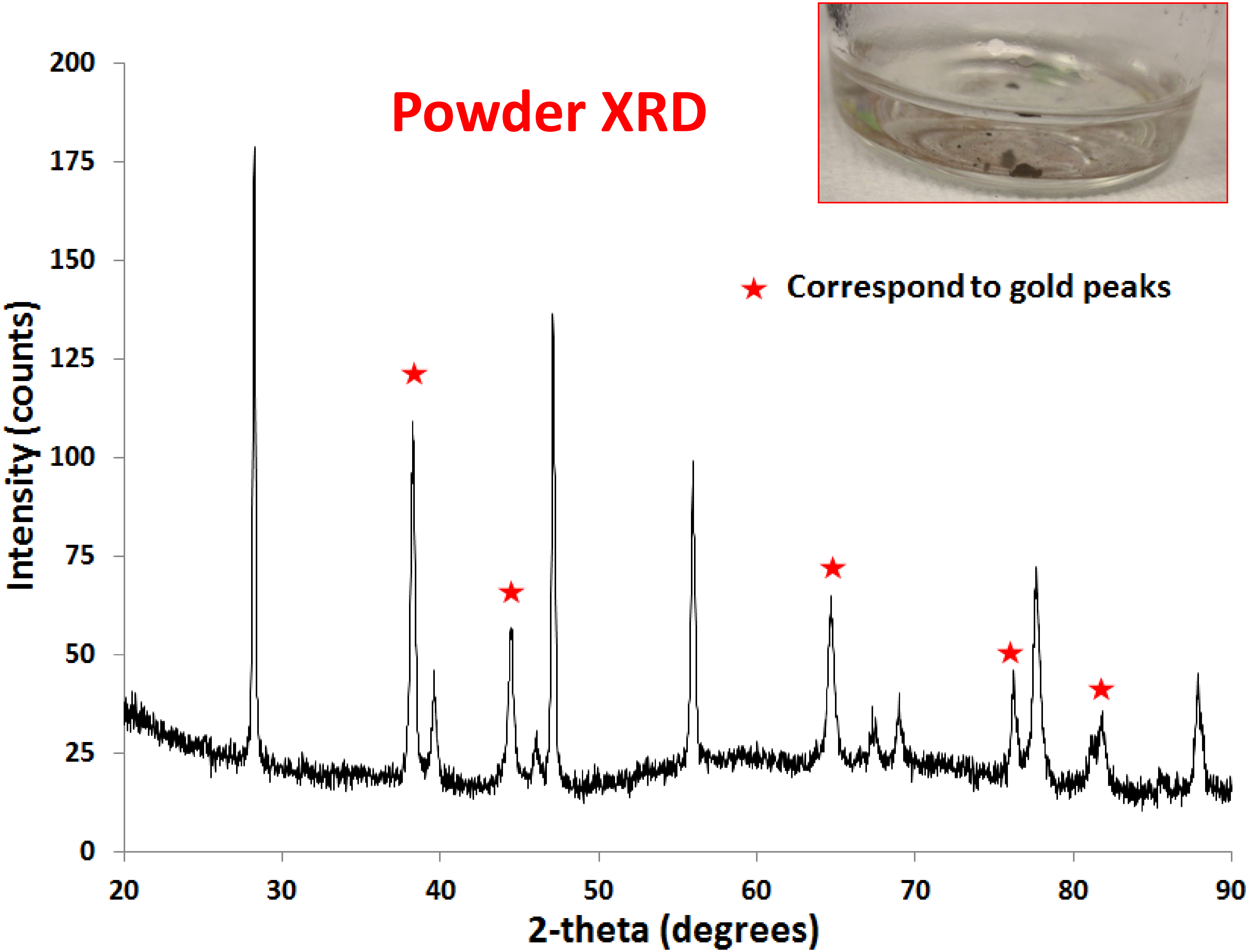
http://unam.bilkent.edu.tr

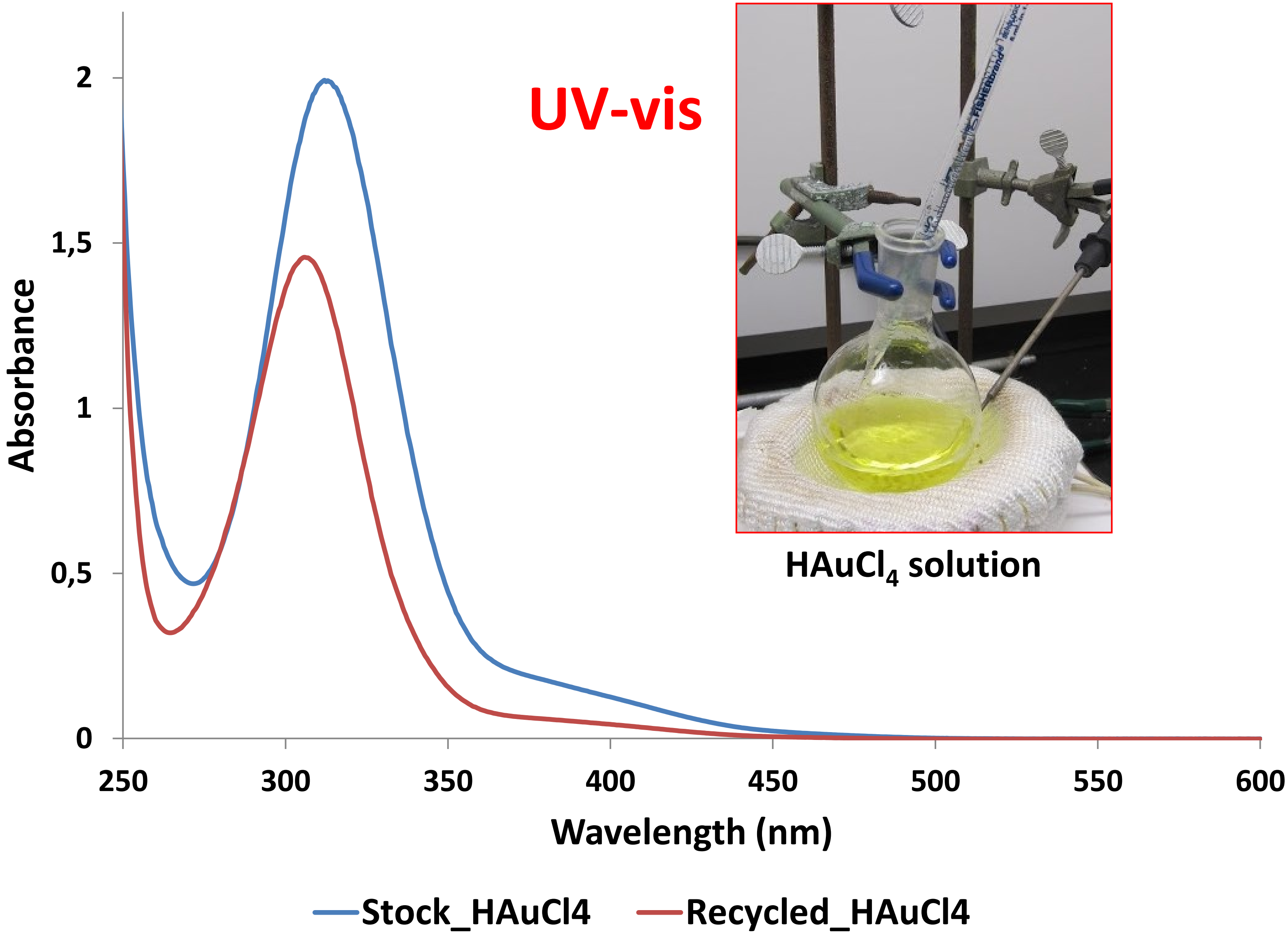




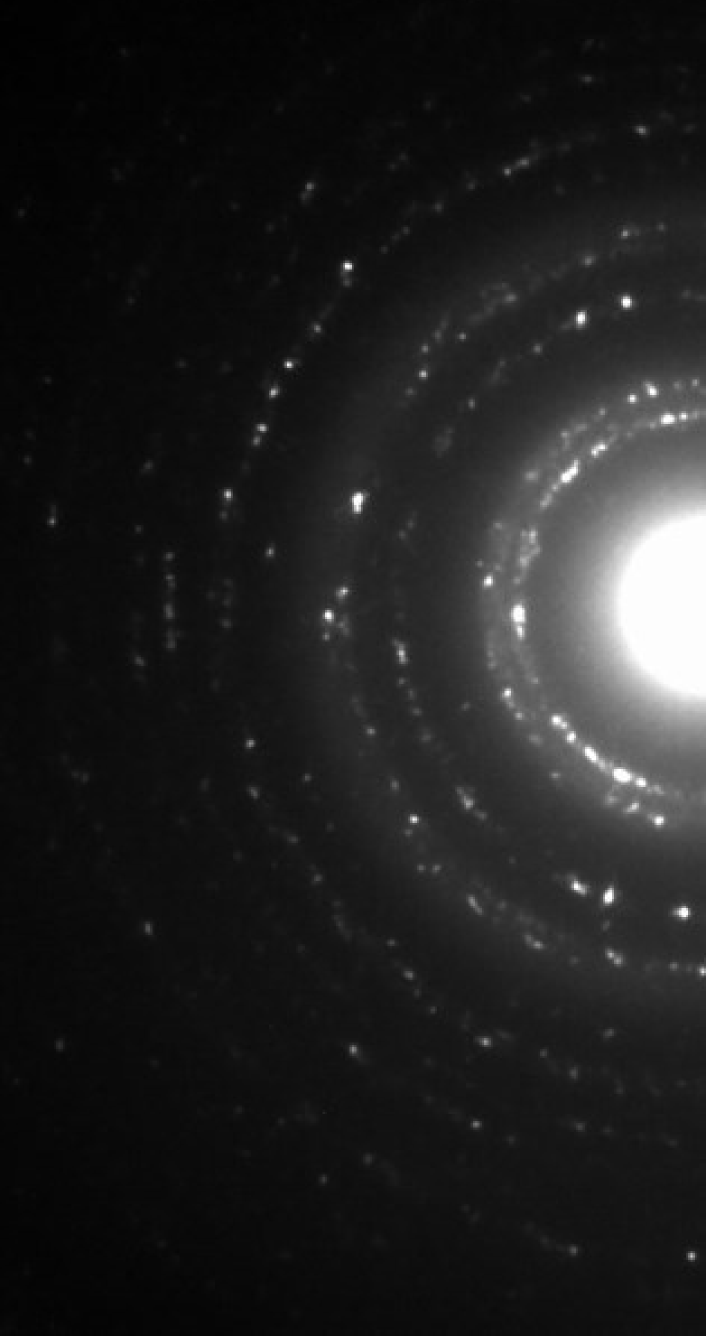
“Selective isolation of gold facilitated by second-sphere coordination with α-cyclodextrin”. *Nature Communications,* Liu *et al.* (2013)


Gold nanowaste
Precipitation
Dissolution in HBr/HNO$_3$
Selective recovery of gold using α-cyclodextrin
Filtration
Schematic of gold recycling experiments
Sonication (Resuspension)
Precipitation of gold using $Na_2S_2O_5$
HCl/HNO$_3$
HAuCl$_4$ solution
Reduction
Gold nanoparticles

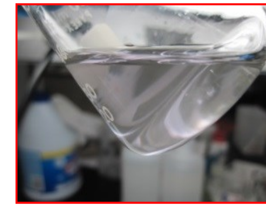

Powder XRD
★ Correspond to gold peaks
Intensity (counts)
2-theta (degrees)
0
25
50
75
100
125
150
175
200
20
30
40
50
60
70
80
90



$HAuCl_4$ solution

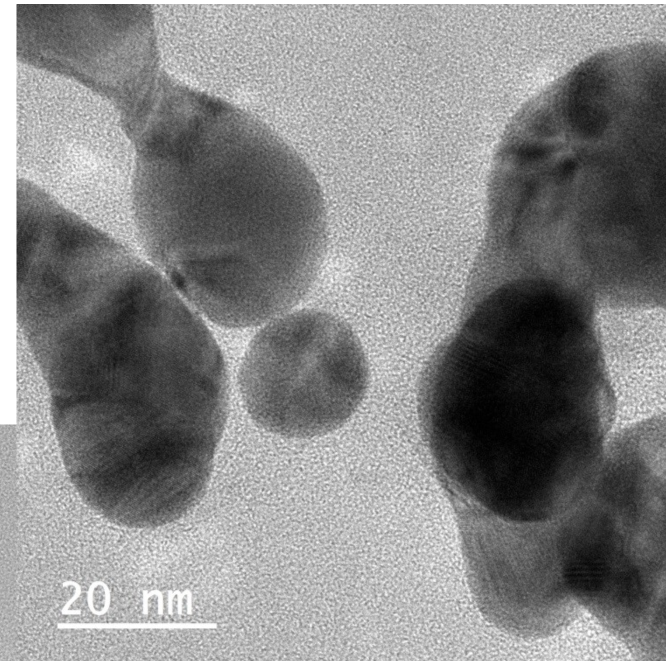


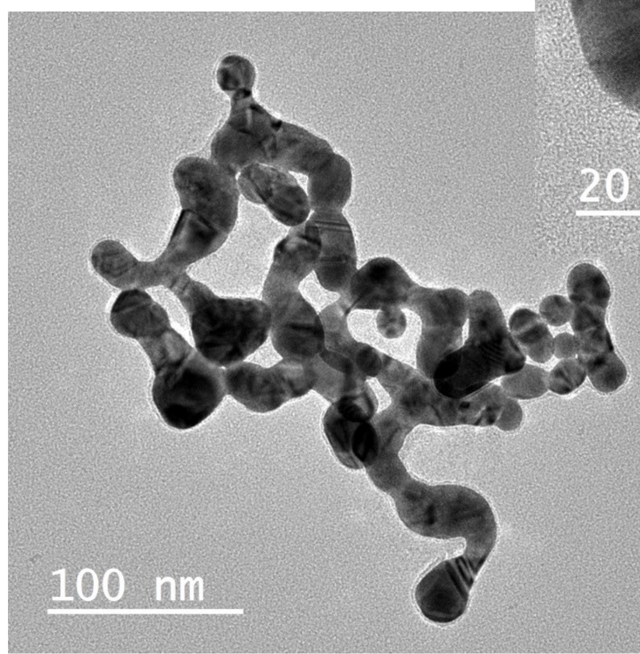
Calculated d-spacing (Å)	d-spacing for gold (Å)
1.25, 1.19	1.23, 1.18
1.46	1.44
2.06	2.04
2.39	2.36

