ЗЕЛЕНА ХІМІЯ.
ЗЕЛЕНІ НАНОТЕХНОЛОГІЇ

GREEN CHEMISTRY.
GREEN NANOTECHNOLOGIES

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- ✓ **Fundamentals of Green chemistry.**
- ✓ **Principles of green chemistry.**
- ✓ **Green chemistry metrics: Atom economy, example.**
- ✓ **Green solutions in the chemical syntheses.**
- ✓ **Green nanomaterials.**

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Ключові слова	Key words
Зелена хімія	Green chemistry
Альтернативні технології	Alternative technologies
Розрахунки в Зеленій хімії	Green chemistry metrics
Зелені технології	Green technologies
Альтернативні джерела сировини	Alternative feedstocks
Наноматеріали	Nanomaterials

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Fundamentals of Green chemistry

Green chemistry is the design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances. Green chemistry applies across the life cycle of a chemical product, including its design, manufacture, use, and ultimate disposal.

Green chemistry:

- Prevents pollution at the molecular level.
- Is a philosophy that applies to all areas of chemistry, not a single discipline of chemistry.
- Applies innovative scientific solutions to real-world environmental problems.
- Results in source reduction because it prevents the generation of pollution.
- Reduces the negative impacts of chemical products and processes on human health and the environment.
- Lessens and sometimes eliminates hazard from existing products and processes.
- Designs chemical products and processes to reduce their intrinsic hazards.

Зелена хімія – [illegible]

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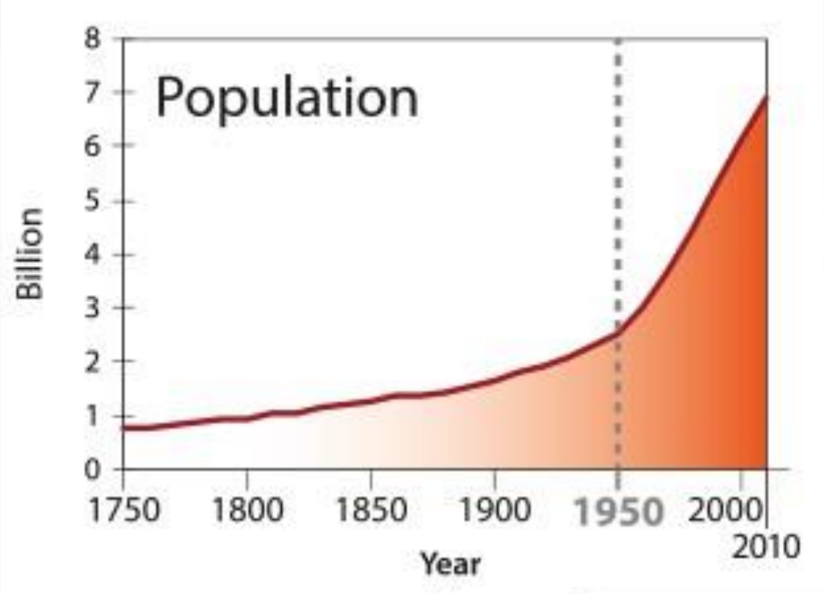
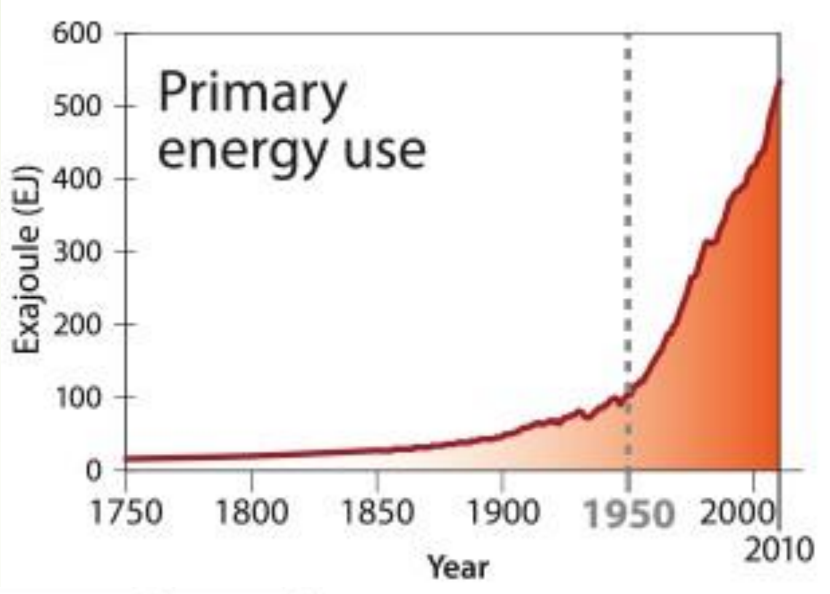
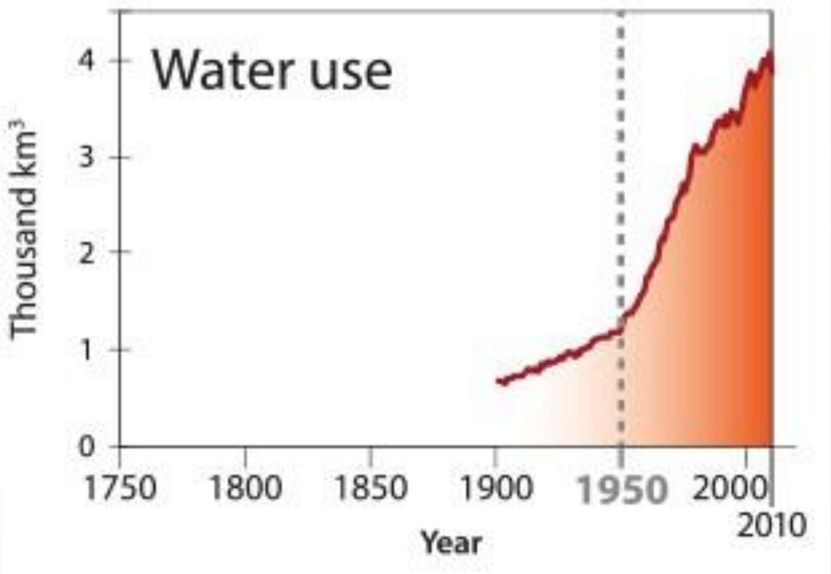
Need for Green chemistry

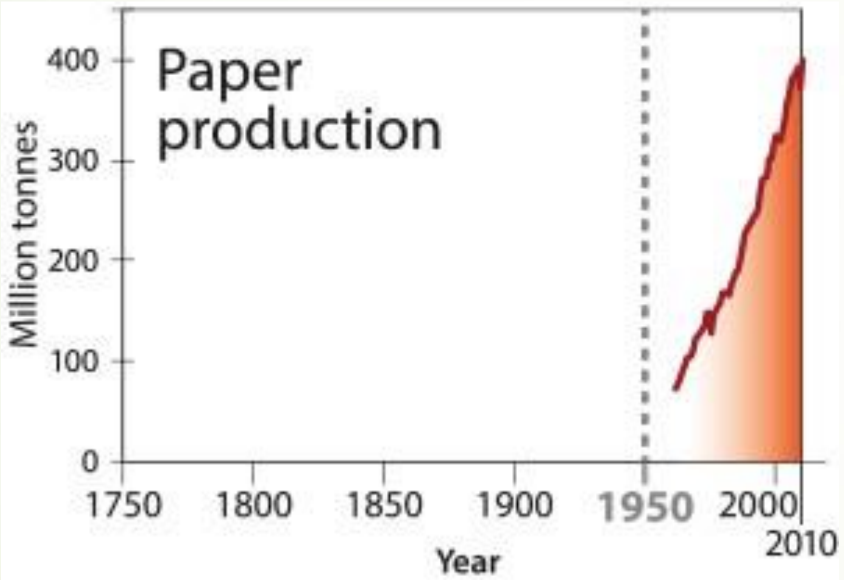


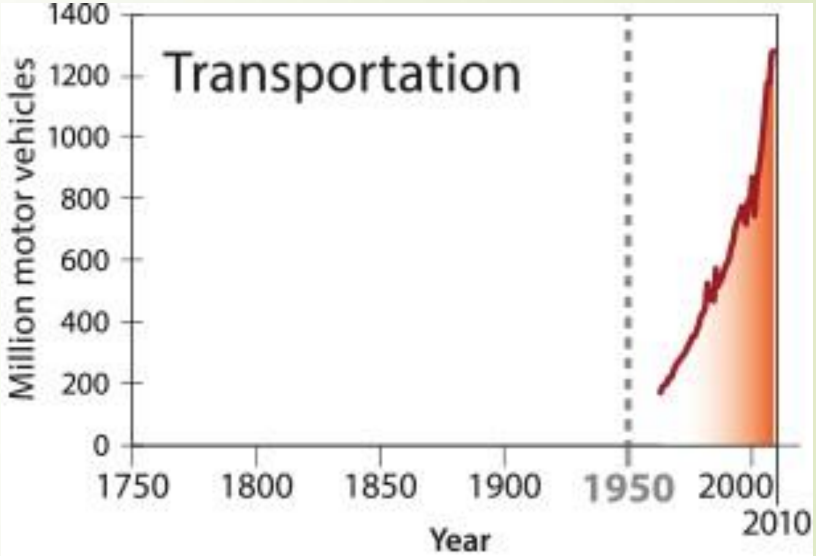




Steffen *et al.* The trajectory of the Anthropocene: The Great Acceleration (*Anthropocene Review)* 16 January 2015. Design: Globaia