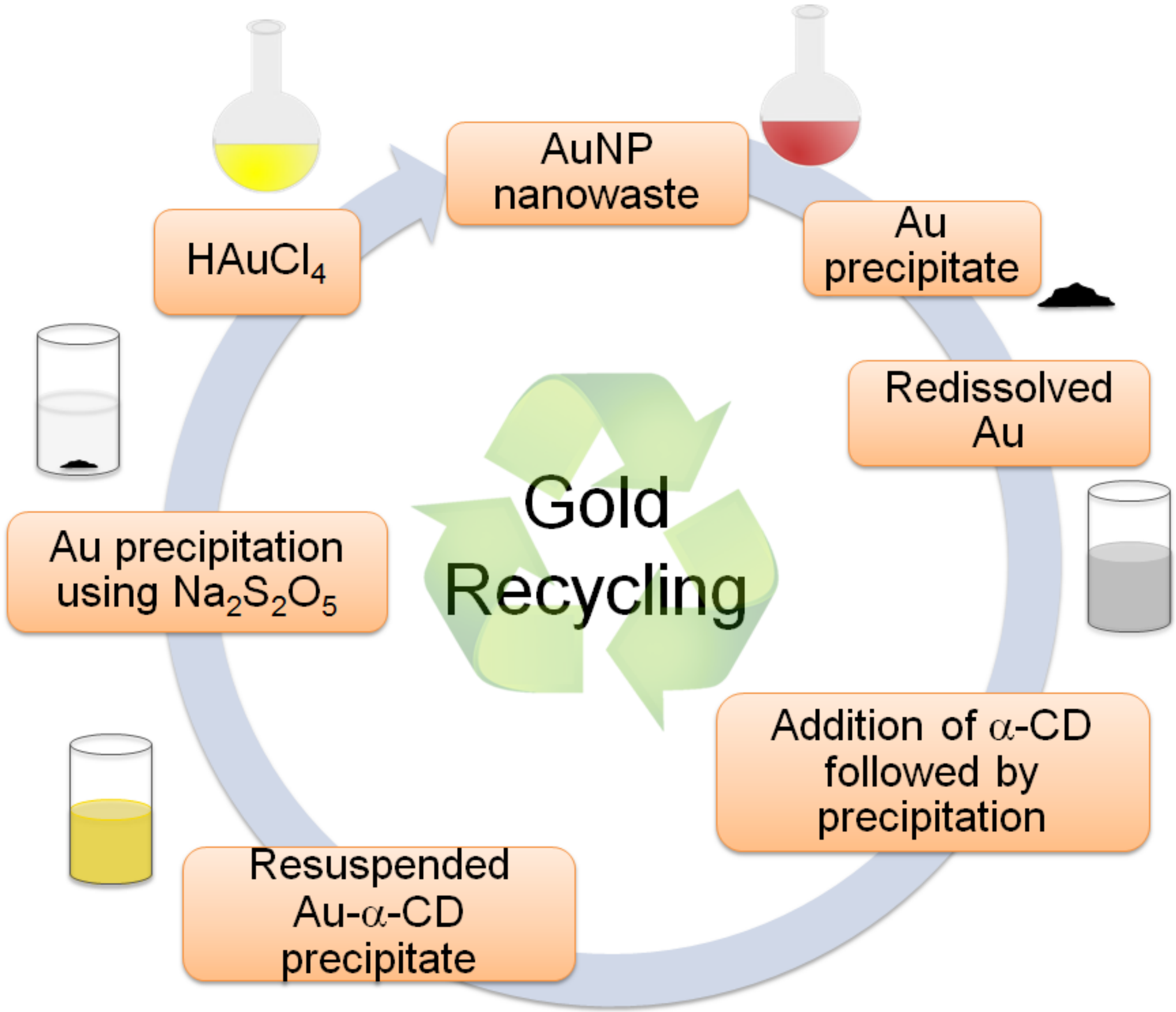


Gold nanoparticles

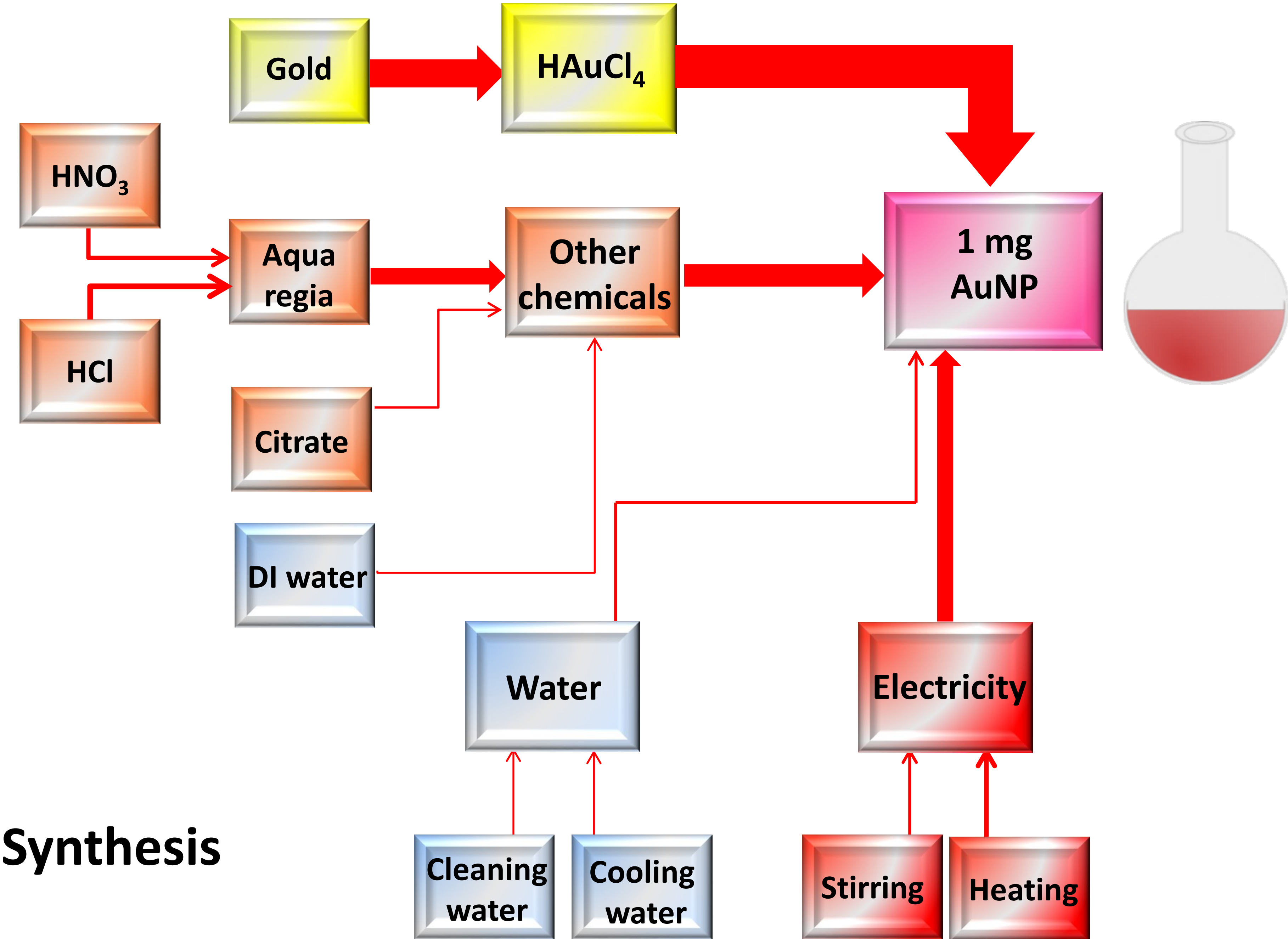
Diffraction



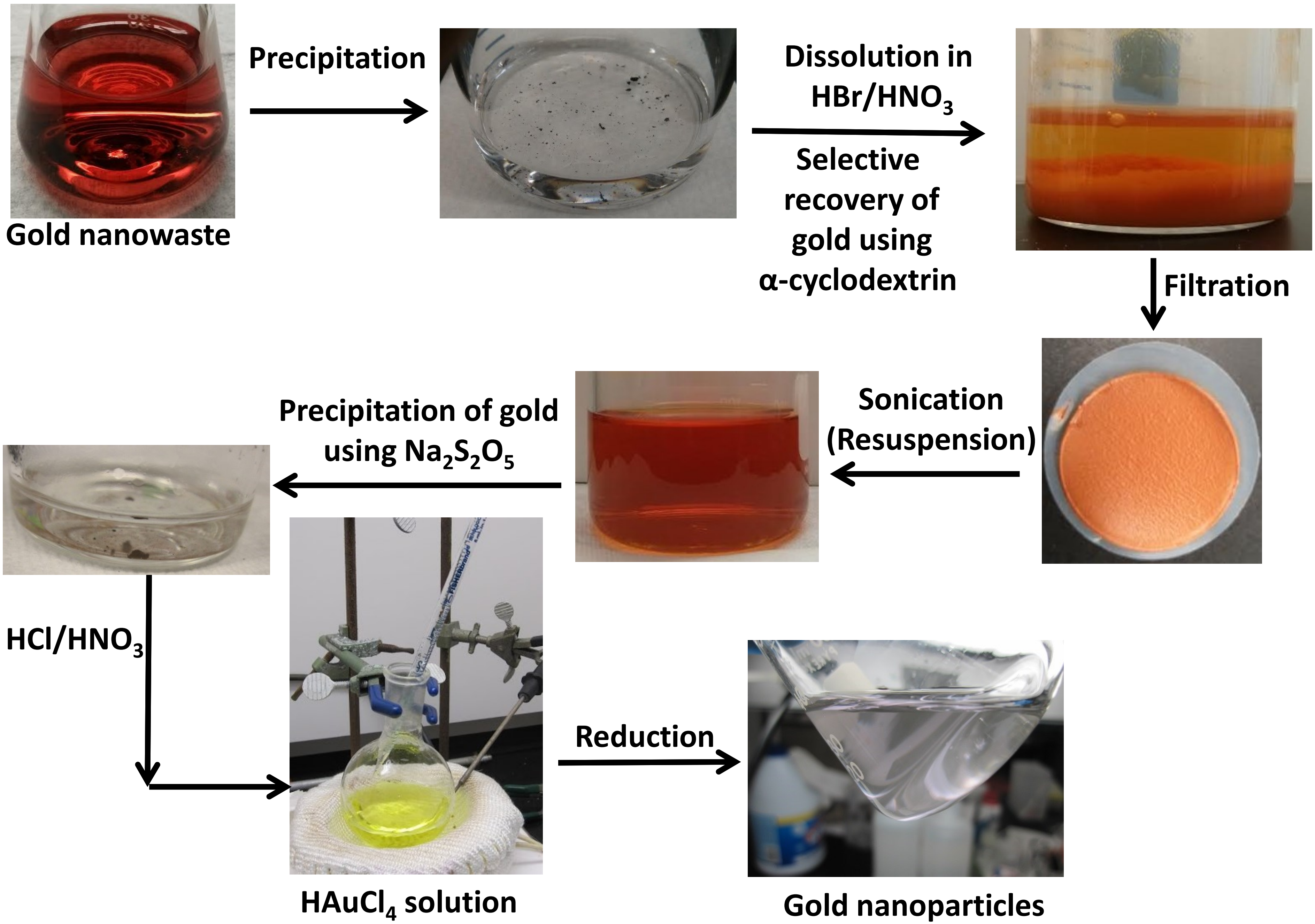




Can we recover gold from nanowaste?
Yes, we can. (But should we?)


Gold
HAuCl4
HNO3
Aqua regia
HCl
Other chemicals
1 mg AuNP
Citrate
DI water
Water
Electricity
Cleaning water
Cooling water
Stirring
Heating

Synthesis


Gold nanowaste
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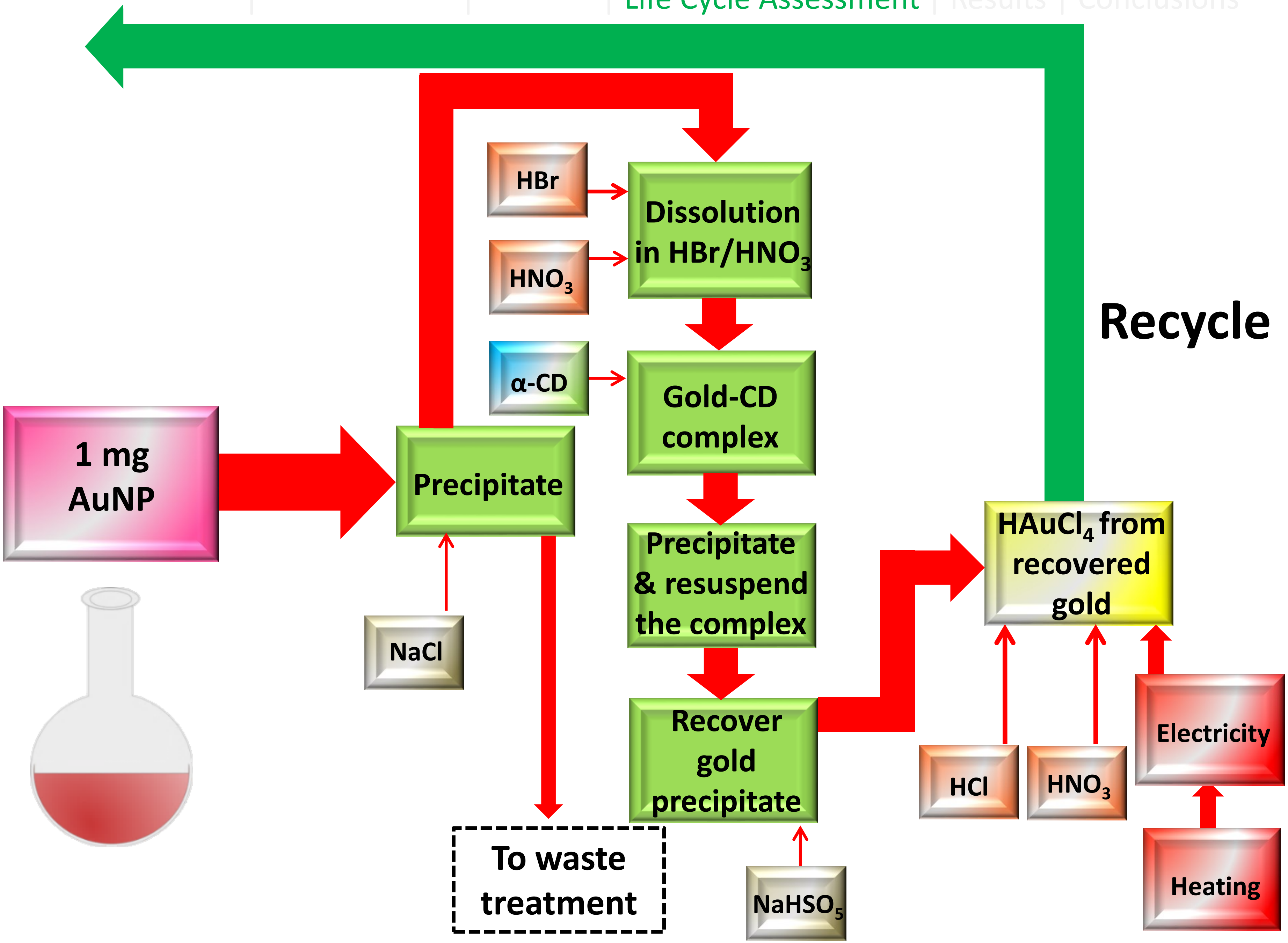
$HAuCl_4$ solution
Reduction
Gold nanoparticles


Recycle
1 mg
AuNP
Precipitate
NaCl
HBr
HNO$_3$
α-CD
Dissolution in HBr/HNO$_3$
Gold-CD complex
Precipitate & resuspend the complex
Recover gold precipitate
NaHSO$_5$
To waste treatment
HAuCl$_4$ from recovered gold
HCl
HNO$_3$
Electricity
Heating

Synthesis

Recycling

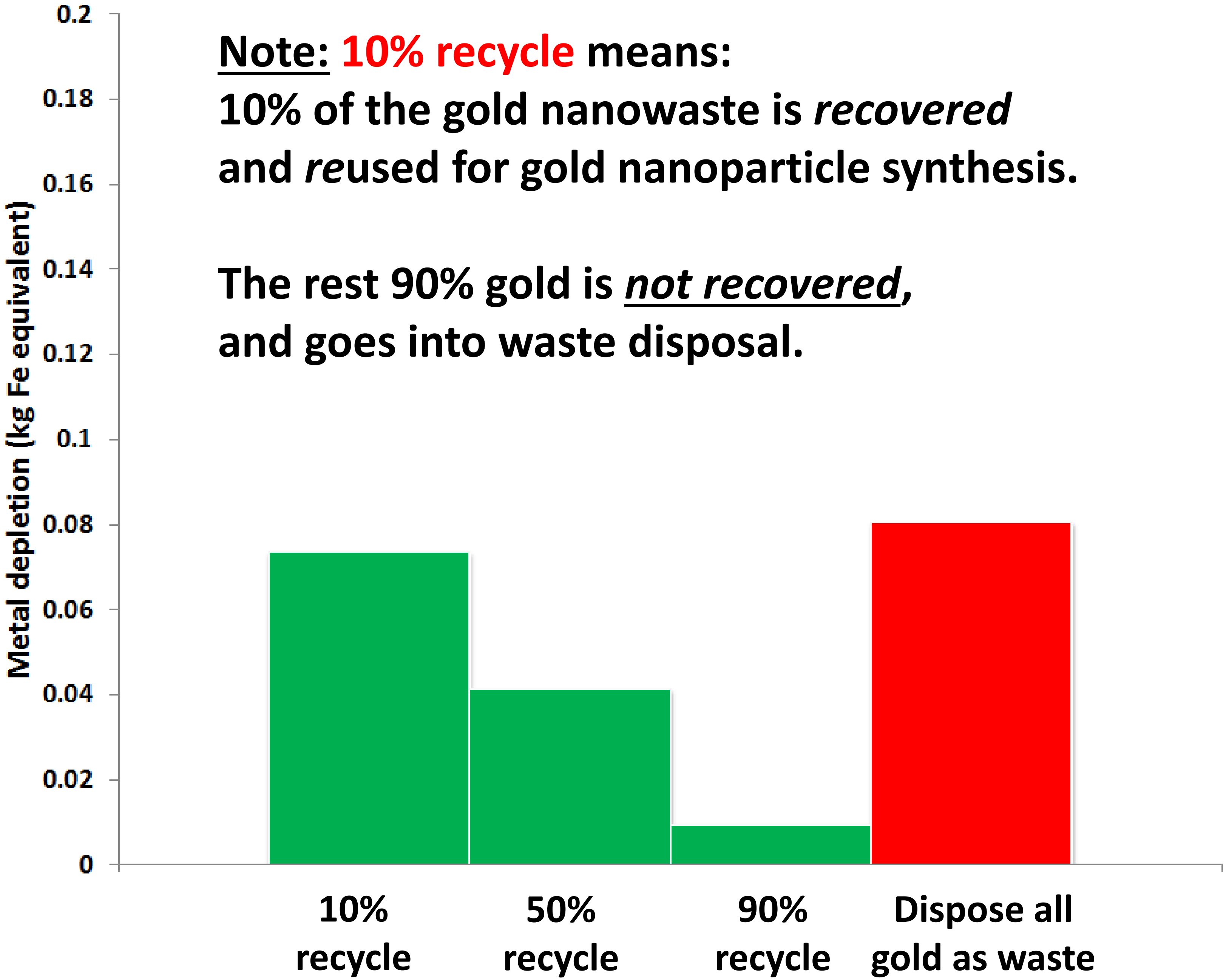
Synthesis

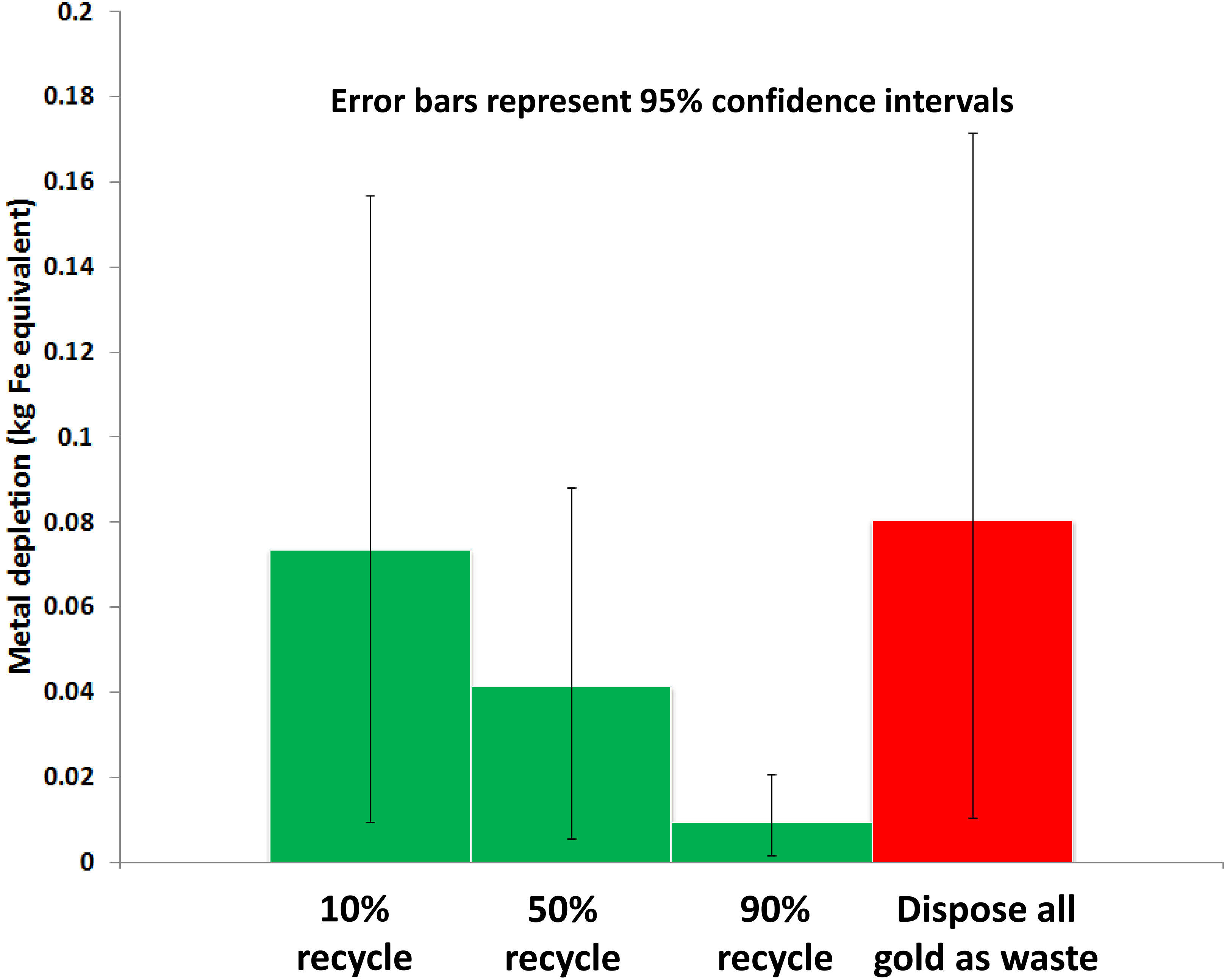
Recycling

Actual LCA model for 90% recycle scenario

<u>Note:</u> 10% recycle means:
10% of the gold nanowaste is *recovered* and *re*used for gold nanoparticle synthesis.

The rest 90% gold is *<u>not recovered</u>*, and goes into waste disposal.




Error bars represent 95% confidence intervals
Metal depletion (kg Fe equivalent)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
10% recycle
50% recycle
90% recycle
Dispose all gold as waste


Hmm.. overlapping error bars… means the difference isn't statistically significant, right? Makes no difference whether we recycle or not…
WRONG! You have correlated uncertainties!

Correlated uncertainties in LCA: An example

Comparing 1 kg of product A vs. 1 kg of Product B:

	Product A	Product B
Aluminium	1 kg	0.8 kg
Cast iron	1 kg	0.8 kg
Polystyrene	1 kg	0.8 kg

(Product B uses 20% less inputs compared to Product A. There are no extra, hidden inputs in products A and B)

Q: Which of the two has a lower environmental impact?

a) Product A
b) Product B 
c) It depends
d) Is this a trick question?

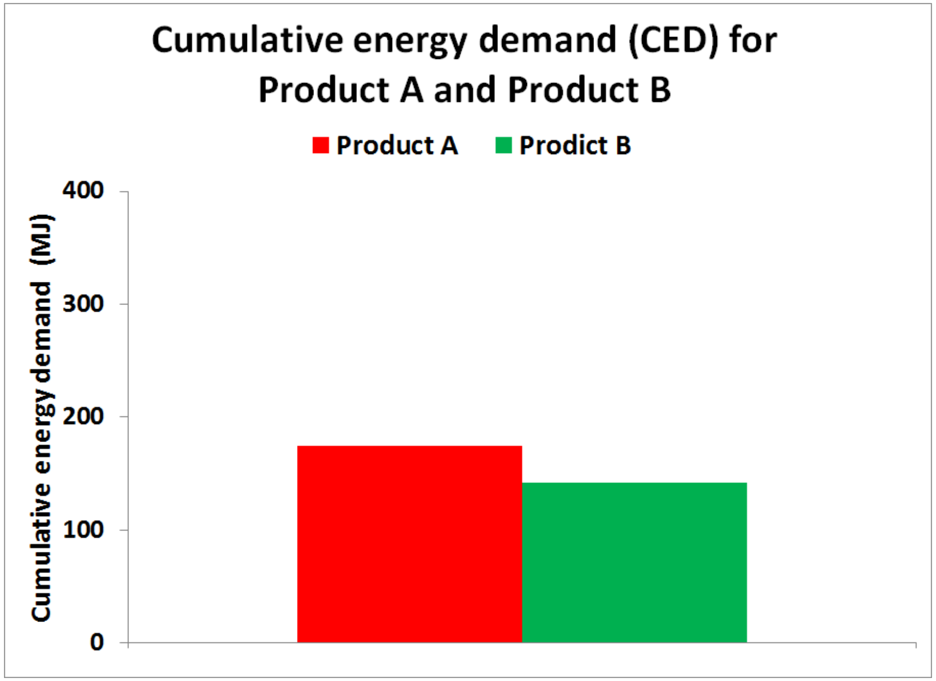
Q: Which of the two has a lower environmental impact?