Need for Green chemistry





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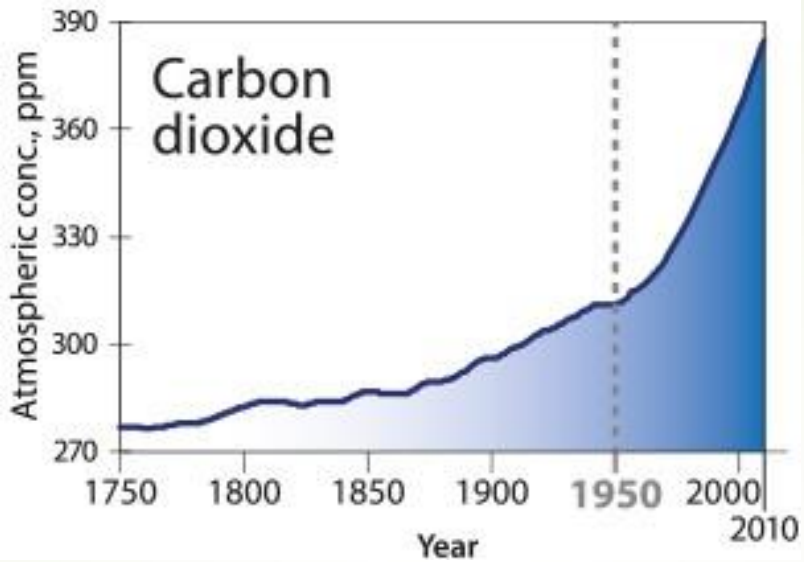
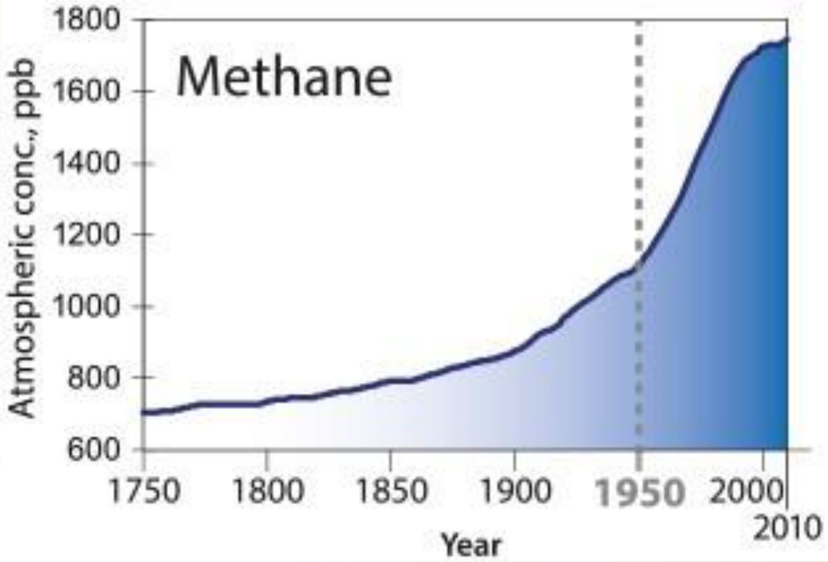
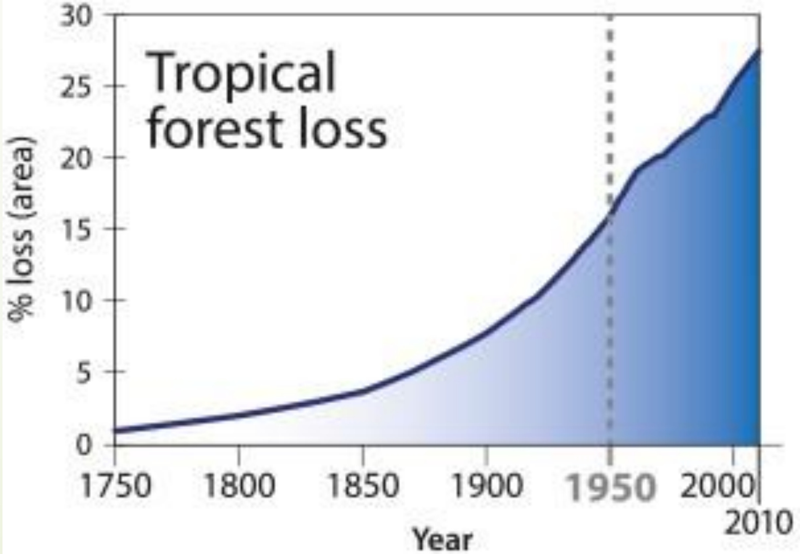
Need for Green chemistry







With an increasing population, the need for resources is even greater – which negatively impacts the environment.

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An overview of the history of Green Chemistry

The first stage (origin and beginnings):

From the second half of the 20th century, people began to realize the deteriorating situation of the environment, which was due to several factors - industrial activity production, developing transport, increasing amount of waste, etc. It triggered many responses from citizens and experts, which supported and later laid the foundation for for the philosophy and principles of Green Chemistry. Already in the nineties, for the first time it mentions the concept of Green Chemistry and at the same time it is recognized as a scientific direction.

- **1962** - **Rachel Carson** published the book **Silent Spring**, which reacted to the inappropriate use of artificial fertilizers in United States agriculture (Lear, 2000).
- **1970** - establishment of the **Environmental Protection Agency - EPA**, which ensures interaction between scientific, industrial and government organizations with the aim of using Green strategies chemistry in new technologies.
- **1990** - the first **Pollution Prevention Act in the United States**, which led to a shift away from control pollution to prevent it.
- **1993** – the **first symposium** in Chicago based on the Alternative program synthetic design for the prevention of pollution from the initiative of the adoption of the Act on Pollution Prevention and the EPA.

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An overview of the history of Green Chemistry

Second stage (1993-1998):

In the next stage, new institutions and organizations are created that serve for dissemination "green" ideas to all spheres of society.

Green chemistry also conquers Europe, creating a network of collaborators who deal with the issue environmental pollution on a larger scale. A significant step the second stage is the formulation and publication of the principles of Green Chemistry, thus Green chemistry gets more weightage than science major.

•**1995** – started **political support** from the **President of the USA** in the form of the Presidential Green Chemistry Challenge Awards.

•**1997** – creation of a non-profit organization called the **Institute of Green Chemistry** (GCI) in order to expand and enable implementation principles of Green Chemistry to chemical companies on a global scale.

•**1998** - establishment of the Green Chemistry Center at the European University of York, whose mission is to promote Green Chemistry throughout society – industrial plants, education, society, with the help of conferences, lectures, websites, or various events for industrialists, teachers and their pupils.

•**1998** – Paul Anastas and John Warner published the 12 Green Principles chemistry in the first book on Green Chemistry Green Chemistry: Theory and Practice.

Paul Anastas

John C. Warner

Anastas, P.T., and Warner, J.C. Green Chemistry Theory and Practice, Oxford University Press, New York, 1998.

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An overview of the history of Green Chemistry

Third stage (1999-present):

Since **2001**, the Institute of Green Chemistry collaborates with the American Chemical Society (ACS) and continues research and education around the world - USA, Great Britain, Italy, Germany, Spain, Japan, Australia and other countries.

• **1999** – first article published in the scientific journal Green Chemistry.

•**2001** – International Green Chemistry Symposium in Dehli and IUPAC CHEMRAWN XIV Green Chemistry Conference: Toward Environmentally Benign Processes and Products in Colorado, which had positive results impact on the great rise of Green Chemistry in 2000-2001 worldwide.

•**2005** – **Nobel Prize** for the discovery of the exchange reaction method and method of organic synthesis, which enabled progress in the field of Green Chemistry and which bearers are Robert Howard Grubbs, Richard Royce Schrock and Yves Chauvin.

•**2007** – John Warner and Jim Babcock founded the Warner Babcock Institute for Green Chemistry, whose goal is the creation of functional, cost-effective undemanding and ecologically sound technologies for clients, society and environment.

•**2007** – creation of the Beyond Benign organization under Warner's leadership, which focuses on green chemistry education.

Currently, it is possible to record positive news, based on analyses EPA that the amount of chemical waste found on the ground, in the air and in water has decreased by seven percent over the last decade.

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Fundamentals of Green chemistry

The 12 Green Chemistry Principles:

1. **Wastes prevention.**
   Waste prevention is better and easier than waste treatment is the first and most important principle.
2. **Atom economy.**
   Maximal incorporation of starting materials into the final product is a fundamental principle to design and development of synthetic methods.
3. **Safer synthesis.**
   The designing of chemical methods with utilization and generation of substances with low or no toxicity to people and the environment is major priority.

12 принципів Зеленої хімії:

1. **Запобігання утворенню відходів.**
   [illegible]
2. **Економіка атомів.**
   [illegible]
3. **Більш безпечний синтез.**
   [illegible]

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Fundamentals of Green chemistry

The 12 Green Chemistry Principles:

4. **Safer chemicals.**
   Chemical products and side products should be designed to achieve a desired function with minimal toxicity.
5. **Safer solvents and auxiliaries.**
   Auxiliary substances such as solvents and separation agents should be minimized or eliminated whenever possible and made innocuous when used.
6. **Energy efficiency.**
   The minimization of the economic and environmental impacts associated with energy use in chemical synthesis is point of importance. The development of methods conducted at ambient temperature and pressure whenever it is possible is invited.

The 12 Green Chemistry Principles:

4. **Пошук безпечніших матеріалі.**
   [illegible]
5. **Більш безпечні розчинники та допоміжні речовини.**
   [illegible]
6. **Енергоефективність.**
   [illegible]

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Fundamentals of Green chemistry

The 12 Green Chemistry Principles:

7. **Renewable feedstocks.** Starting materials from renewable origins should be used whenever economically and technically practicable.
8. **Derivatives minimization.** The utilization of protection/deprotection, blocking groups, and temporary modification of physical/chemical processes should be excluded or at least minimized with purposes of waste reduction.
9. **Catalysts.** Catalytic reagents that are engineered for high selectivity and efficiency for less waste production are needed.

12 принципів Зеленої хімії:

7. **Використання сировини з відновлюваних джерел.**
   [illegible]
8. **Мінімізація похідних.**
   [illegible]
9. **Каталізатори.**
   [illegible]

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Fundamentals of Green chemistry

The 12 Green Chemistry Principles:

10. **Design for degradation.** The design chemical products which break down into innocuous degradation materials at the end of their function and not dangerous for the environment is important.
11. **Real-time analysis.** It is important to develop and adopt real-time analytical methods that provide continuous process monitoring and control of the formation of hazardous compounds.
12. **Accident prevention for safer chemical production.** The potential for chemical accidents such as releases, explosions, and fires should be minimized by choosing inherently safer substances.

12 принципів Зеленої хімії:

10. **Розробка продуктів, що розкладаються в довкіллі.**
    [illegible]
11. **Експресний моніторинг технологічного процесу.**
    [illegible]
12. **Запобігання нещасним випадкам у хімічному виробництві.**
    [illegible]

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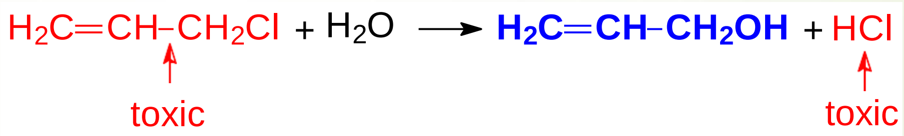
Fundamentals of Green chemistry

The 12 Green Chemistry Principles:

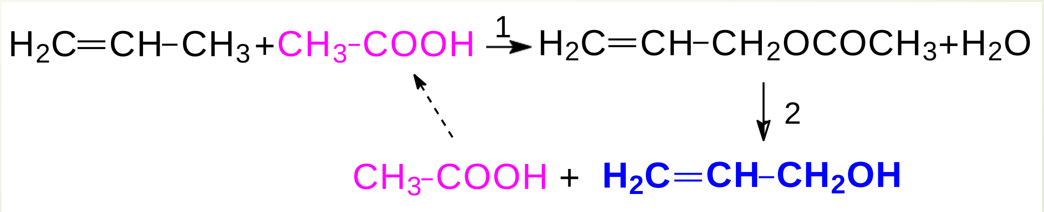
1. Wastes prevention.