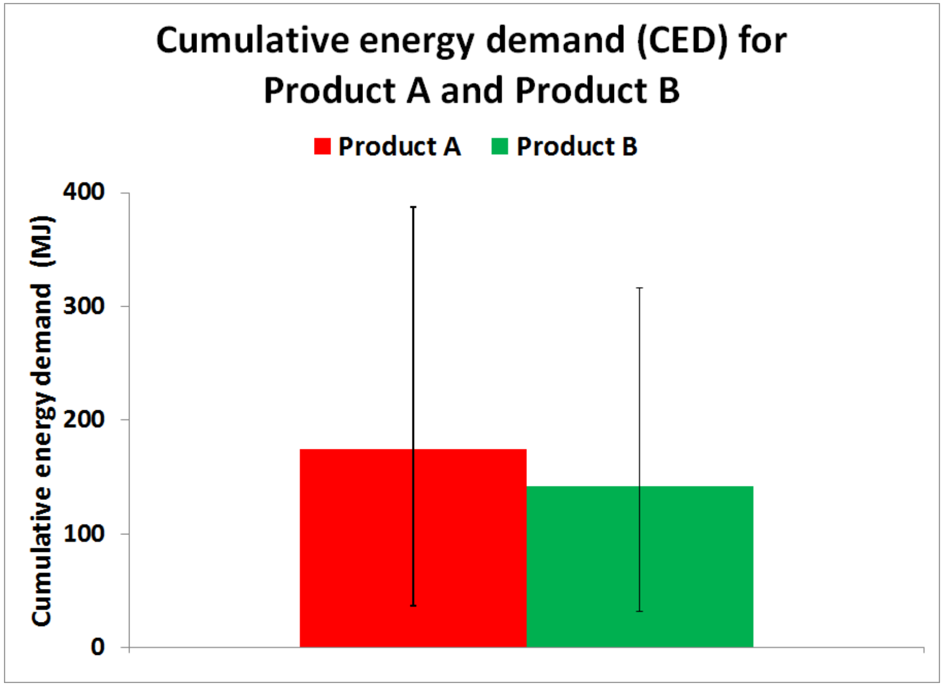
a) **Product A**

b) **Product B** 

c) **It depends**

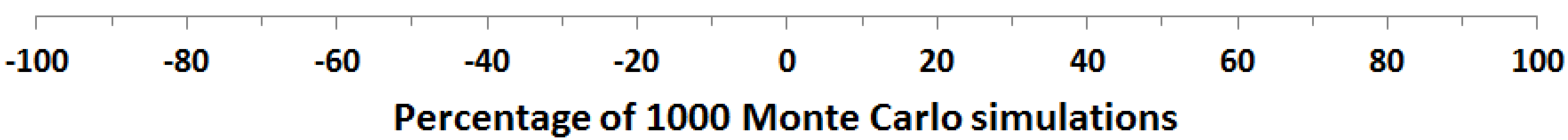
d) **Is this a trick question?**

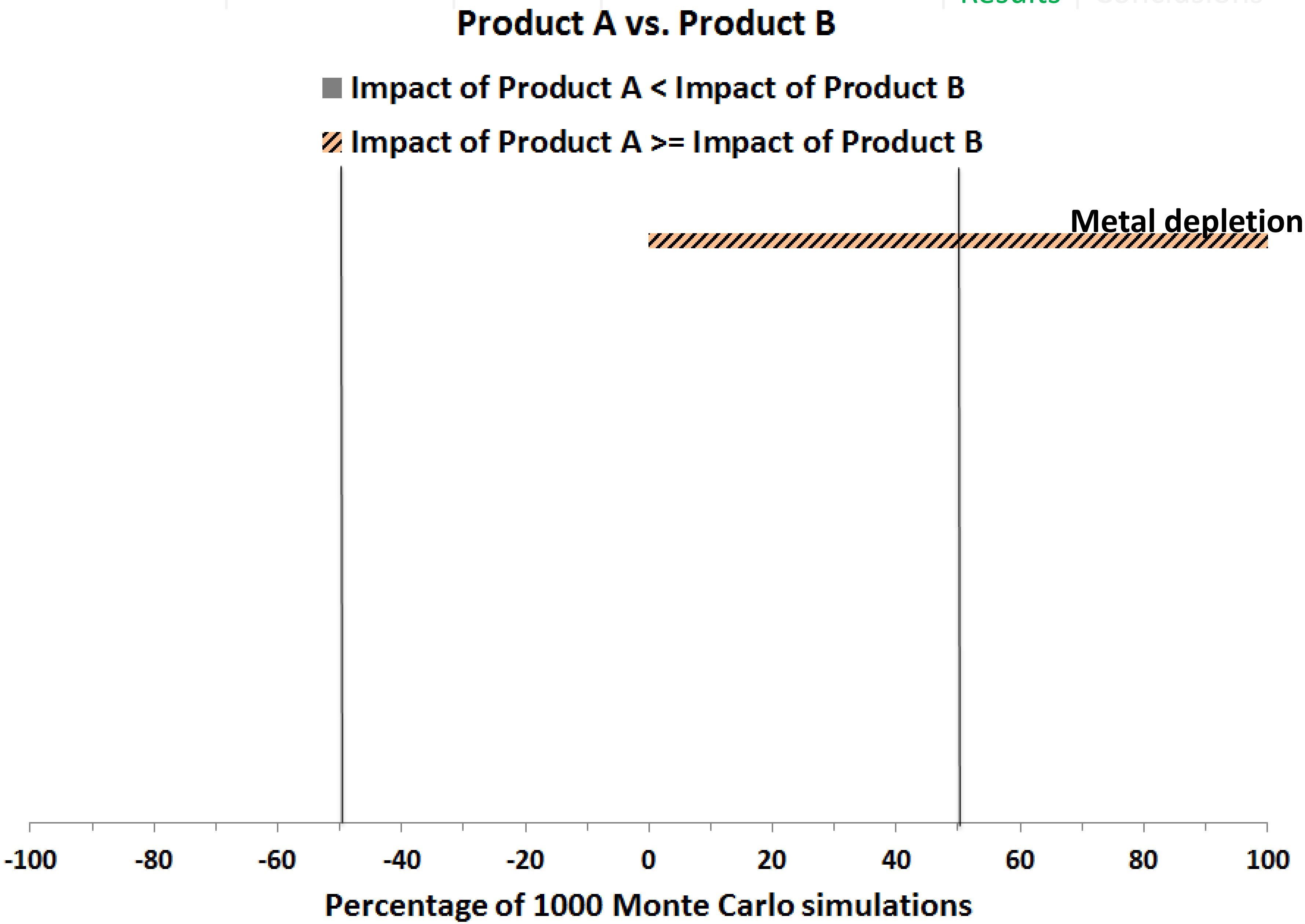


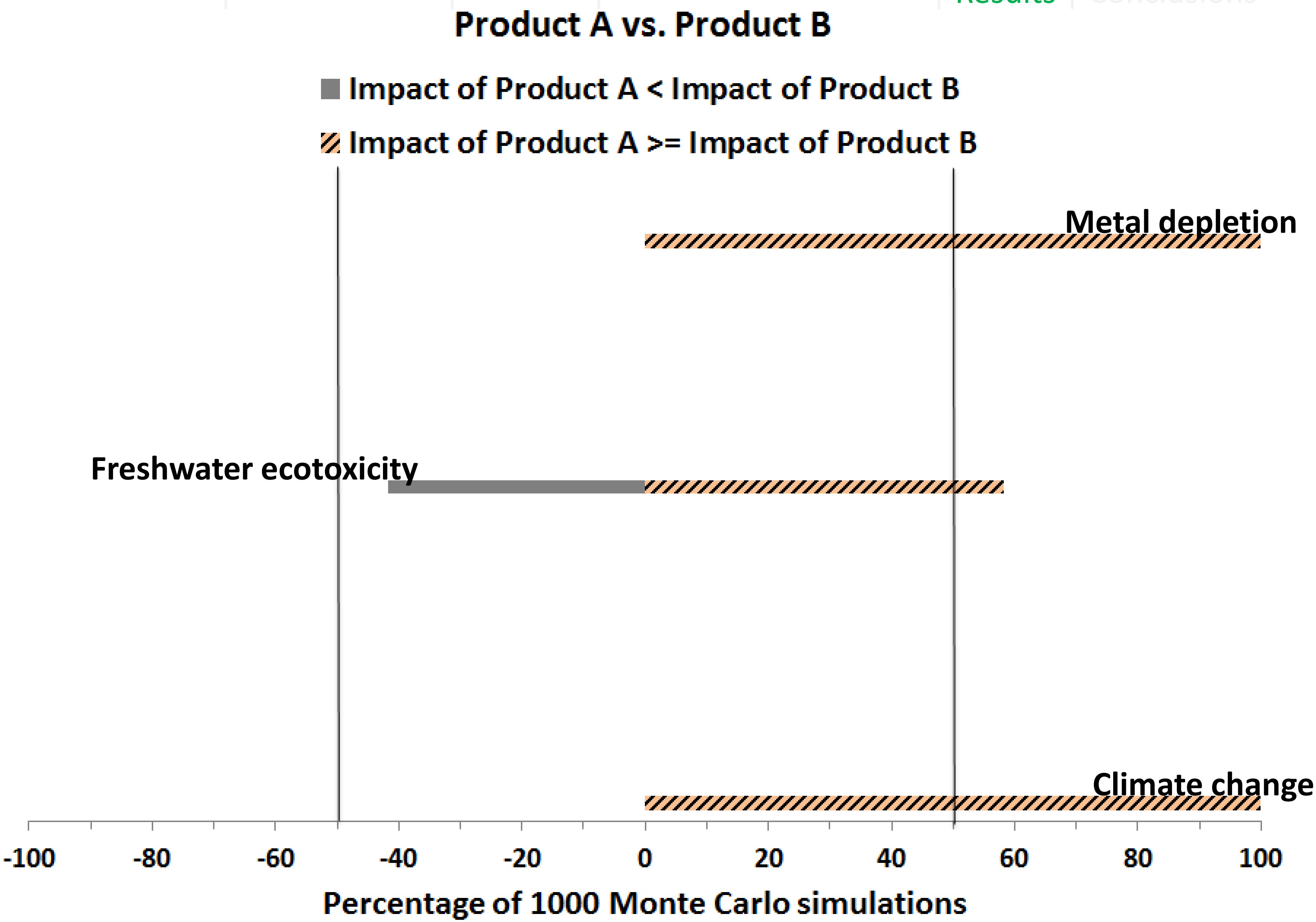


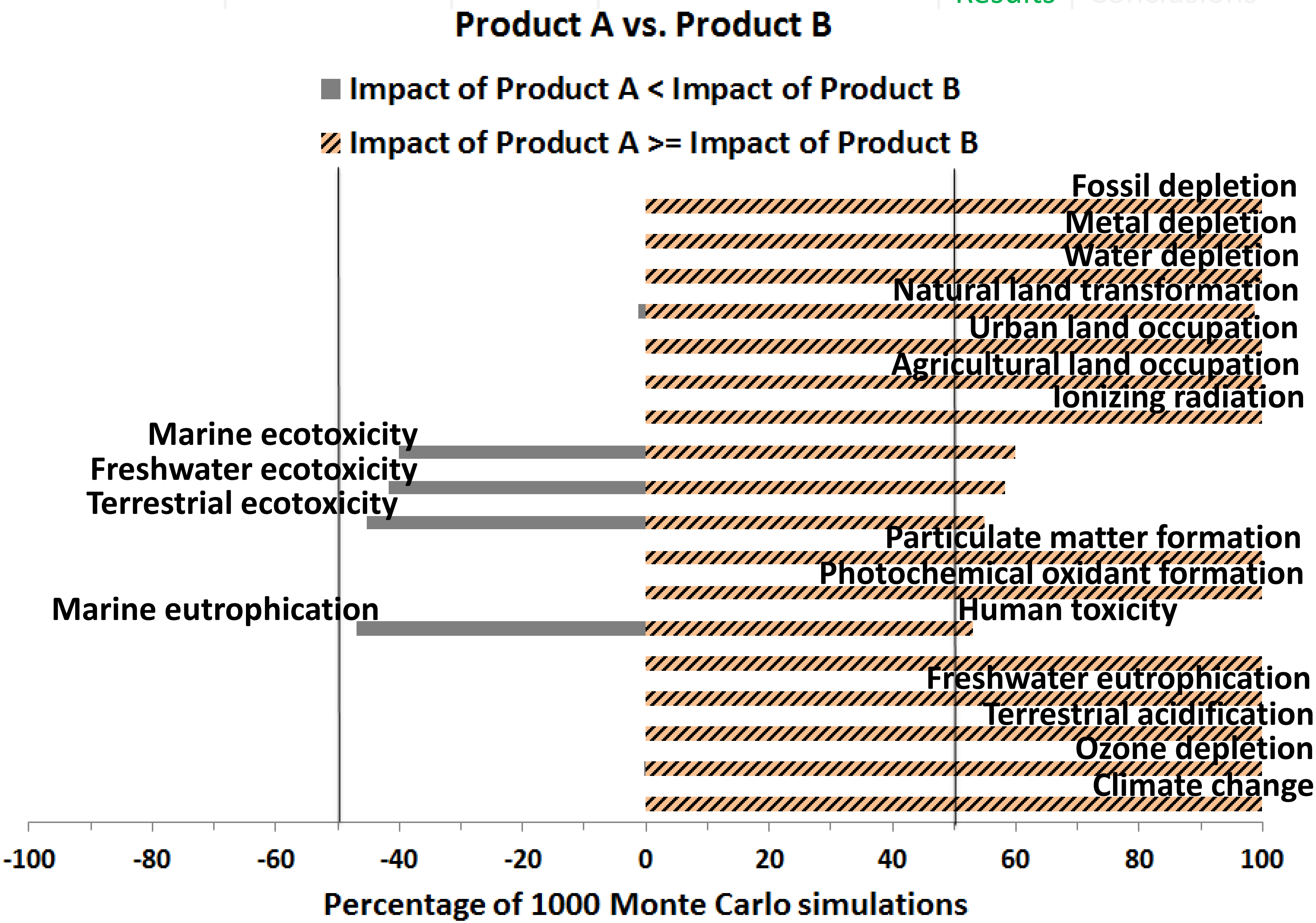
The key here: correlated uncertainties.

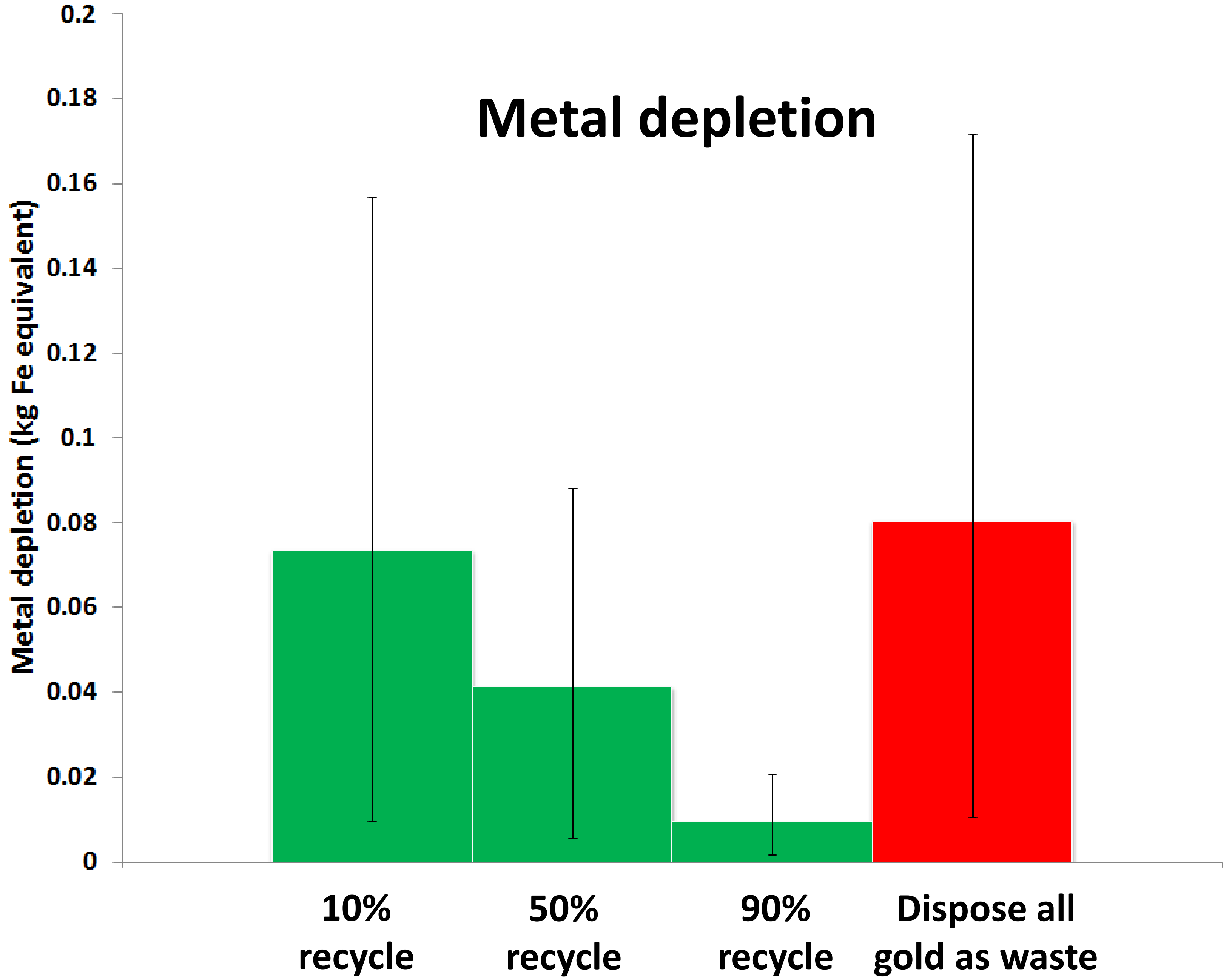
All three inputs (aluminium, cast iron and polystyrene) have uncertainties that are *common* to both Product A and Product B.