The main idea is that it is better to prevent waste formation than invest to the treatment, clean up or storage of waste after it is formed. According to this principle, the traditional routes for synthesis of organic compounds must be substituted by an alternative, which minimize or even eliminate the use and production of toxic compounds.

For example, the **production of allyl alcohol**.
The **traditional route** consists in hydrolysis of allyl chloride.
Despite the advantage, that this is one step production, this route involves the usage of toxic reactant (allyl chloride) and production of toxic side product (hydrochloric acid). Both compounds are toxic and harmful for the environment in case of an accidental release during the transportation, storage, or manipulation.



However, there is an **alternative** two step **route** is available. Allyl alcohol can be synthesized using propylene (CH_2=$CHCH_3$), acetic acid (CH_3COOH) and oxygen. Only the **side-product** (acetic acid) produced in the second reaction can be received and used again for the first reaction. Therefore, no unwanted by-product in this route.



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Fundamentals of Green chemistry

The 12 Green Chemistry Principles:

1. Atom economy.

In the chemical industry, there are many examples of highly “efficient” reactions that generate waste far greater in mass and volume than the desired product.

Therefore, the alternative criteria for evaluation of accordance to the Green chemistry principles were developed. One of them is Atom economy which measure the amount of atoms from the starting material that are present in the final product at the end of a chemical process. High Atom economy means most of the atoms of the reactants are incorporated in the desired products. Only small amount of waste is produced, hence lesser problem of waste disposal.

$$\%\ \textbf{Atom economy} = \frac{\sigma(\textbf{FW of the desired products})}{\sigma(\textbf{FWs of all the reactants})} \times \mathbf{100\%}$$

1. Економіка Атомів.

[illegible]

[illegible]

[illegible]

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Fundamentals of Green chemistry

High Atom economy (100%)

A + B → C,

where A and B are reagents, C is desired product.

Low Atom economy (<100%)

A + B → C + D,

where D is side product.

Example: Industrial production of iron:

$$Fe_2O_3 + 3\,CO \rightarrow 2\,Fe + 3\,CO_2.$$

$$\%\ Atom\ economy = \frac{2 \times FW\ (Fe)}{FW\ (Fe_2O_3) + 2 \times FW\,(CO)} \times 100\% =$$

$$= \frac{112}{244} \times 100\% = 45.9\%.$$

Fundamentals of Green chemistry

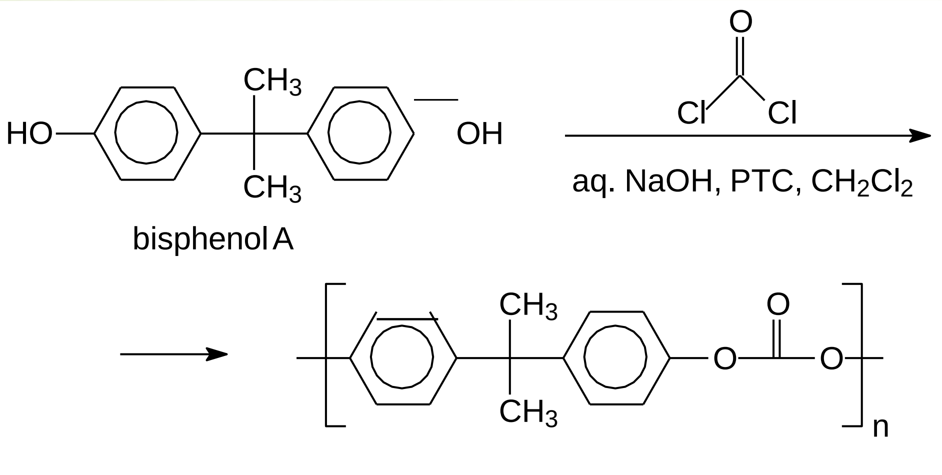
3. Safer synthesis.

Synthetic methods should use and generate substances that possess little or no toxicity to human health and the environment.

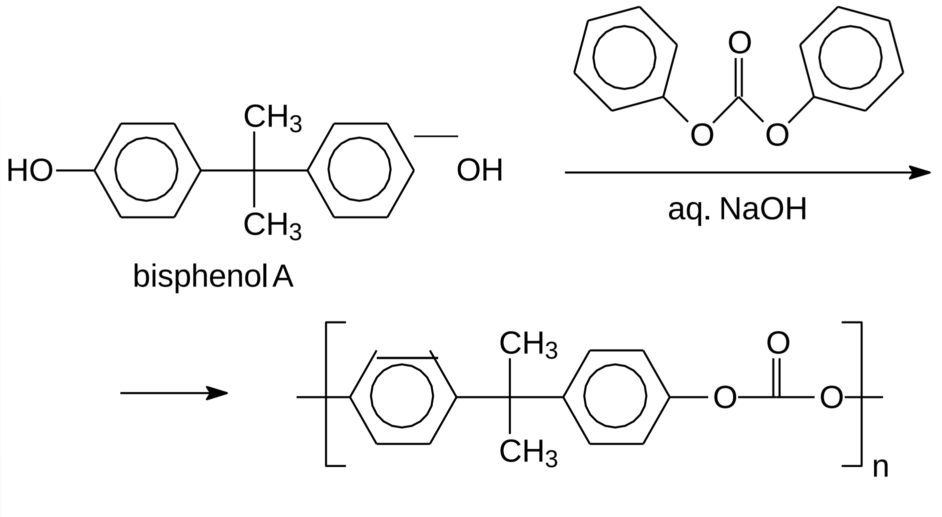
For example, the **synthesis of polycarbonate**. The first route through the phosgene process.

Traditional route involves the utilization of a toxic reagent (phosgene) and large amounts of toxic solvent (dichloromethane). Produced polycarbonate is also contaminated with chlorine impurities.

An **alternative route** involves the use of diphenylcarbonate instead of phosgene, eliminates the use of dichloromethane and produces high-quality polycarbonates.



polycarbonate



polycarbonate

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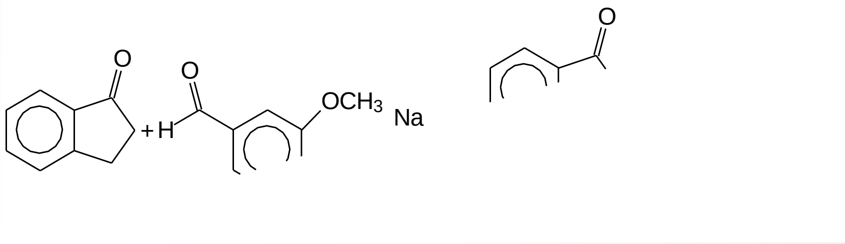
Green solvents

Solventless Reactions. Solventless design of reaction can be used when all reagents and products are liquids which can react without solvent.

For example, the Crossed-Aldol condensation. Solvents are necessary for the synthesis of organic compounds, but their vapour creates air pollution. Therefore, efforts are being made to use solvents with high boiling points or to avoid solvent (solvent free reaction).



Реакції без розчинника.

Наприклад,

Solid state reaction is another alternative of solventless reaction. In such a situation, two fine grinded macroscopic solids interact directly and form a third, solid product without the intervention of a liquid or vapour phase (for example, oxidation, reductions, halogenations, hydrohalogenations etc.). However, not all reactions will work in the absence of solvent.

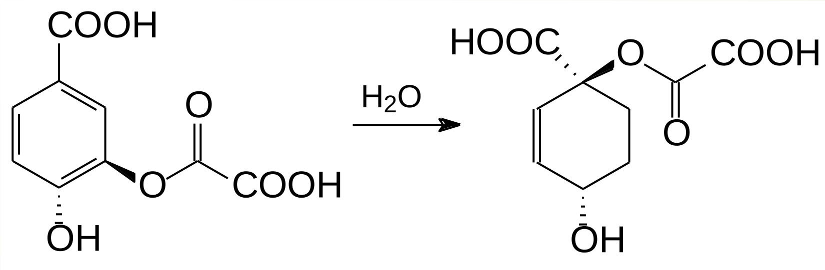
Реакція в твердому стані

Green solvents

Water**.** Water is one of the green solvents. It is easily available, not expensive, safe, and non-hazardous to environment. Water is also a "universal solvent" in nature. Living cells represent the most complex chemical reactions (termed as biochemical reaction) and all such reactions occur in environment with >90% water. Both, inorganic and organic reactions are also carried out using water as a solvent.

Most of the important reactions in organic synthesis have been tried using water as a solvent or one of the components in the solvent mixture; of course, with some modifications in the conventional methodologies.

For example, in Claisen rearrangement of chorismic acid, pure water is used to promote the reaction.



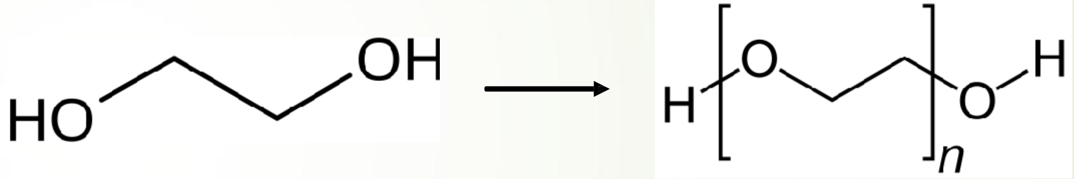
Another example, oxidation of alkene using aqueous solution of $KMnO_4$ and in presence of a phase transfer catalyst gives carboxylic acid with good yield.

$$R-(CH_2)_n-CH=CH_2 \xrightarrow[\text{Catalyst}]{\text{aq.}KMnO_4} R-(CH_2)_n-CH_2\,COOH$$

Green solvents

Polyethylene glycol. Polyethylene glycol is a linear polymer formed from the polymerization of ethylene oxide. It is available in a variety of molecular weights. The numerical designations of polyethylene glycol indicate the average molecular weight, for instance, PEG-200, PEG-400, PEG-2000 etc. Low molecular weight polyethylene glycols are liquid and completely miscible in water. Polyethylene glycols with high molecular weight are waxy white solids and highly soluble in water. The compound is inexpensive, non-flammable, biologically compatible, recoverable, non-toxic, thermally stable and biodegradable.