-100
-80
-60
-40
-20
0
20
40
60
80
100
Percentage of 1000 Monte Carlo simulations

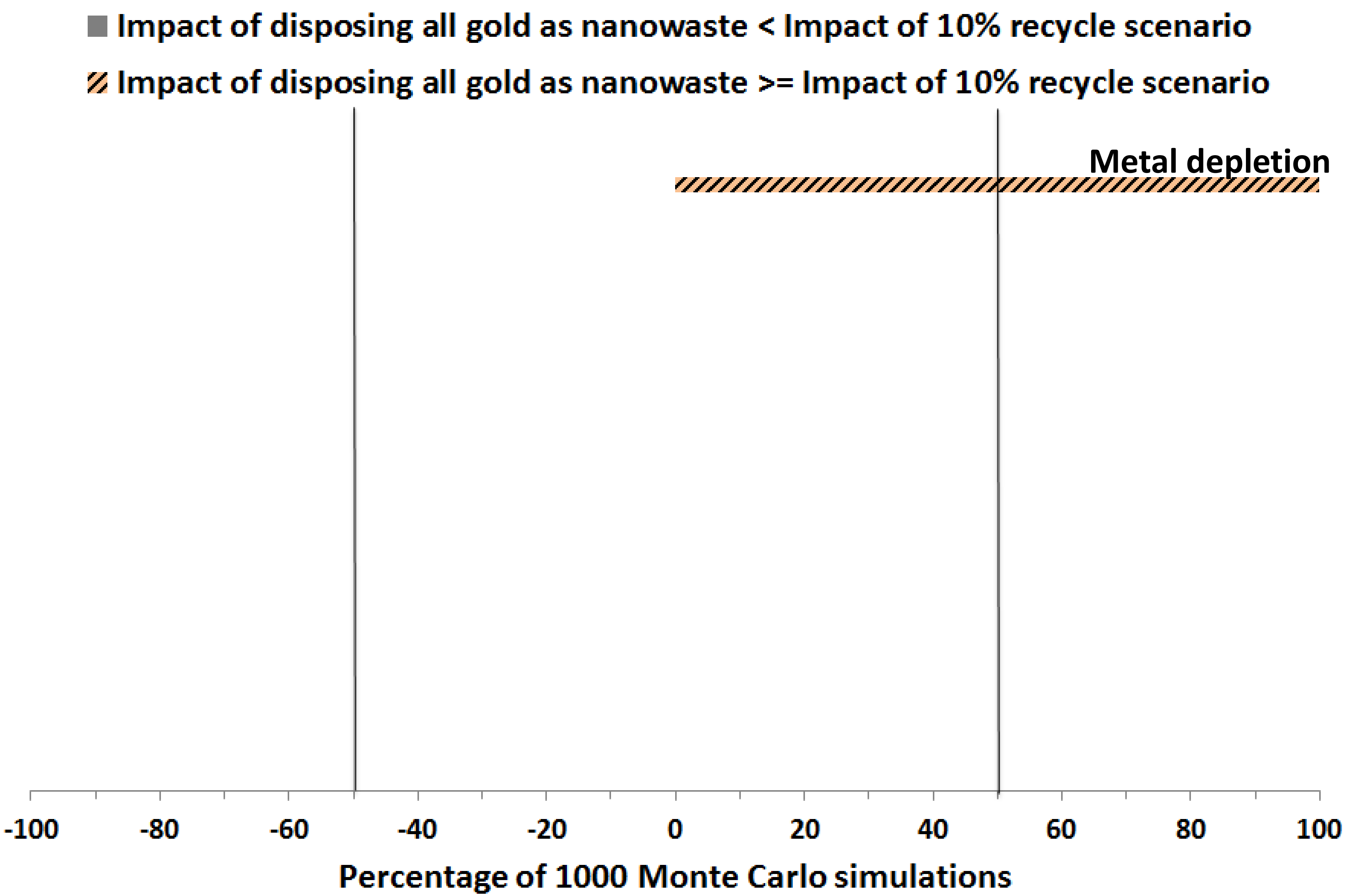

Product A vs. Product B
Impact of Product A < Impact of Product B
Impact of Product A >= Impact of Product B
Metal depletion
-100
-80
-60
-40
-20
0
20
40
60
80
100
Percentage of 1000 Monte Carlo simulations


Product A vs. Product B
Impact of Product A < Impact of Product B
Impact of Product A >= Impact of Product B
Metal depletion
Freshwater ecotoxicity
Climate change
-100
-80
-60
-40
-20
0
20
40
60
80
100
Percentage of 1000 Monte Carlo simulations

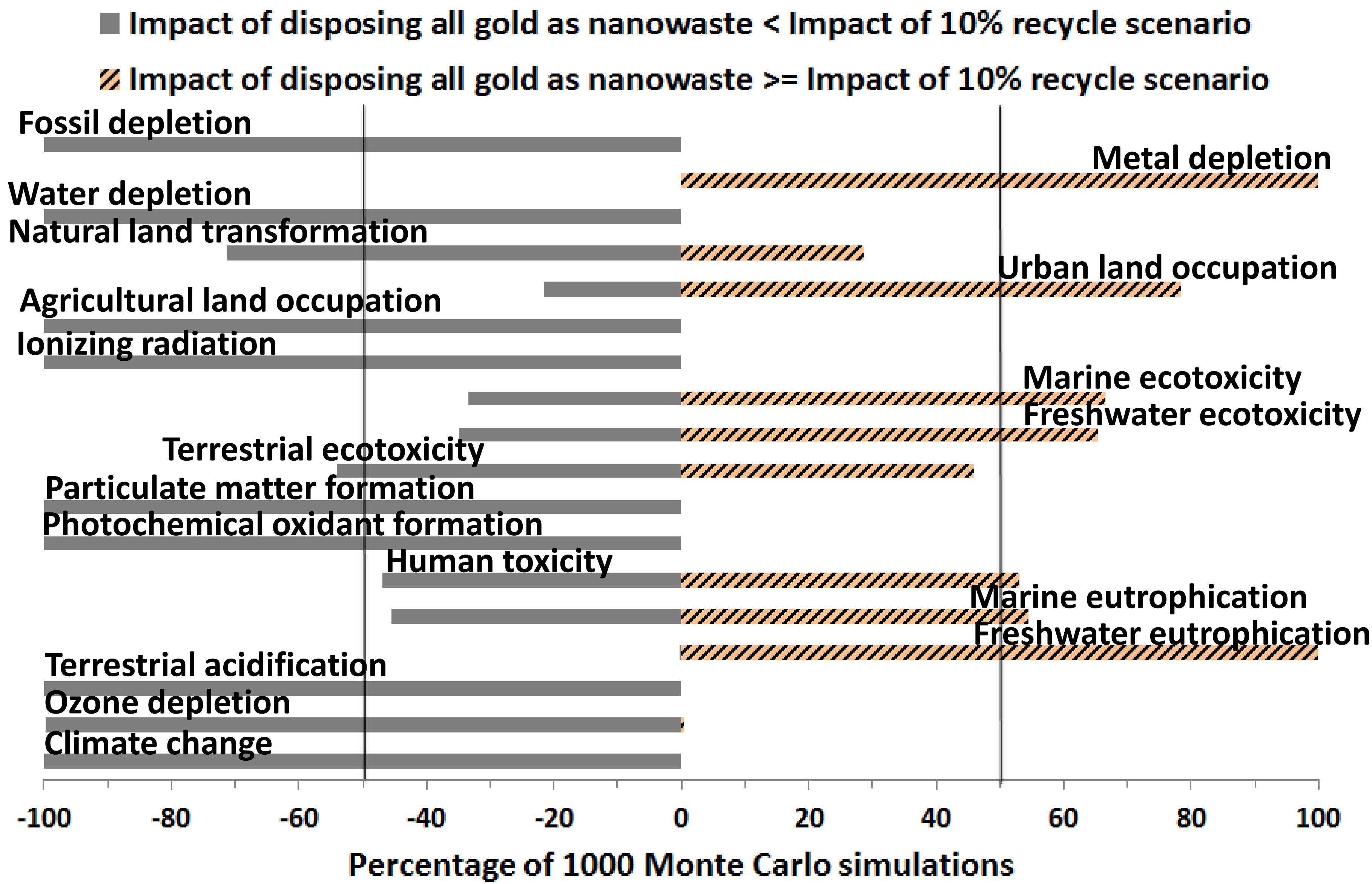

Product A vs. Product B
Impact of Product A < Impact of Product B
Impact of Product A >= Impact of Product B
Fossil depletion
Metal depletion
Water depletion
Natural land transformation
Urban land occupation
Agricultural land occupation
Ionizing radiation
Marine ecotoxicity
Freshwater ecotoxicity
Terrestrial ecotoxicity
Particulate matter formation
Photochemical oxidant formation
Marine eutrophication
Human toxicity
Freshwater eutrophication
Terrestrial acidification
Ozone depletion
Climate change
-100
-80
-60
-40
-20
0
20
40
60
80
100
Percentage of 1000 Monte Carlo simulations


Metal depletion
Metal depletion (kg Fe equivalent)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
10% recycle
50% recycle
90% recycle
Dispose all gold as waste

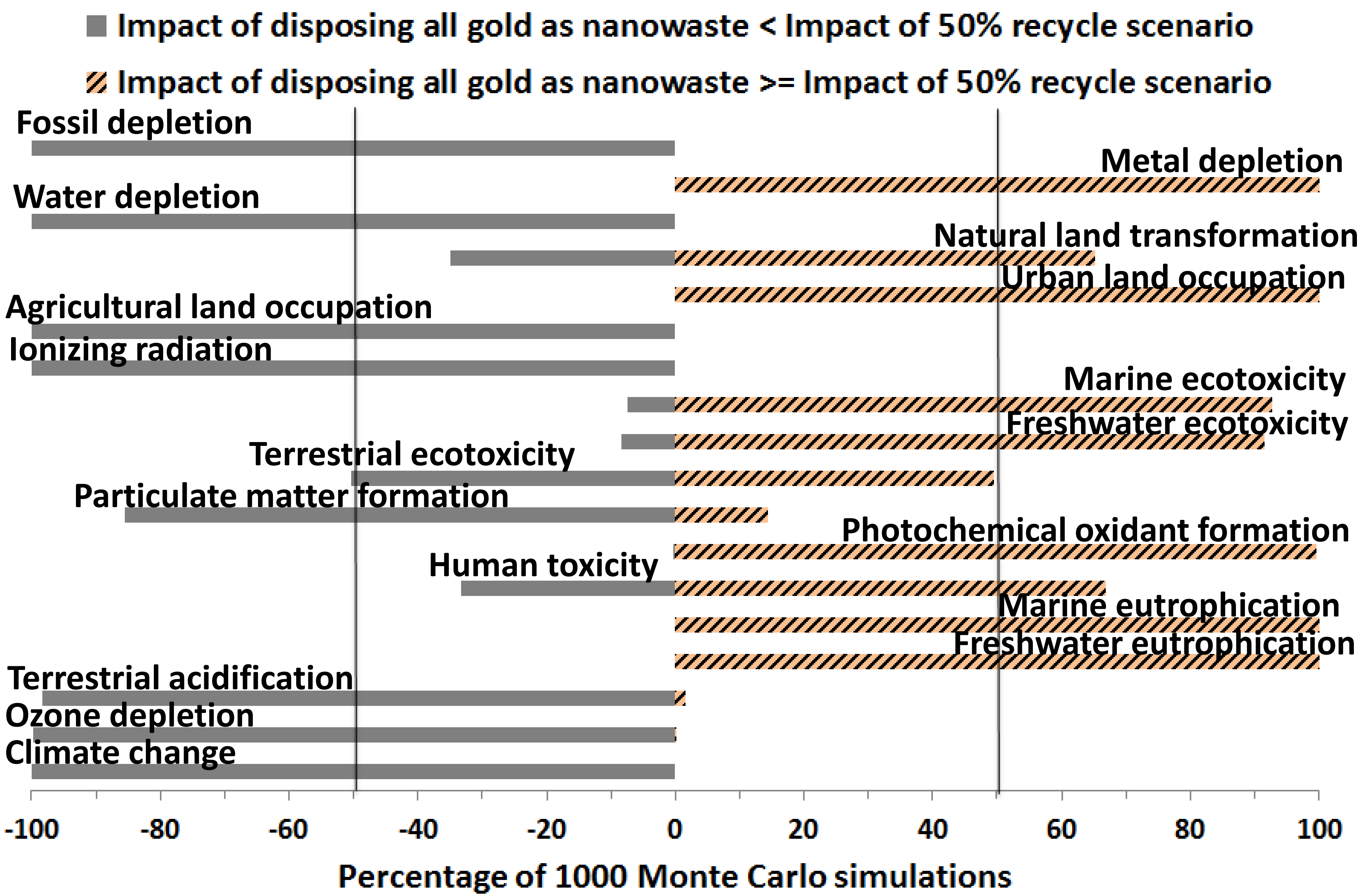
Disposing all gold as nanowaste vs. 10% recycle scenario



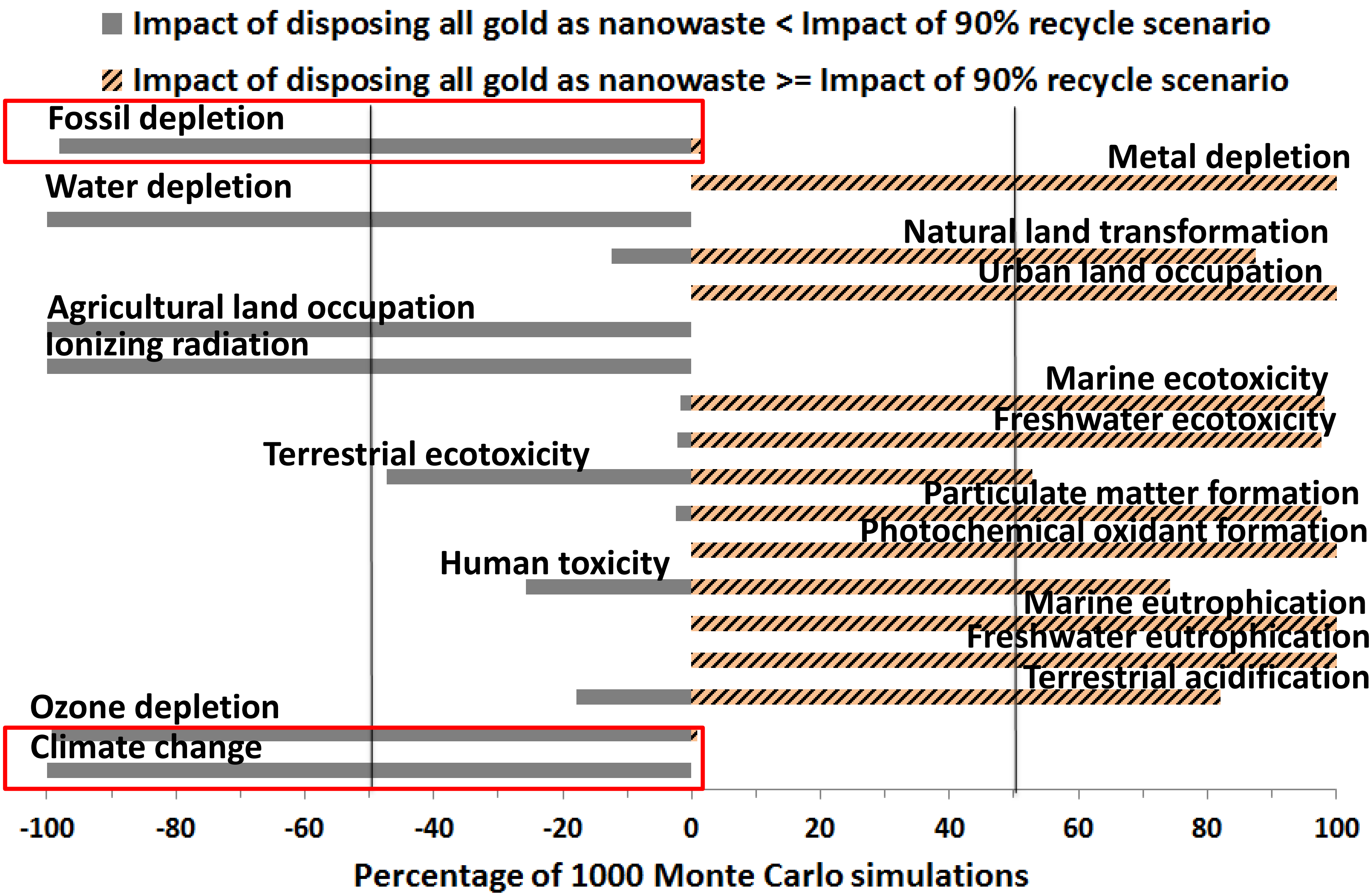
Disposing all gold as nanowaste vs. 10% recycle scenario