Therefore, it can be considered not only as an environmentally benign solvent but also as biologically acceptable polymer, which has immense importance in drug delivery and approved for internal consumption.



Поліетиленгліколь. [illegible] PEG-200, PEG-400, PEG- 2000 [illegible] є [illegible]

[illegible]

***Glycerol**. Glycerol is another effective green solvent due to its polarity (capable for dissolving of polar and hydrophobic compounds low volatility (can easily be separated by distillation), low toxicity, low vapor pressure, low environmental impact, availability, easy handling, and storage.

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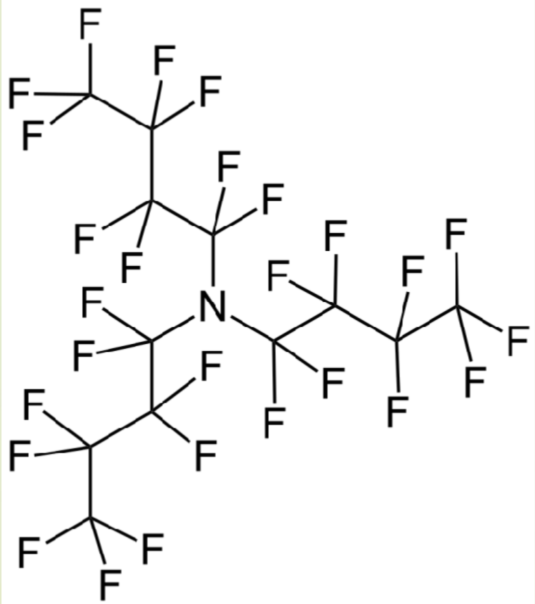
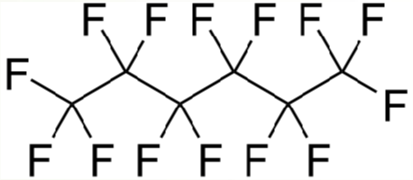
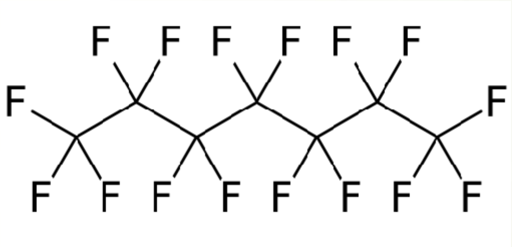
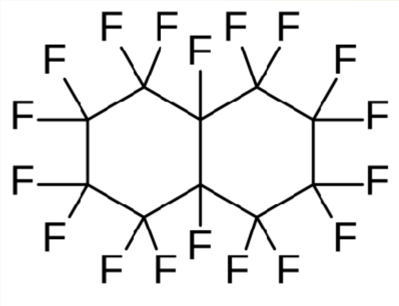
Green solvents

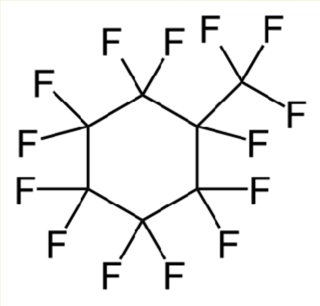
Perfluorinated solvents. Perfluorinated solvents are highly fluorinated hydrocarbons based upon sp[3] hybridized carbon (perfluorohexane C_6F_{14}, perfluoroheptane C_7F_{16}, perfluorodecalin $C_{10}F_{18}$, perfluoromethylcyclohexane C_7F_{14}, perfluorotributyl amine $C_{12}F_{27}N$). They are found to be unique solvents due to the immiscibility with water and most of the common organic solvents and form third liquid phase, nontoxic, non-flammable, thermally stable, recyclable and having high ability to dissolve oxygen. Fluorous fluids have high density, low intermolecular interaction, low surface tension, low dielectric constant and high stability.









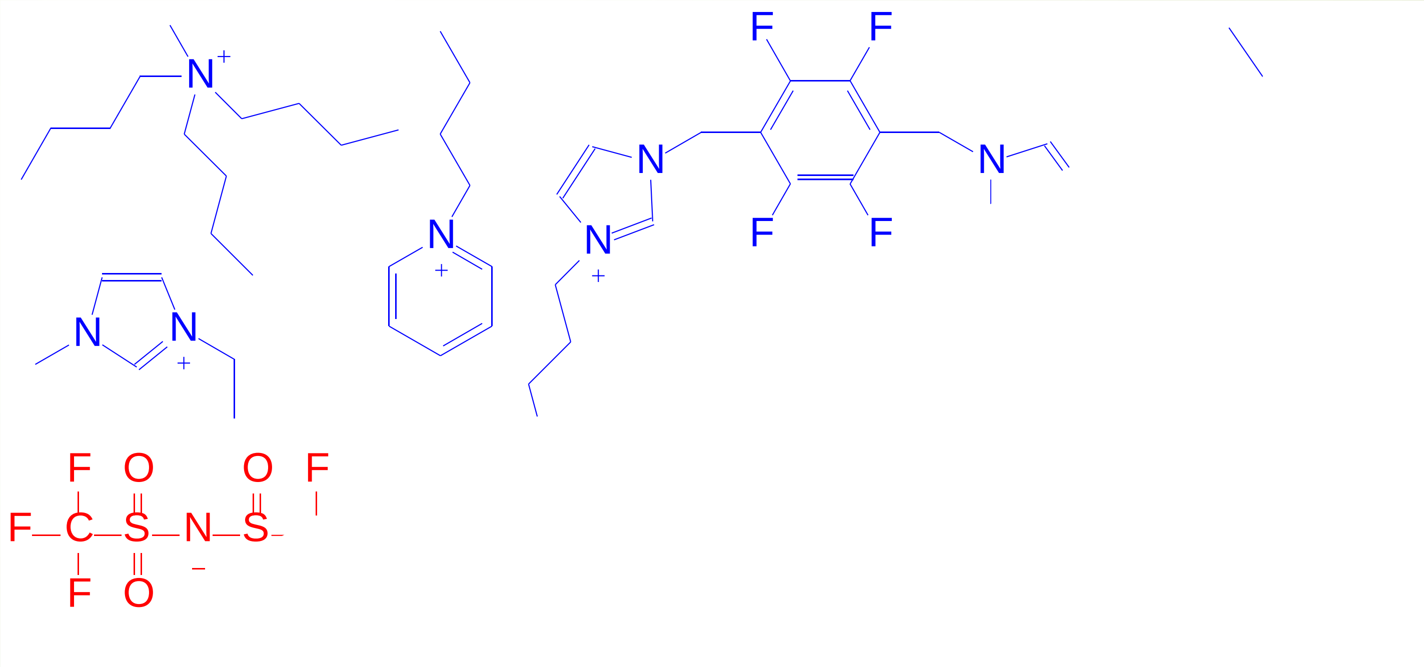


Перфторовані розчинники. [illegible] C_6F_{14}, [illegible] C_7F_{16}, [illegible] $C_{10}F_{18}$, [illegible] C_7F_{14}, [illegible] $C_{12}F_{27}N$). [illegible]

Green solvents

Ionic liquids. A new class of solvents has emerged, which are fluid in a wide range of the temperature. As these solvents have high boiling point, it means lower vapour pressure of that solvent, and hence, no volatile organic compounds are escaped from these liquids at lower temperatures.

Ionic liquids are made-up of two components: cations and anions, which vary with different types of groups. Some examples of most common cations (blue) and anions (red). The nature of the cations and anions has a significant influence on the properties of these ionic liquids. The most employed ionic liquid anions are polyatomic inorganic species, halogens, and organic anions.



Ionic liquids are biodegraded via different pathways depending upon the length of the substituted alkyl chain. Biodegradation products are non-toxic to aquatic test organisms.

Green solvents

Supercritical fluids. Another green alternative of solvents are supercritical fluids. A supercritical fluid is a substance at a temperature and pressure above its critical point, where distinct liquid and gas phases do not exist. It can effuse through solids like gas and dissolve materials like a liquid. In addition, close to the critical point, small changes in pressure or temperature results in large changes in density allowing many properties of a supercritical fluid to be “fine-tuned”.

Supercritical fluids are suitable as a substitute for organic solvents in a range of industrial and laboratory processes. Carbon dioxide and water are the most commonly used supercritical fluids, and also being used for decaffeination and power generation, respectively.

Надкритичні рідини. [illegible]

[illegible]

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Green solvents

Water is described as superheated water, **subcritical water** or pressurized hot water between 100°C and its supercritical point at 374°C. Subcritical water has been used in synthetic organic chemistry because of having some unique properties different from those of ambient water. Water has similar properties to an organic solvent such as methanol, but also has some unique properties and these characteristics are lower viscosity as compared to water that results in faster diffusion of the compound, lower surface tension, higher solubility of polar compounds due to lower hydrogen bonding, increased heat capacity (in 2-5 times compared to liquid water), which improves transfer of heat, single homogeneous phase results in no interfacial mass transfer limitation.

[illegible] **субкритична вода** [illegible] 100°C [illegible] 374°C. [illegible] (2-5 [illegible]) [illegible]

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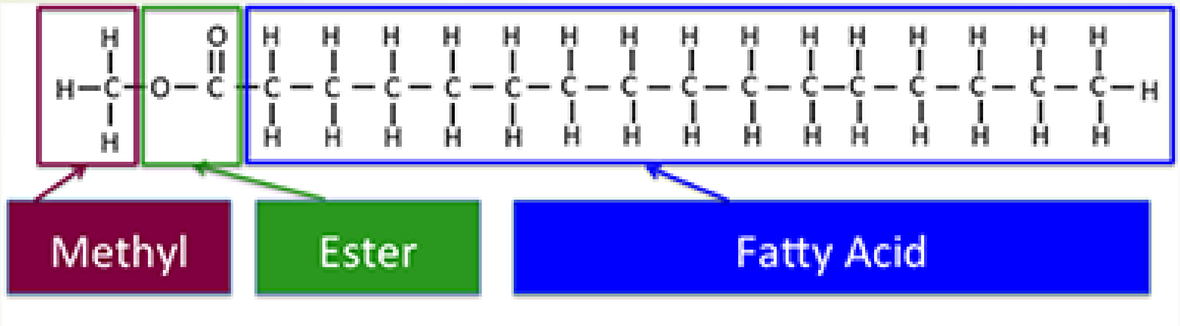
Green solvents

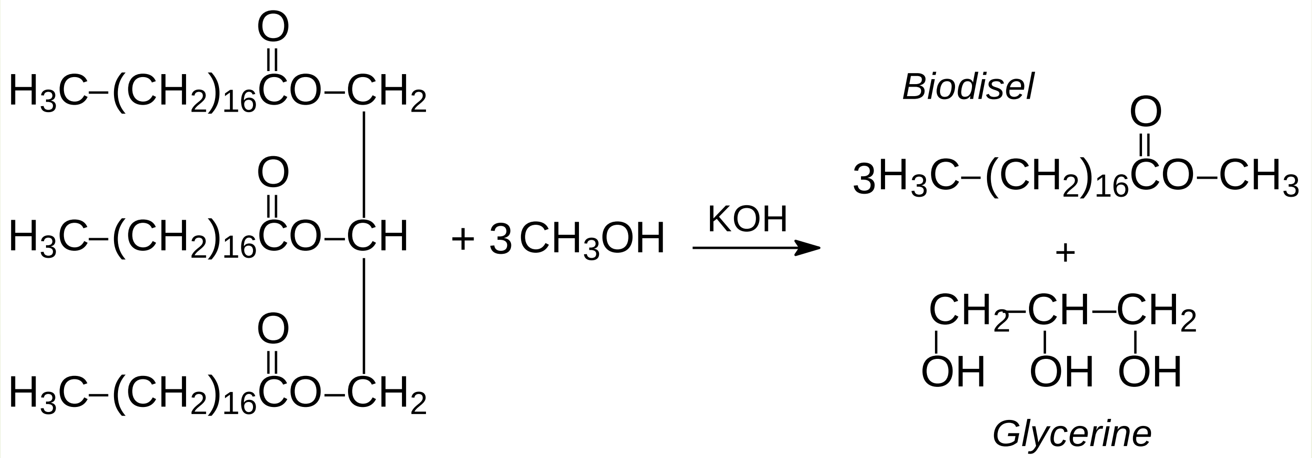
Carbon dioxide exists in three phases, that is, solid, liquid and gas. The solid phase of CO_2 is called ‘dry ice’ and it is used for cooling. The gas phase is well-known, and at atmospheric temperature and pressure the solid transforms to gas without liquification. Only in certain specified conditions, it can be liquefied. With the increasing pressure on gas or heating of solid CO_2, liquid phase can be achieved. The critical temperature of CO_2 is 31°C. At the temperature of -56°C and 5.1 atm, all three phases of carbon dioxide exist simultaneously. At 31°C and 73 atm, it exists as a **supercritical fluid**. At this condition, it has unique properties, that is, viscosity similar to the gas phase and density similar to the liquid phase.

Вуглекислий газ [illegible] CO_2 [illegible]
[illegible] CO_2 [illegible] CO_2 [illegible] 31°C. [illegible] -56°C і 5,1 [illegible] 31°C і 73
[illegible]

Alternative fuel: biodiesel

Chemistry of biodiesel production





Biofuels made from corn that **compete** with **food, livestock feed**, and **land use !**

Alternative Fuels from Biomass Sources. https://www.e-education.psu.edu/egee439/

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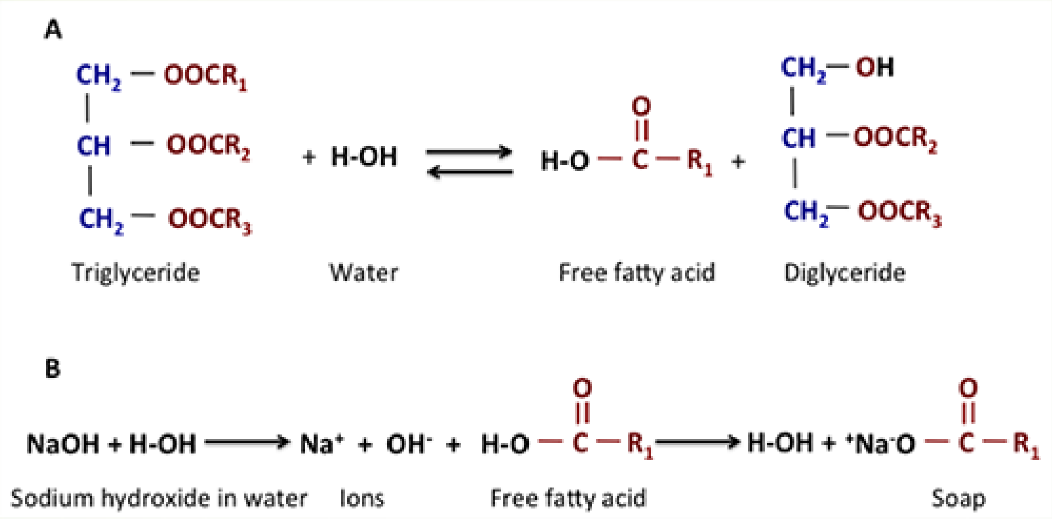
Alternative fuel: biodiesel



	Stoichiometric	Typical
Fat or Oil	100 l	100 l
+		
Alcohol [Methanol]	10 l	16-20 l
+		
Catalyst [NaOH; 1% w/w oil]	1 l	1 l
↓		
Biodiesel [Methyl Ester]	100 l	100 l
+		
Glycerin	10 l	10 l

Problems:

Formation of by-products (soap) !

Excess of methanol !

Alternative Fuels from Biomass Sources. https://www.e-education.psu.edu/egee439/

Alternative fuel: algae

Oil yields from various plants and microalgae

Source	Annual oil yield (m^3/ha)
Corn	0.14
Soybeans	0.45
Sunflower	0.95
Canola (Rape)	1.20
Jatropha	1.90
Palm	5.90
Microalgae (30% lipids)	59.00
Microalgae (50% lipids)	98.00
Microalgae (70% lipids)	140.00

So why make biofuels from algae?

- Algae have high lipid content (up to 70%).
- They grow rapidly and will produce more lipids per area than other terrestrial plants (10-100 times).
- To grow algae, non-arable land (used for farming) can be used along with saline or brackish water.
- Algae don't have the same competition with generating food or feed as other oil producing plants.
- Use of CO_2 in growing algae; it helps grow algae significantly.
- Use nutrient (N, P) removal in agricultural and municipal wastewater.
- High annual oil yield from a variety of plants and algae.

Mata et al. (2010) Renew. Sust. Energy Rev. 14: 217–232.

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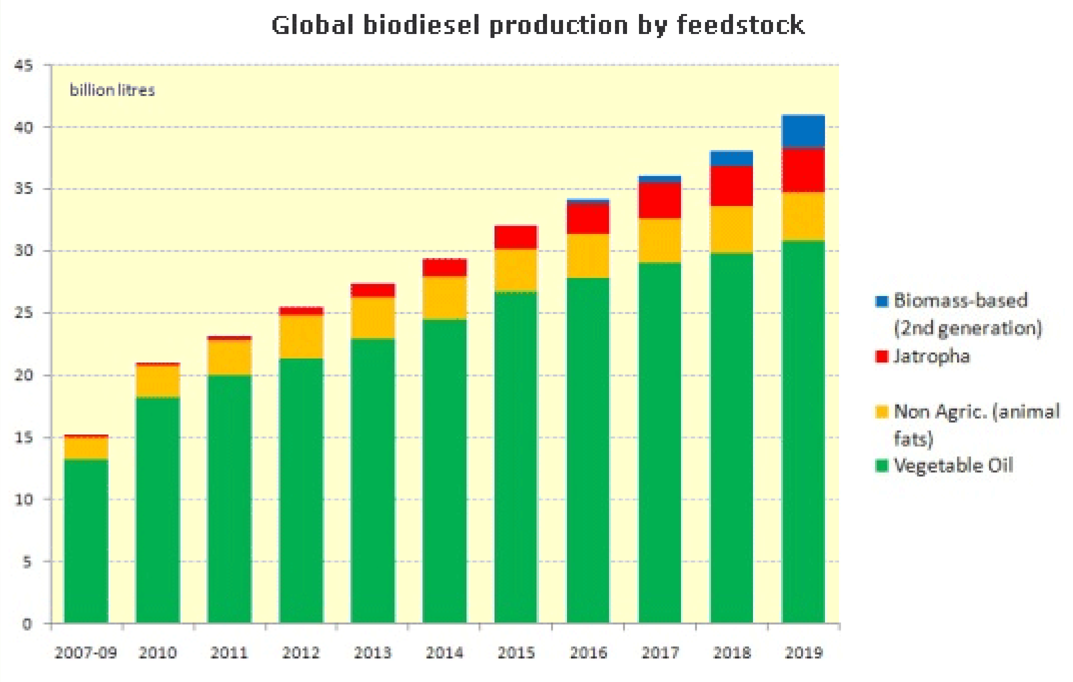
Alternative fuel



- The **major feedstocks** for biodiesel is **soy oil** or any **other vegetable oil**.
- **Animal fats** can also be used, but animal fats can produce more by-products that cause issues (i.e., free fatty acids which can cause soap formation).
- ***Jatropha*** is another oil used for biodiesel production.
- **Second-generation biodiesel** can be produced from **algae**, and use of algae for biodiesel production is a growing market.

The Crop Site. http://www.thecropsite.com/articles/1781/biofuel-production-greater-shares-of-commodities-used/

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Fundamentals of Green chemistry

Renewable feedstocks.

A raw material of feedstock should be renewable rather than depleting wherever technically and economically practicable.

For example, plants are in use for the obtaining of pesticides, medicines or other compounds.

Відновлювана сировина.

[illegible]

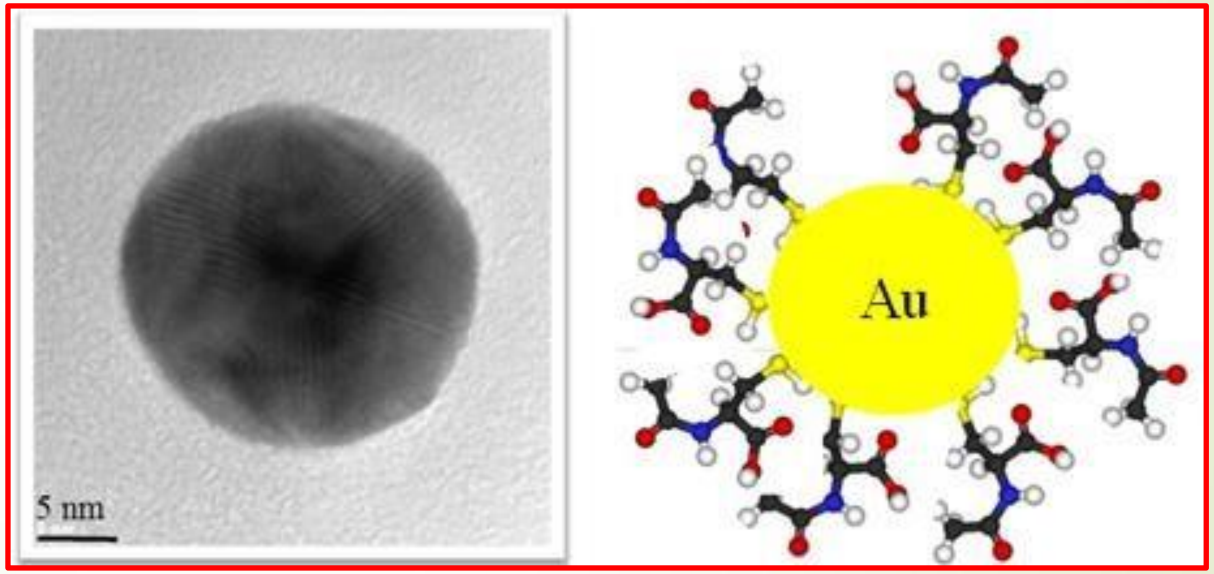
[illegible]

Nanomaterials

A **nanoparticle** is a small particle that ranges between 1 to 100 nanometres in size.