Disposing all gold as nanowaste vs. 50% recycle scenario



Disposing all gold as nanowaste vs. 90% recycle scenario



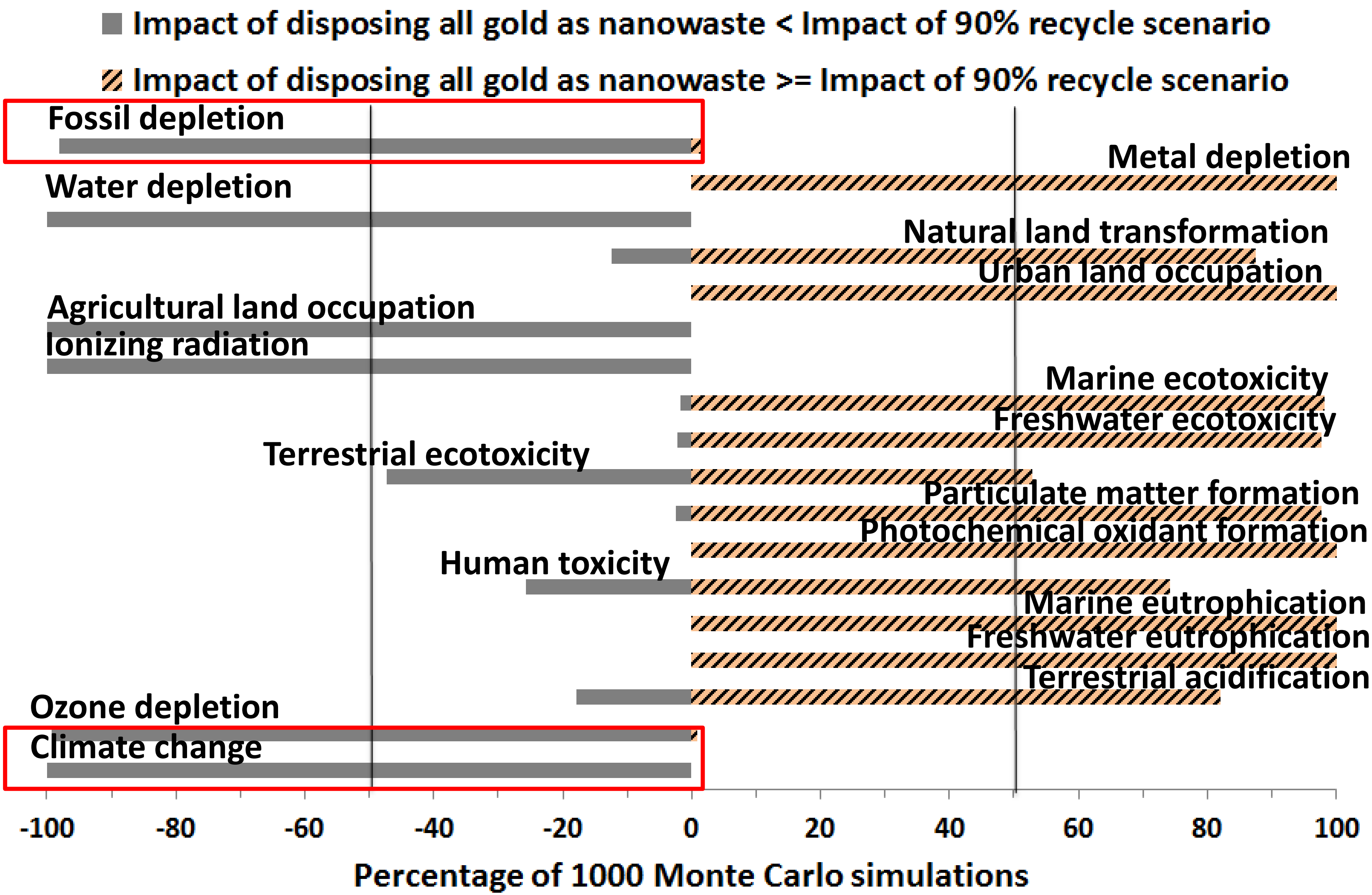
Synthesis

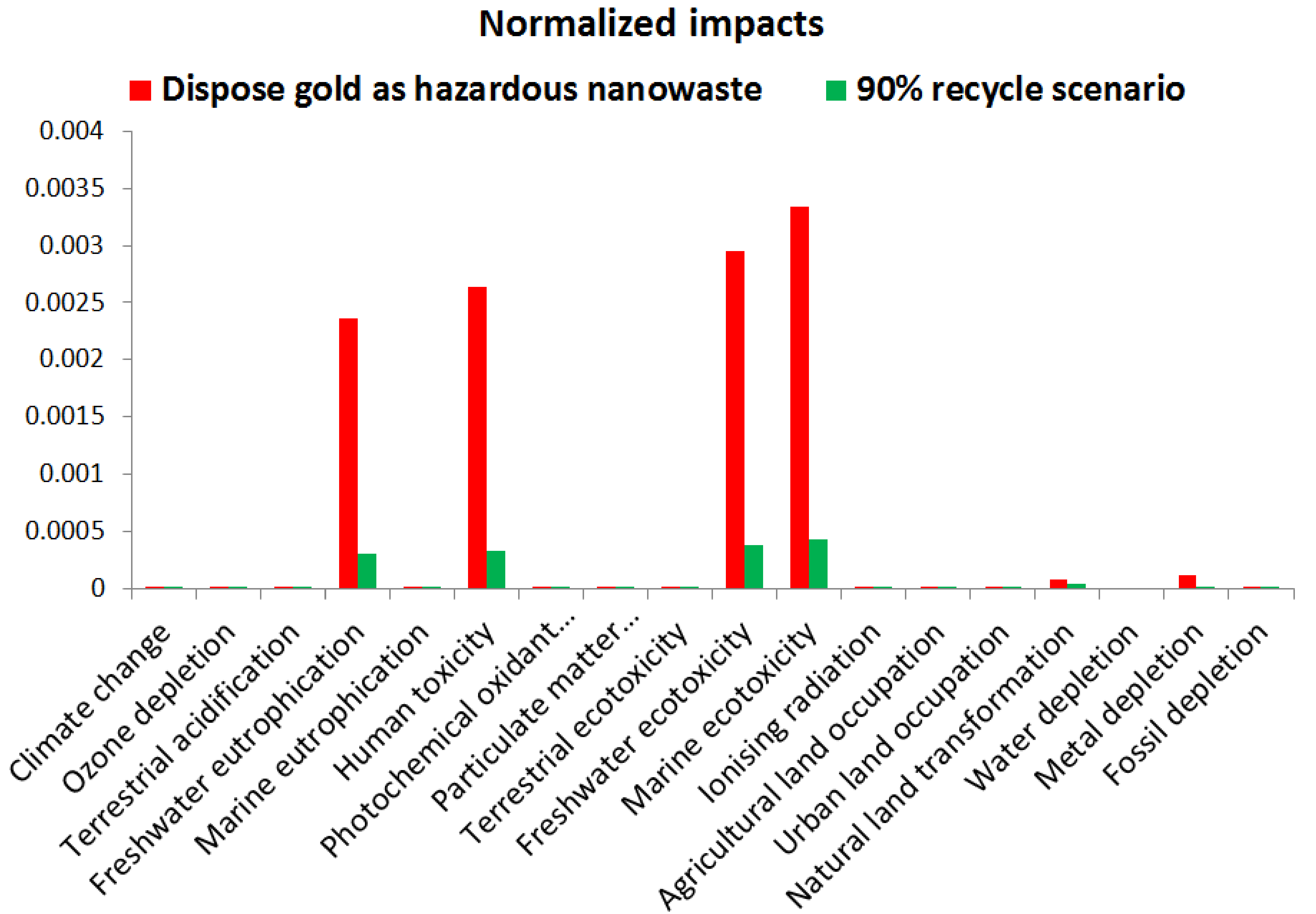
Recycling

High impacts in climate change and fossil fuel depletion are driven by mainly the iling step in the recovery process.

90% recycle scenario

Disposing all gold as nanowaste vs. 90% recycle scenario

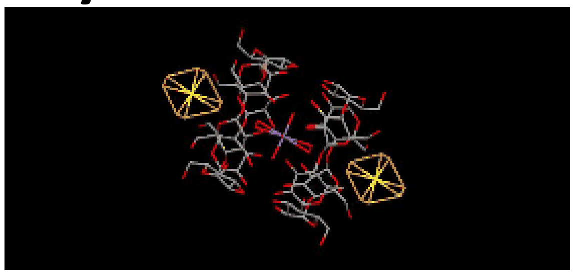




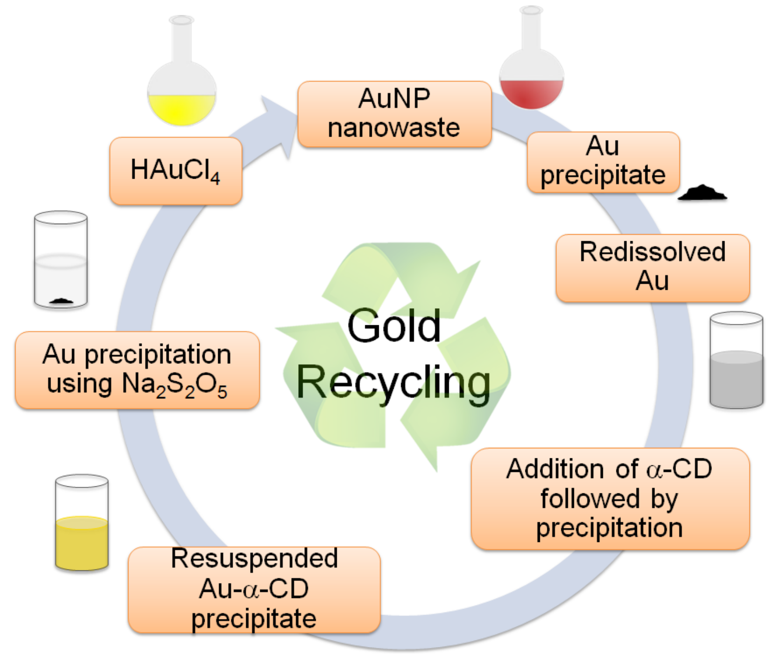
Normalized impacts
Dispose gold as hazardous nanowaste
90% recycle scenario
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
Climate change
Ozone depletion
Terrestrial acidification
Freshwater eutrophication
Marine eutrophication
Human toxicity
Photochemical oxidant...
Particulate matter...
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Ionising radiation
Agricultural land occupation
Urban land occupation
Natural land transformation
Water depletion
Metal depletion
Fossil depletion

Conclusion:

Gold recovery from nanowaste is feasible



Even at low yields, recovery beats regular gold nanowaste disposal



Challenges:

Reducing the energy footprint of the recovery step.

Refining the models to account for different waste disposal and recovery scenarios (e.g., recovery but no reuse).

Acknowledgments

Dr. Sean McGinnis
Director, **Green Engineering Program**, Virginia Tech

Leejoo Wi
Undergraduate researcher
(Vikesland group)

Virginia **T**ech Centre for **Su**stainable **N**anotechnology (**VTSuN**)

Institute for **C**ritical **T**echnology and **A**pplied **S**cience (**ICTAS**)