Undetectable by the human eye, nanoparticles can exhibit significantly different physical and chemical properties to their larger material counterparts.

The definition given by the European Commission states that the particle size of at least half of the particles in the number size distribution must measure 100 nm or below. Most nanoparticles are made up of only a few hundred atoms.



Наночастинка — [illegible] 1 до 100 [illegible]

[illegible] 100 н[illegible] або менше [illegible]

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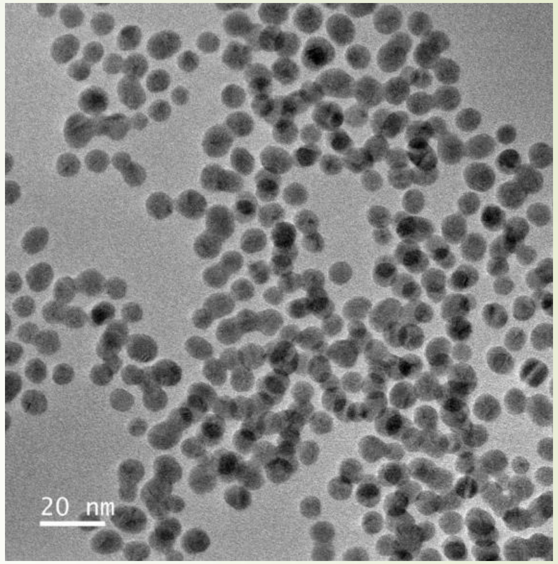
Nanomaterials

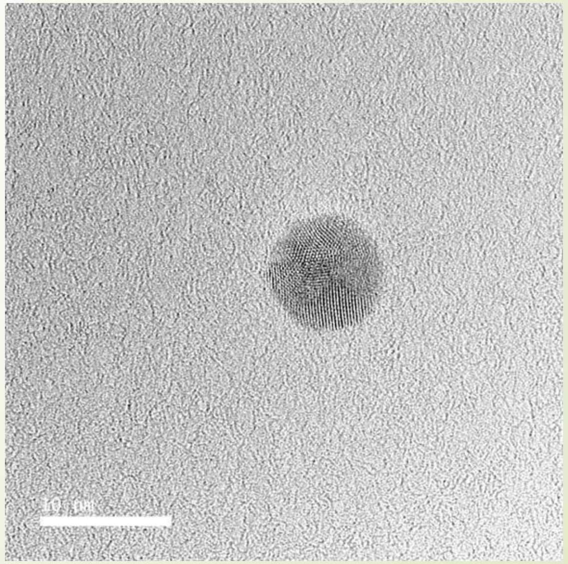
The **size** of nanoparticles compared to other structures:

- Atoms and small molecules - **0.1nm**
- Nanoparticles - **1 to 100 nm**
- Fine particles - **100 to 2,500 nm**
- Coarse particles (dust) - **2500 to 10,000 nm**
- Thickness of paper - **100,000 nm**

Розмір [illegible]

- [illegible] - **0,1 нм**
- [illegible] - **від 1 до 100 нм**
- [illegible] - **від 100 до 2500 нм**
- [illegible] - **від 2500 до 10 000 нм**
- [illegible] - **100 000 нм**





Mariychuk, R., Porubská, J., Ostafin, M. *et al. Appl Nanosci* (2020). https://doi.org/10.1007/s13204-020-01324-y

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Nanomaterials

Colloidal Ag nanoparticles

Colloidal Au nanoparticles

Colloidal Se nanoparticles

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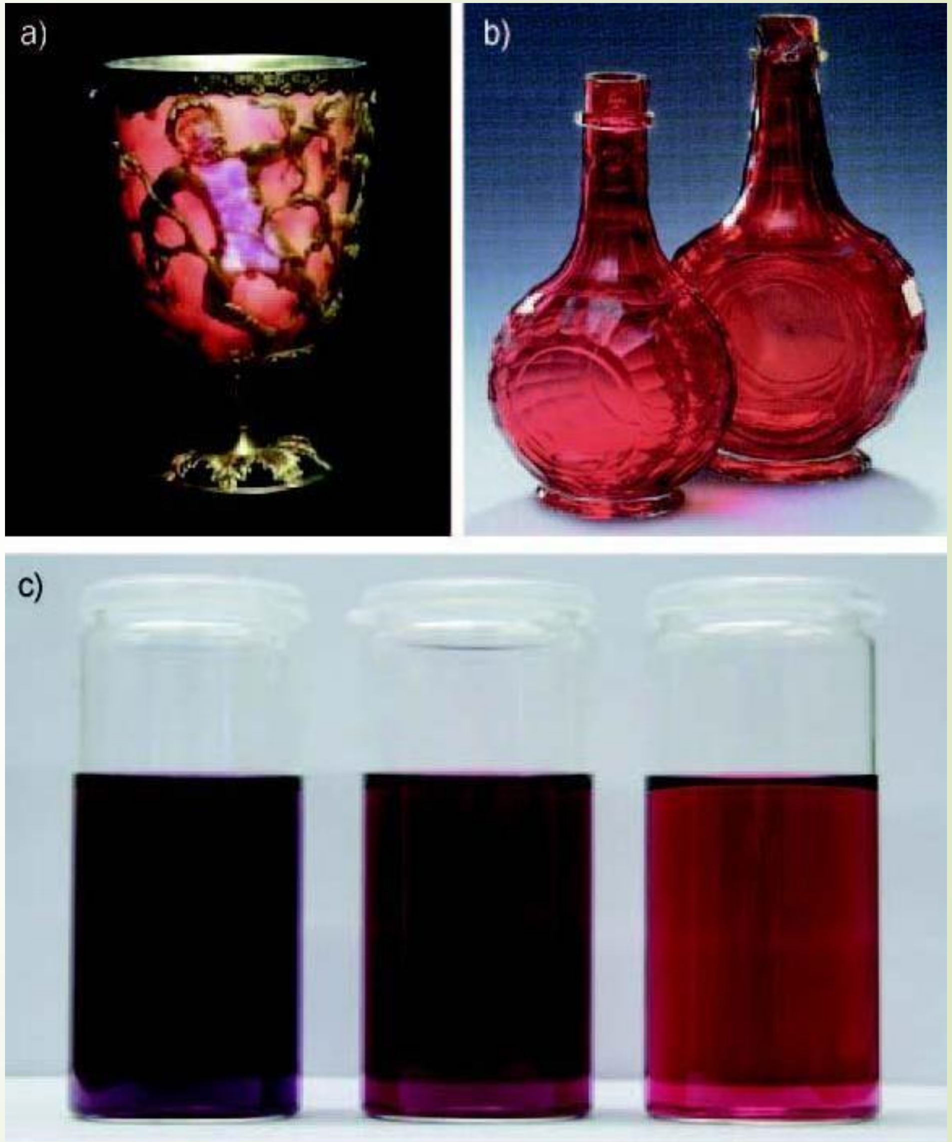
Nanomaterials

Gold nanoparticles:
a) Late Roman Lycurgus cup,
b) baroque ruby glass,
c) colloidal Au nanoparticles



Наночастинки золота:
а) [illegible]
б) [illegible]
в) [illegible] Au

H. Goesmann, C. Feldmann, Angew. Chem. Int. Ed. 2010, 49, 1362–1395

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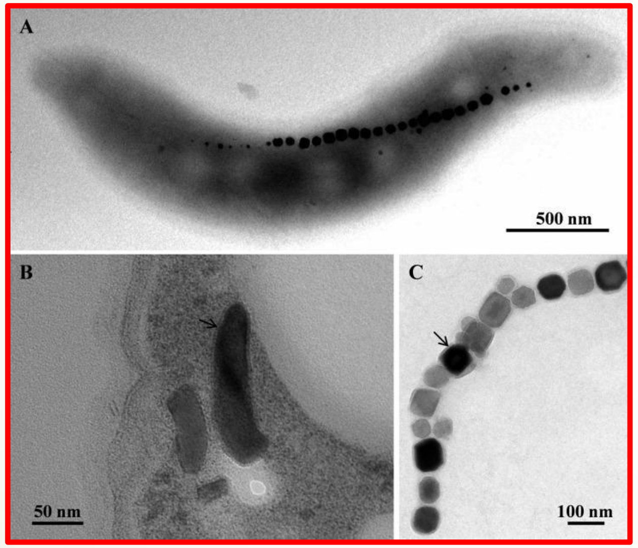
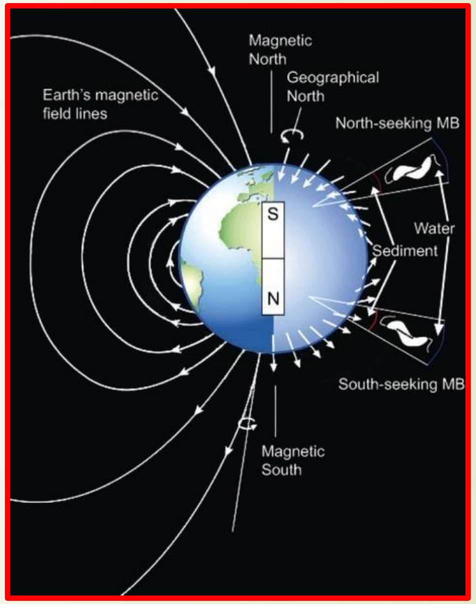
Nanoparticles in Nature

Magnetotactic bacteria are a polyphyletic group of bacteria that orient themselves along the magnetic field lines of Earth's magnetic field.
Discovered in 1963 by Salvatore Bellini and rediscovered in 1975 by Richard Blakmore, this alignment is believed to aid these organisms in reaching regions of optimal oxygen concentration. To perform this task, these bacteria have organelles called magnetosomes that contain magnetic crystals.