Email: pvikes@vt.edu

VirginiaTech
Invent the Future

CEINT
Center for the Environmental Implications of NanoTechnology

Spam slides

Here be dragons…

Synthesis

Recycling

$HAuCl_4$

2

1

Gold

1: Gold obtained from mining

2: Gold from recycling

90% recycle

Synthesis

Recycling

2

1

1: Gold obtained from mining

2: Gold from recycling

50% recycle

Synthesis

Recycling

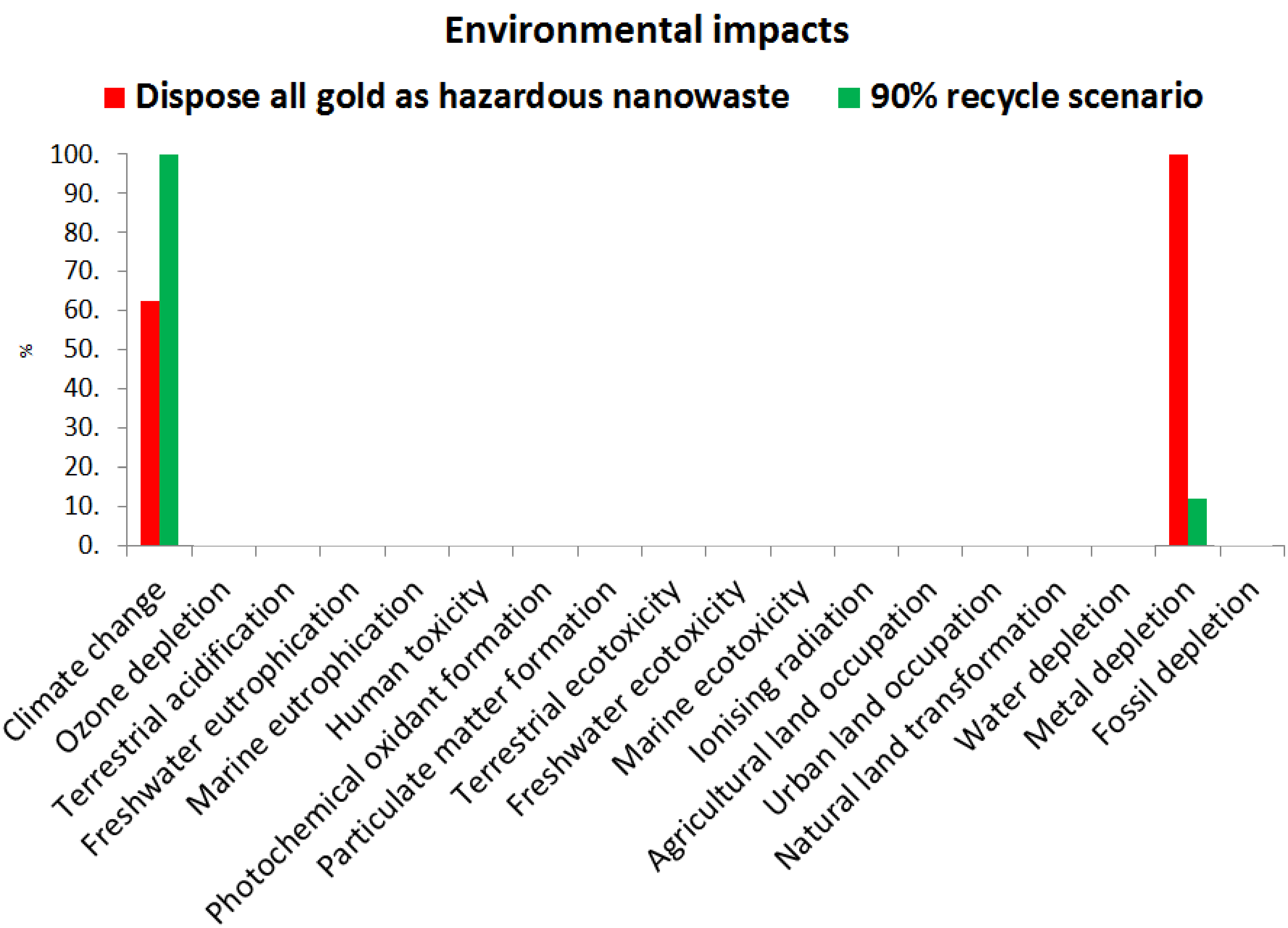
2

1

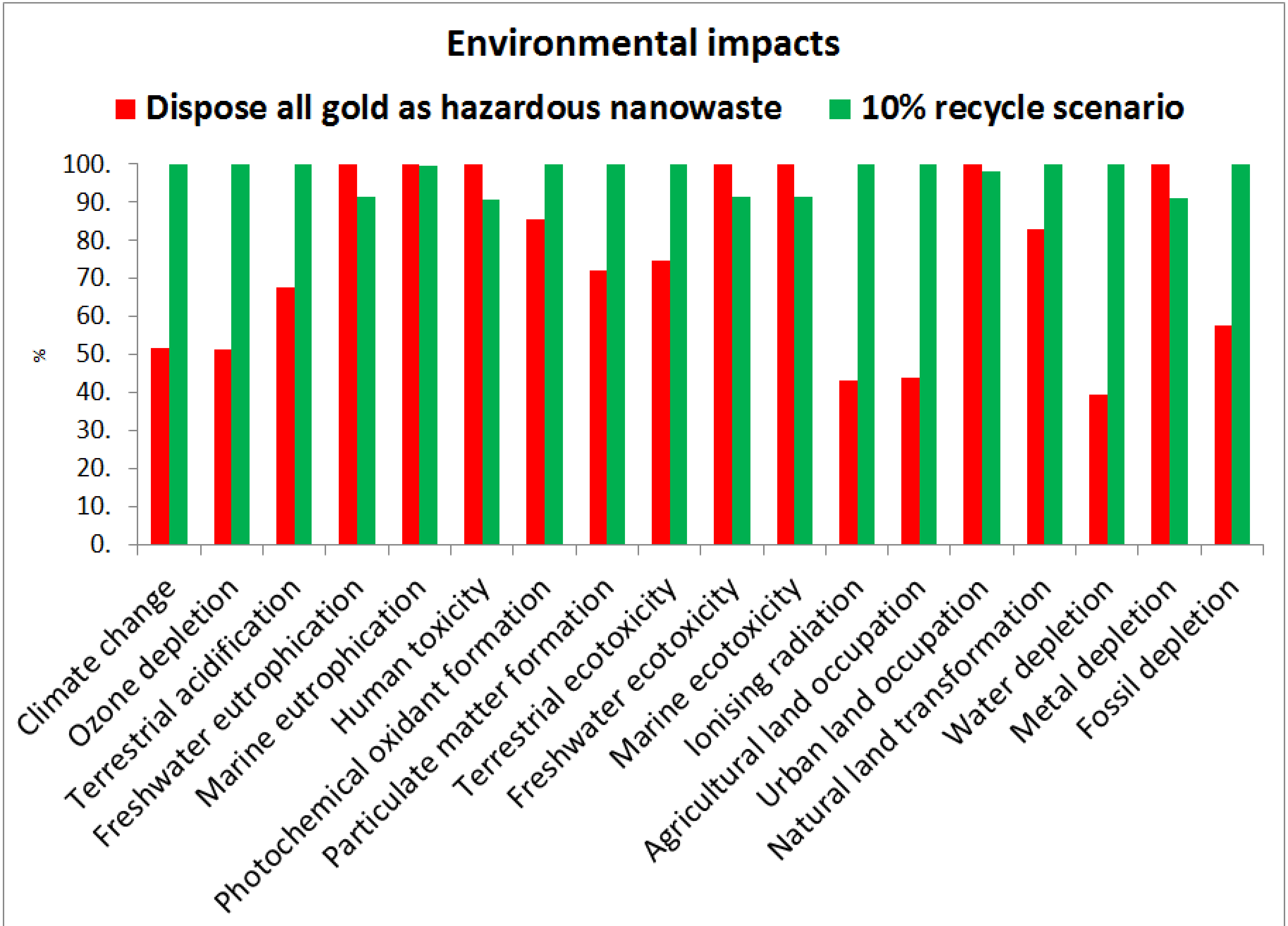
1: Gold obtained from mining

2: Gold from recycling

10% recycle



Environmental impacts
Dispose all gold as hazardous nanowaste
90% recycle scenario
%
100.
90.
80.
70.
60.
50.
40.
30.
20.
10.
0.
Climate change
Ozone depletion
Terrestrial acidification
Freshwater eutrophication
Marine eutrophication
Human toxicity
Photochemical oxidant formation
Particulate matter formation
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Ionising radiation
Agricultural land occupation
Urban land occupation
Natural land transformation
Water depletion
Metal depletion
Fossil depletion



Environmental impacts
Dispose all gold as hazardous nanowaste
10% recycle scenario
%
100.
90.
80.
70.
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30.
20.
10.
0.
Climate change
Ozone depletion
Terrestrial acidification
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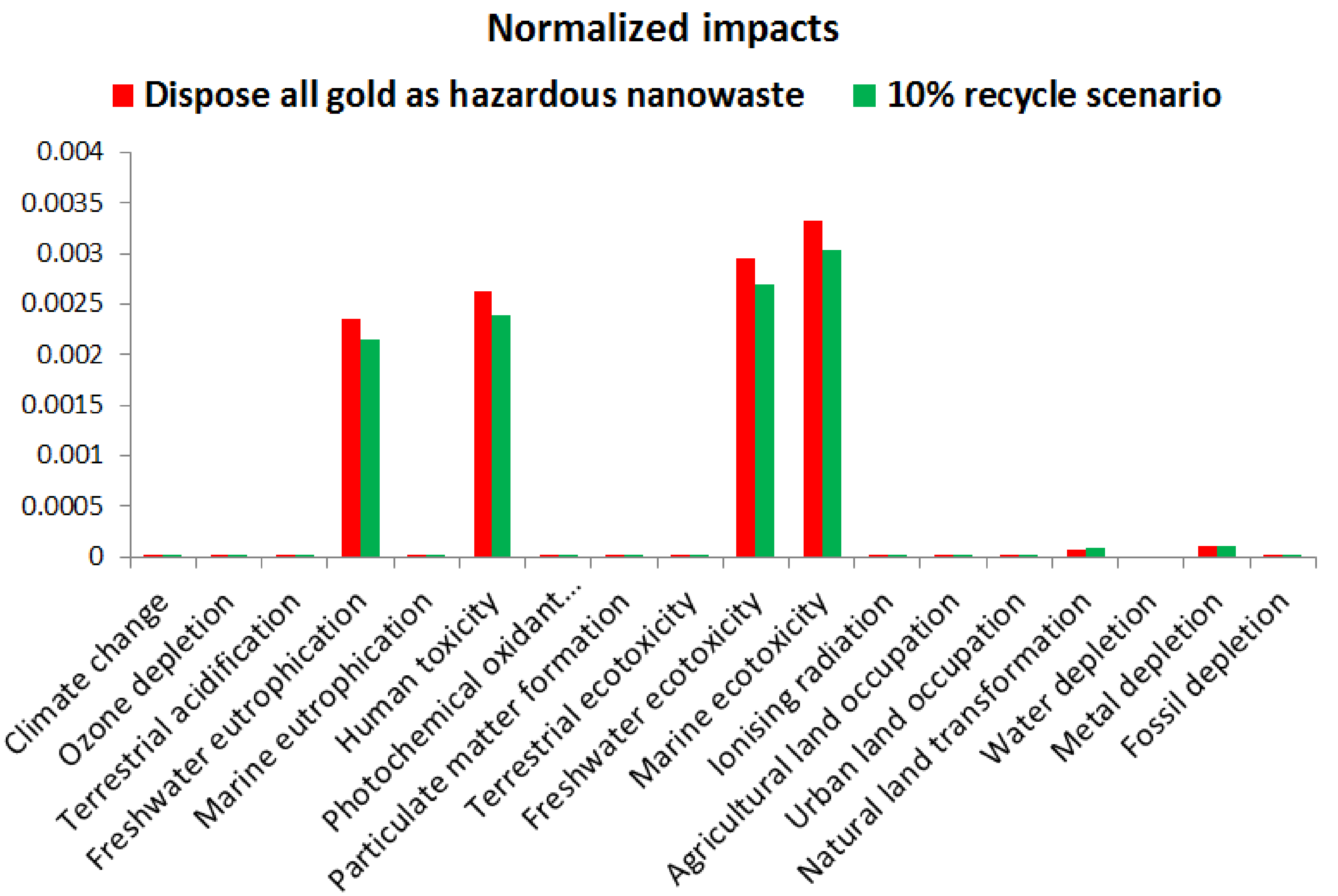
Normalized impacts
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0.004
0.0035
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0.0025
0.002
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0.0005
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Climate change
Ozone depletion
Terrestrial acidification
Freshwater eutrophication
Marine eutrophication
Human toxicity
Photochemical oxidant...
Particulate matter formation
Terrestrial ecotoxicity
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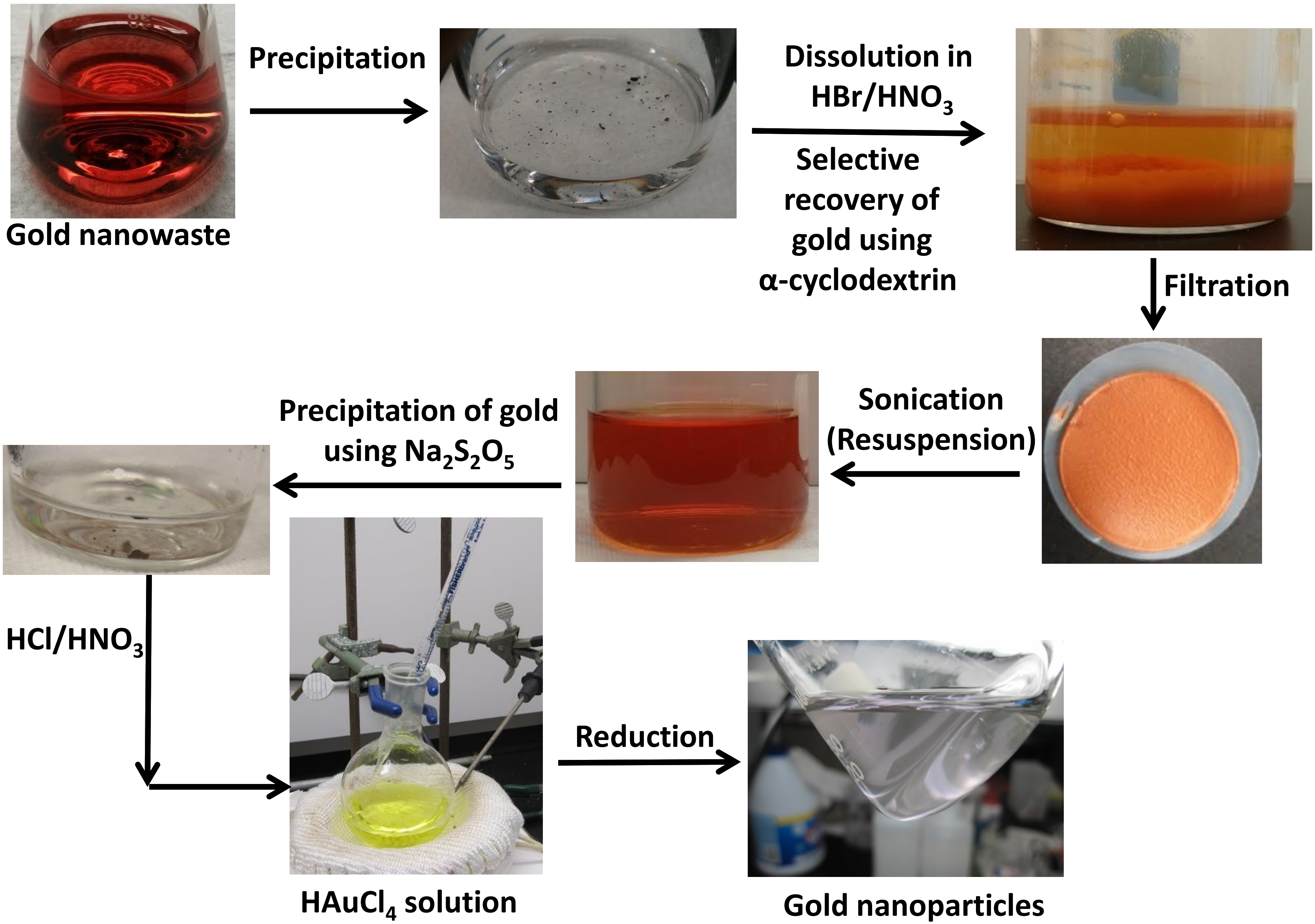
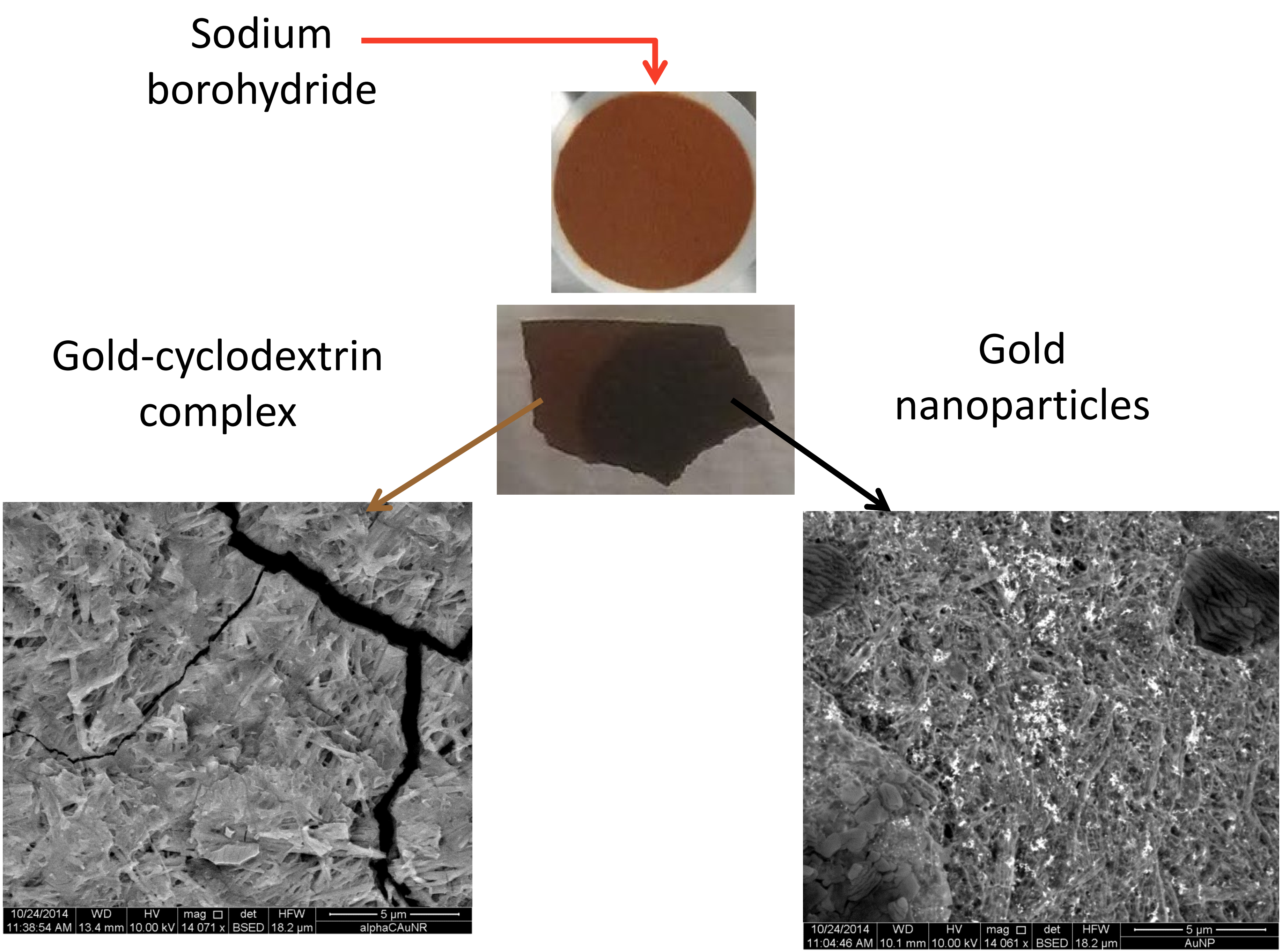
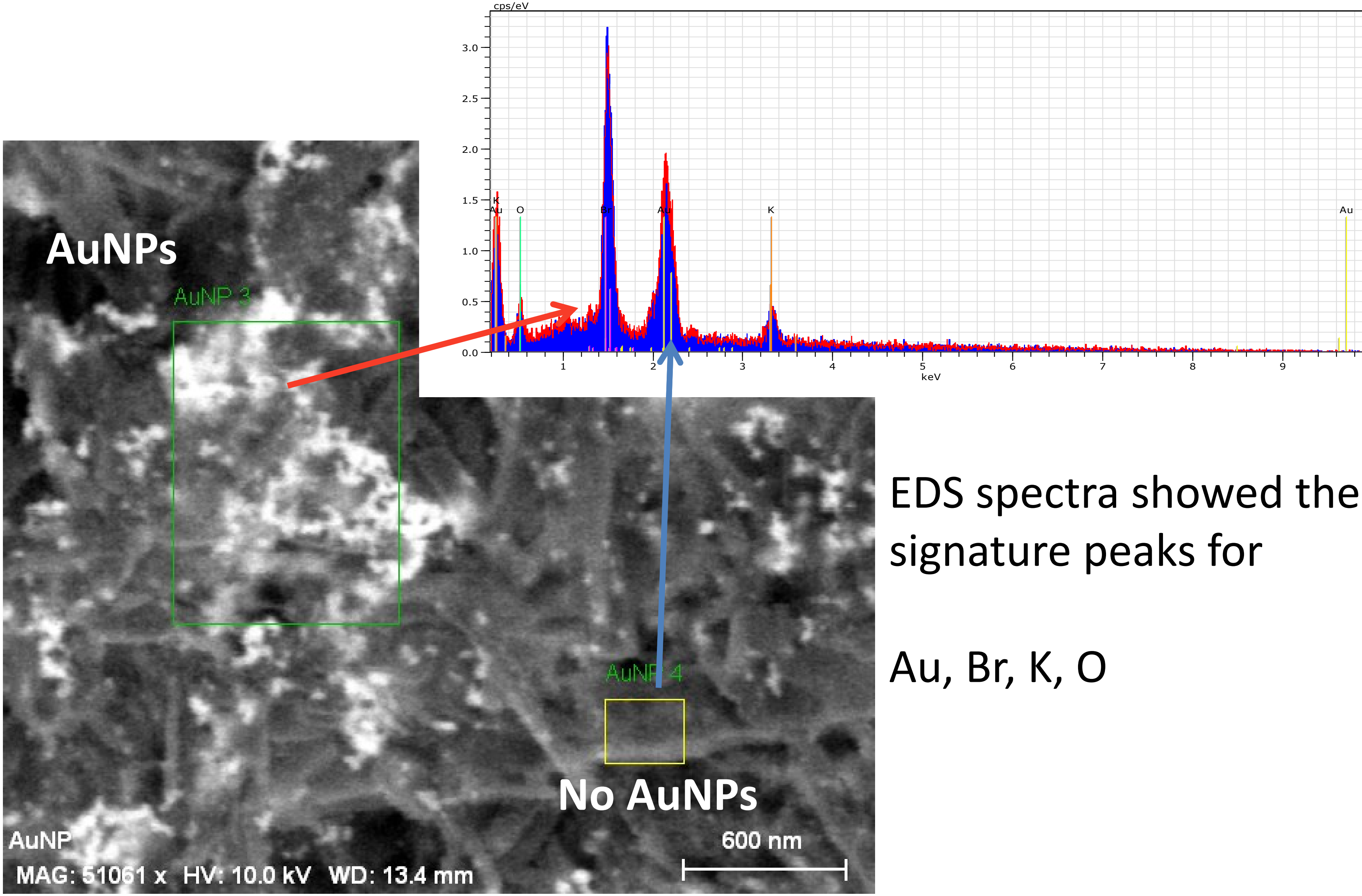
Metal depletion
Fossil depletion