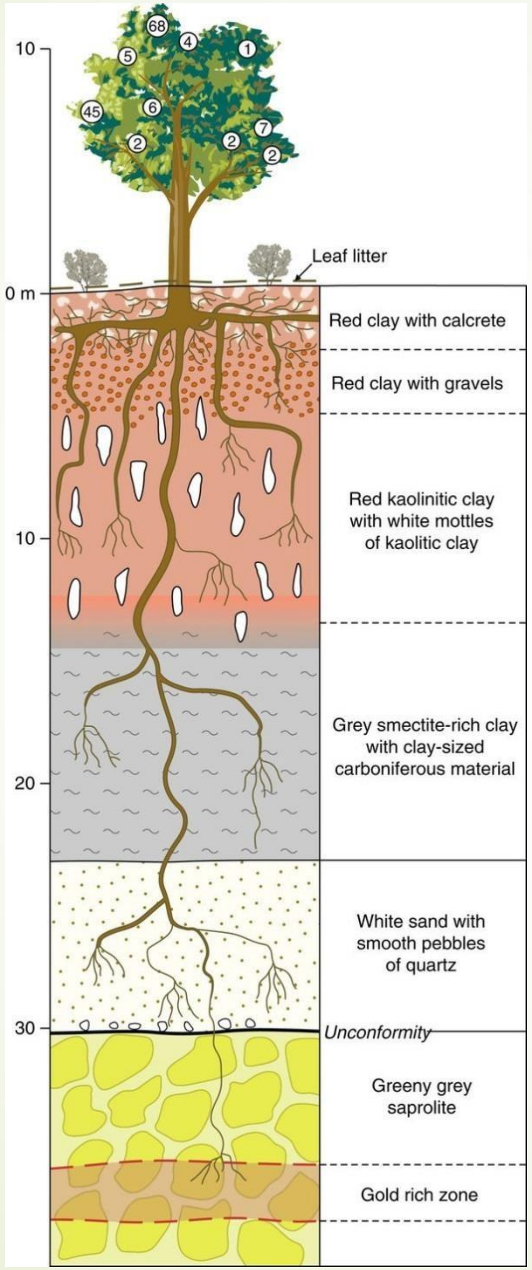
Magnetite (Fe_3O_4)



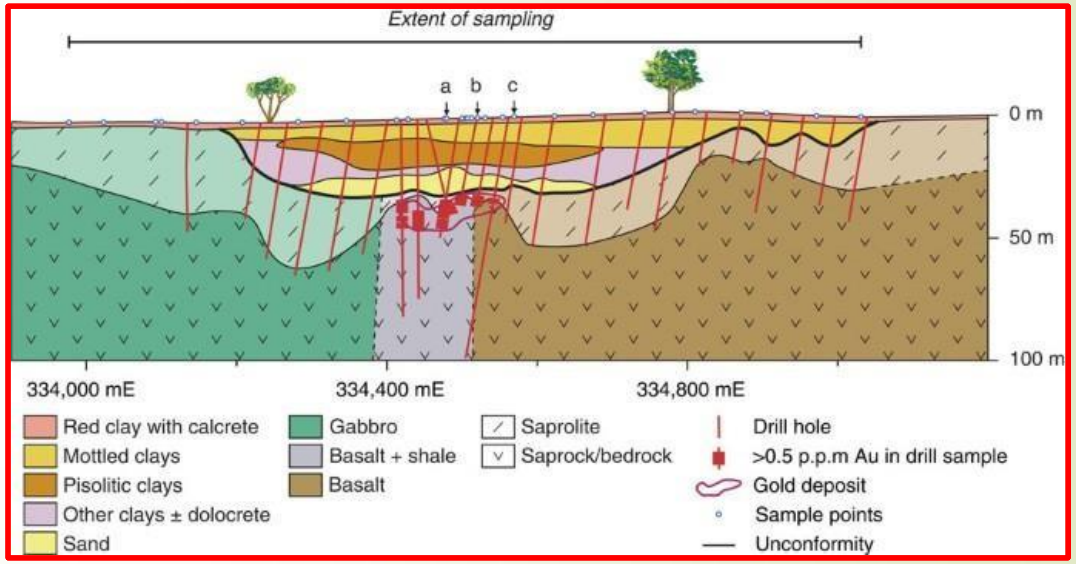
Магнітотактичні бактерії —

1963 … 1975

Nanoparticles in Nature



Transportation of Au-nanoparticles from gold mine by tree root.



Lintern, M., Anand, R., Ryan, C. et al. *Nat Commun* 4, 2614 (2013). https://doi.org/10.1038/ncomms3614

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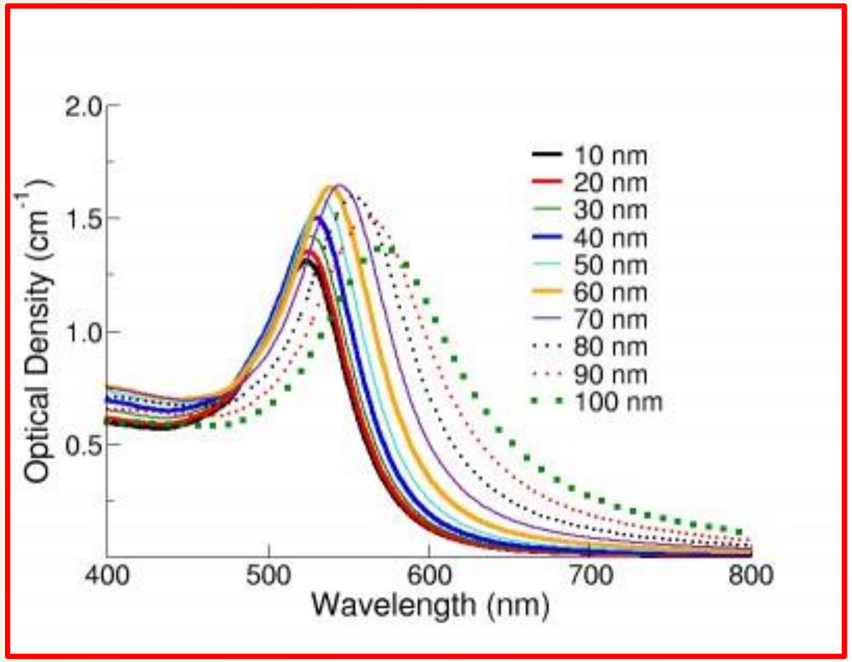
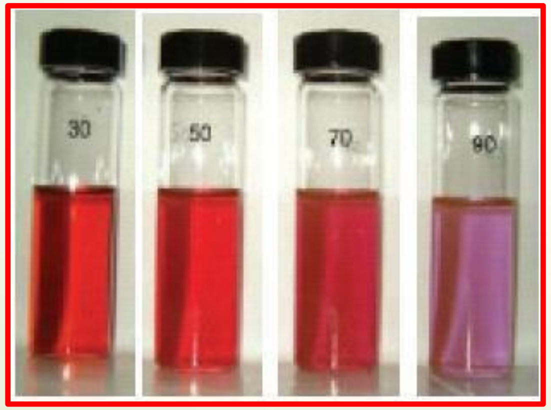
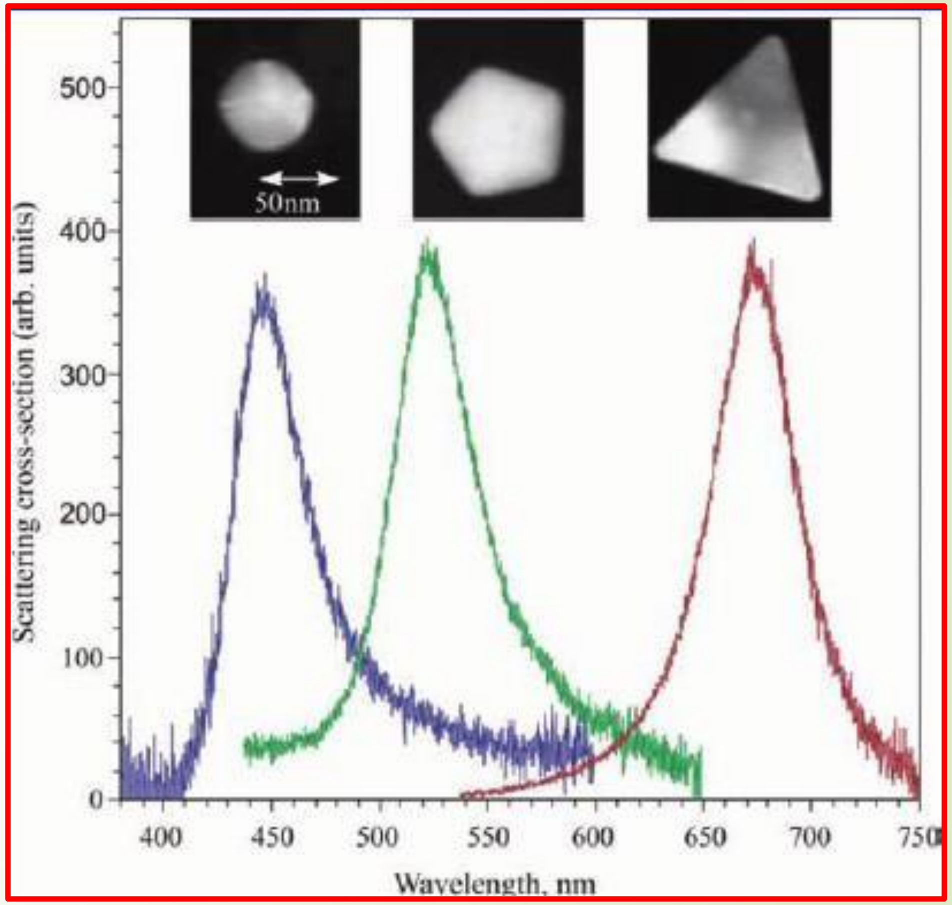
Properties of Nanoparticles