Gold nanowaste
Precipitation
Dissolution in HBr/HNO$_3$
Selective recovery of gold using α-cyclodextrin
Filtration
Sonication (Resuspension)
Precipitation of gold using $Na_2S_2O_5$
HCl/HNO$_3$
HAuCl$_4$ solution
Reduction
Gold nanoparticles

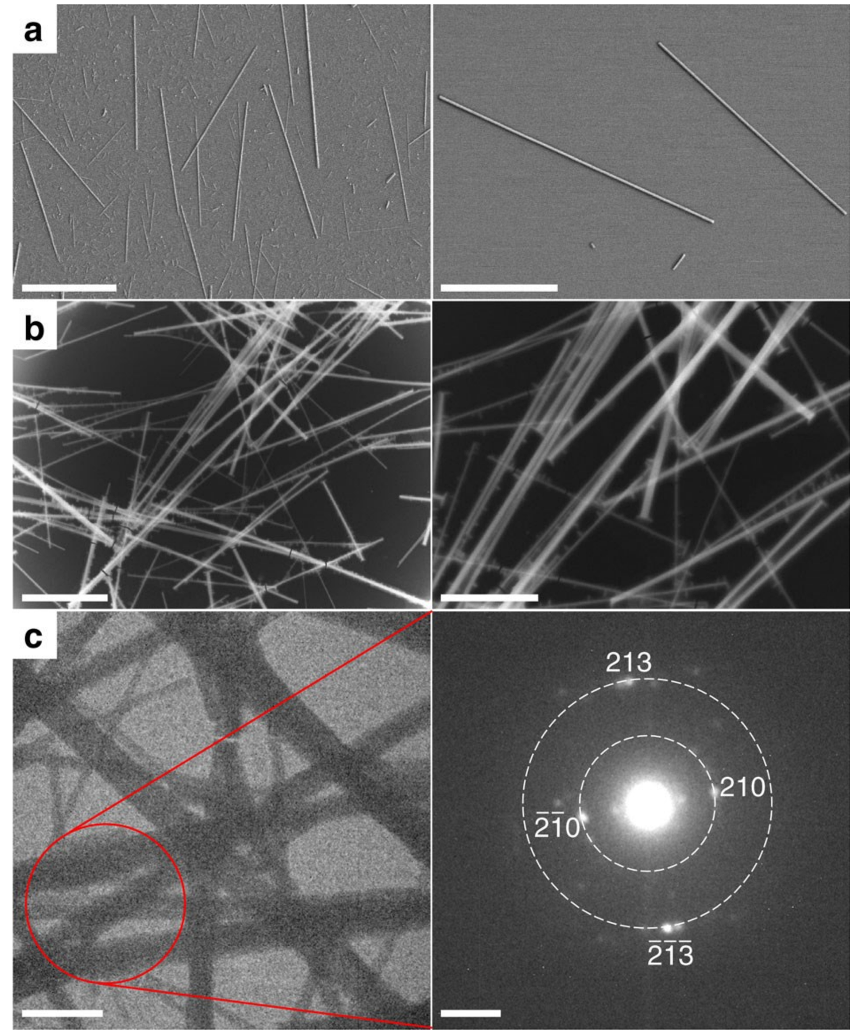

Sodium borohydride
Gold-cyclodextrin complex
Gold nanoparticles
10/24/2014 11:38:54 AM | WD 13.4 mm | HV 10.00 kV | mag 14 071 x | det BSED | HFW 18.2 µm | 5 µm | alphaCAuNR
10/24/2014 11:04:46 AM | WD 10.1 mm | HV 10.00 kV | mag 14 061 x | det BSED | HFW 18.2 µm | 5 µm | AuNP



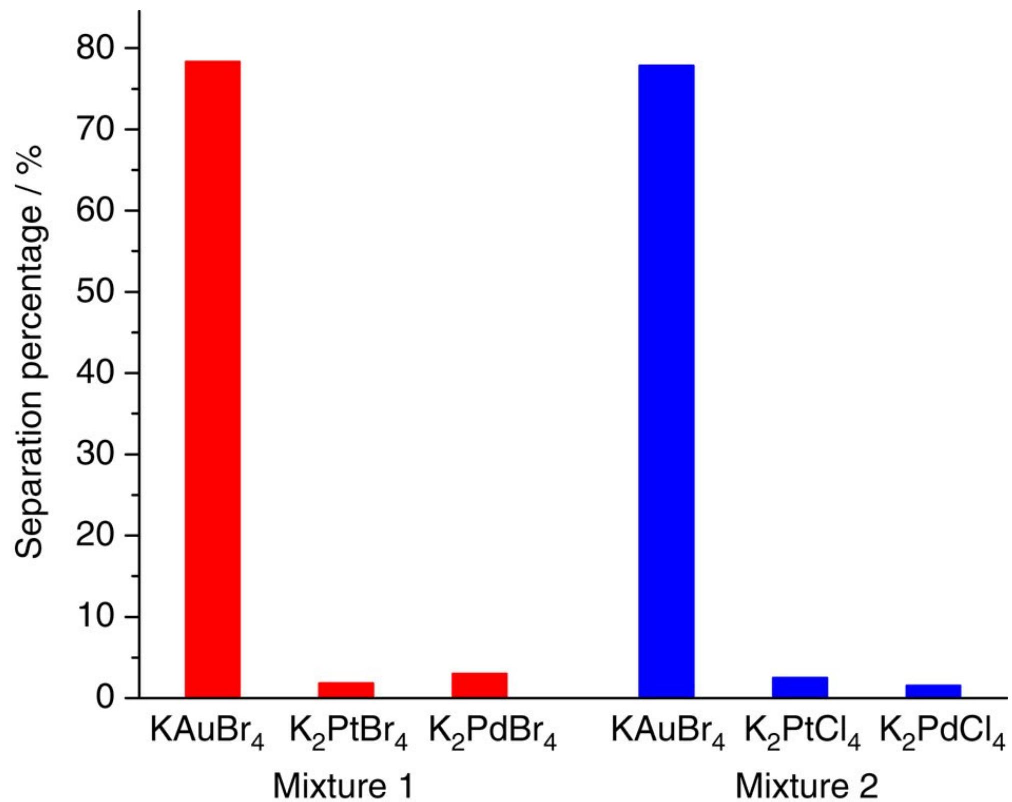
EDS spectra showed the signature peaks for

Au, Br, K, O

(**a**) SEM images of a crystalline sample prepared by spin-coating an aqueous suspension of **α·Br** onto a silicon substrate, and then air-drying the suspension. (**b**) TEM images of **α·Br** prepared by drop-casting an aqueous suspension of **α·Br** onto a specimen grid covered with a thin carbon support film and air-dried. (**c**) Cryo-TEM image (left) and SAED pattern (right) of the nanostructures of **α·Br**. As the selected area includes several crystals with different orientations and the crystals are so small that the diffraction intensities are relatively weak, we can assign the diffraction rings composed of diffraction dots but not the specific angles between different diffraction dots from the same crystal. The scale bars in **a** and **b** are 25 (left), 5 (right), 10 (left), 5 μm (right) and in **c** are 1 μm (left) and 1 nm^{-1}(right), respectively.



"Selective isolation of gold facilitated by second-sphere coordination with α-cyclodextrin". *Nature Communications,* Liu *et al.* (2013)



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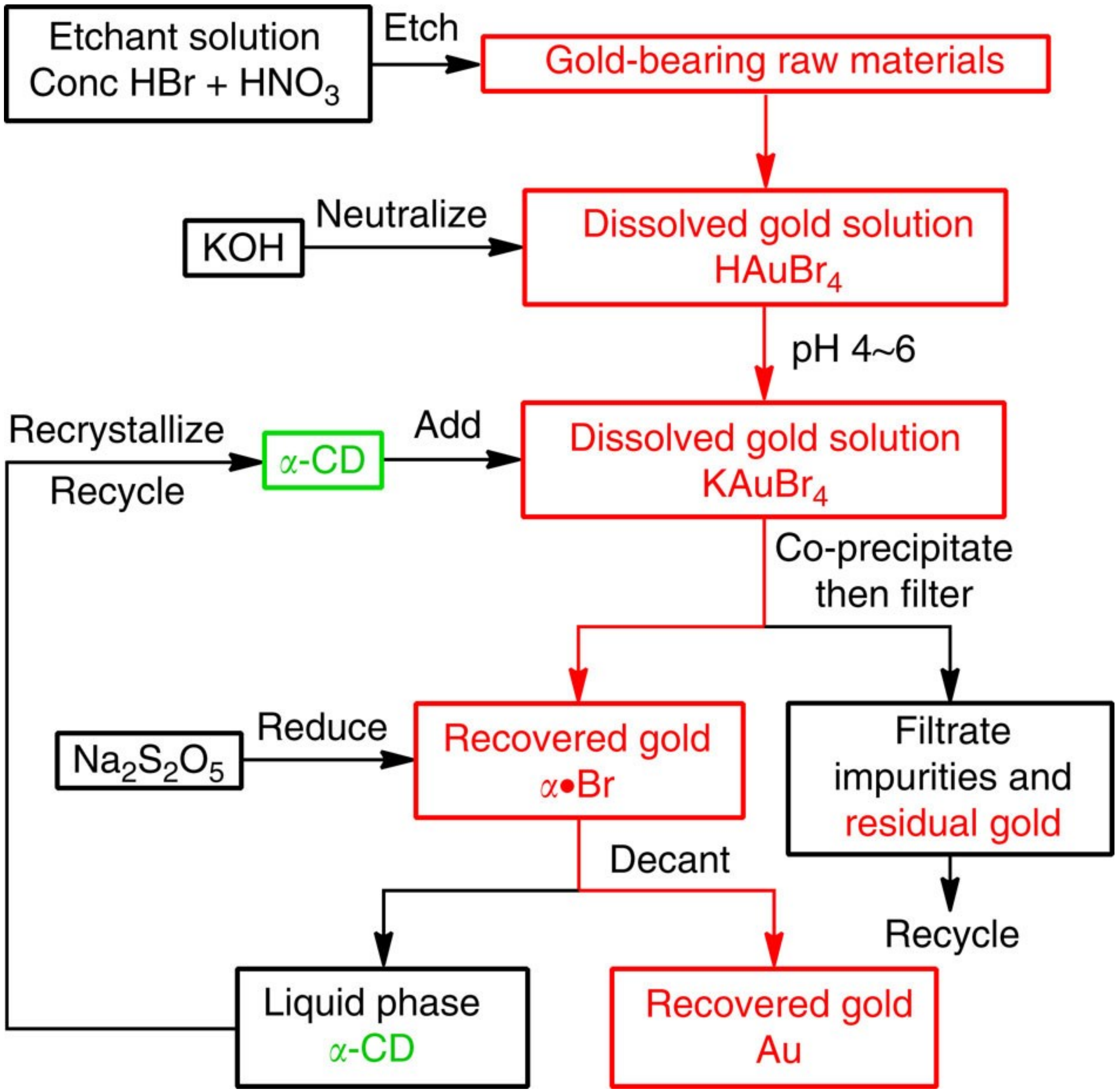

“Selective isolation of gold facilitated by second-sphere coordination with α-cyclodextrin”. *Nature Communications,* Liu *et al.* (2013)