Size





Shape



Mock, J.J. et al. (2002) J. Chem. Phys., 116, 6755–6759

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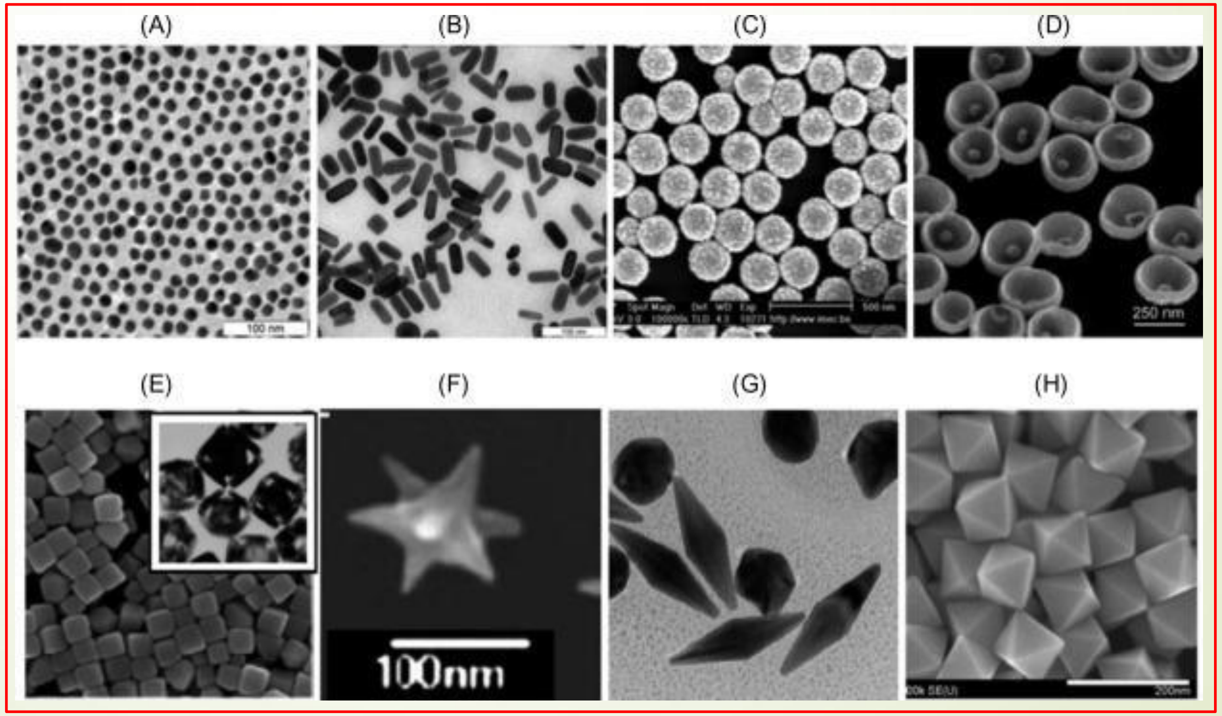
Applications of Nanoparticles

Potential applications of nanoparticles:

- Electronics
- Engineering
- Sensorics
- Agriculture
- Food industry
- Cosmetics
- Medicine
  - ➢ heating with infrared radiation
  - ➢ drug delivery

Застосування наночастинок:

- [illegible]
- [illegible]
- [illegible]
- [illegible]
- [illegible]
- [illegible]
- [illegible]
  - ➢ [illegible]
  - ➢ [illegible]



Khlebtsov, N.G., Dykman, L.A., 2010. J. Quant. Spectrosc. Radiat. Transfer, 111, 1–35

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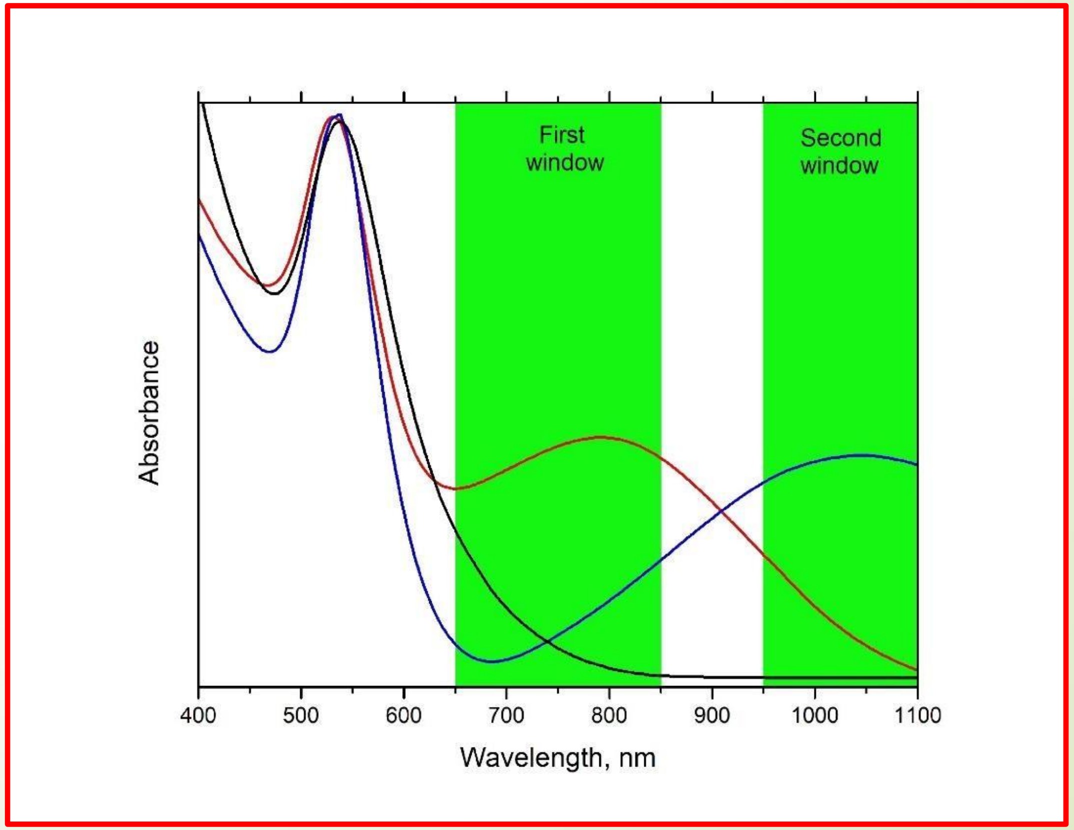
Applications of Nanoparticles

1. Biocompatibility
2. Surface modification
3. Optical properties (therapeutic windows)

The biological transparency window is in the range of 650–1350 nm.
This region is divided into two optical near-infrared ranges:
650–850 nm and **950–1350 nm**.



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Green synthesis of Nanoparticles

Nanoparticle preparation

Top down methods (size reduction)

Mechanical milling / ball milling
Chemical etching
Thermal ablation / laser ablation
Explosion processes
Sputtering

Bottom up methods (build up from smaller entities)

Chemical / electrochemical precipitation
Vapor deposition
Atomic / molecular deposition
Sol-gel process
Spray pyrolysis
Laser pyrolysis
Aerosol processes

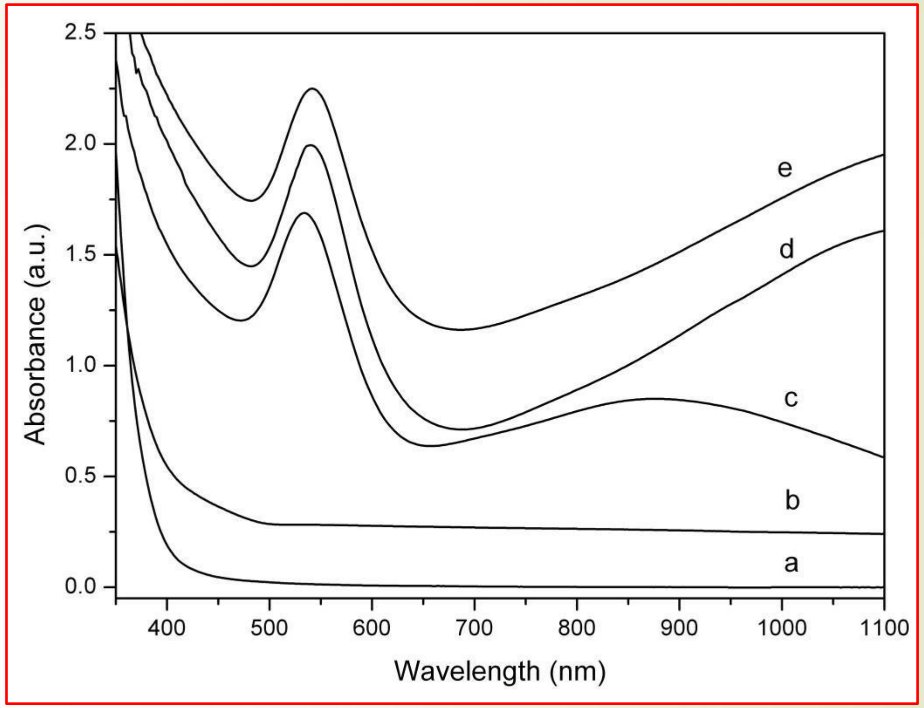
Bioreduction

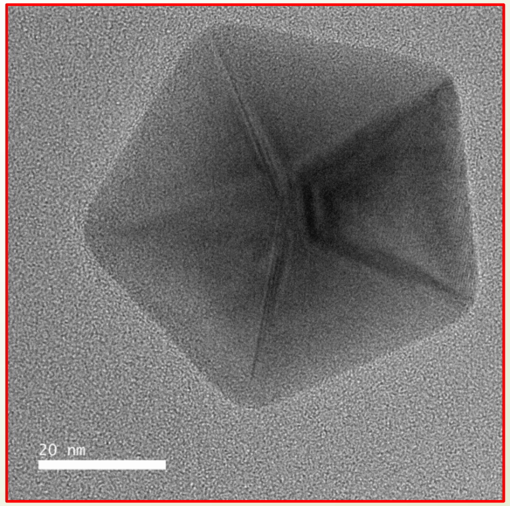
Using cell-free extracts: plants, microorganisms, macrofungi, macroalgae

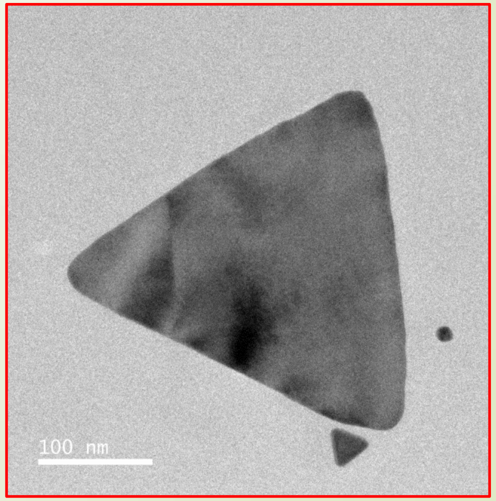
Using whole organisms: plants, mushrooms, seaweeds, microbial cells

Green synthesis of Nanoparticles

Solidago canadensis
Canada goldenrod







Mariychuk, R., Grulova, D., Grishchenko, L.M. *et al.* Green synthesis of non-spherical gold nanoparticles using *Solidago canadensis* L. extract. *Appl Nanosci* (2020). https://doi.org/10.1007/s13204-020-01406-x

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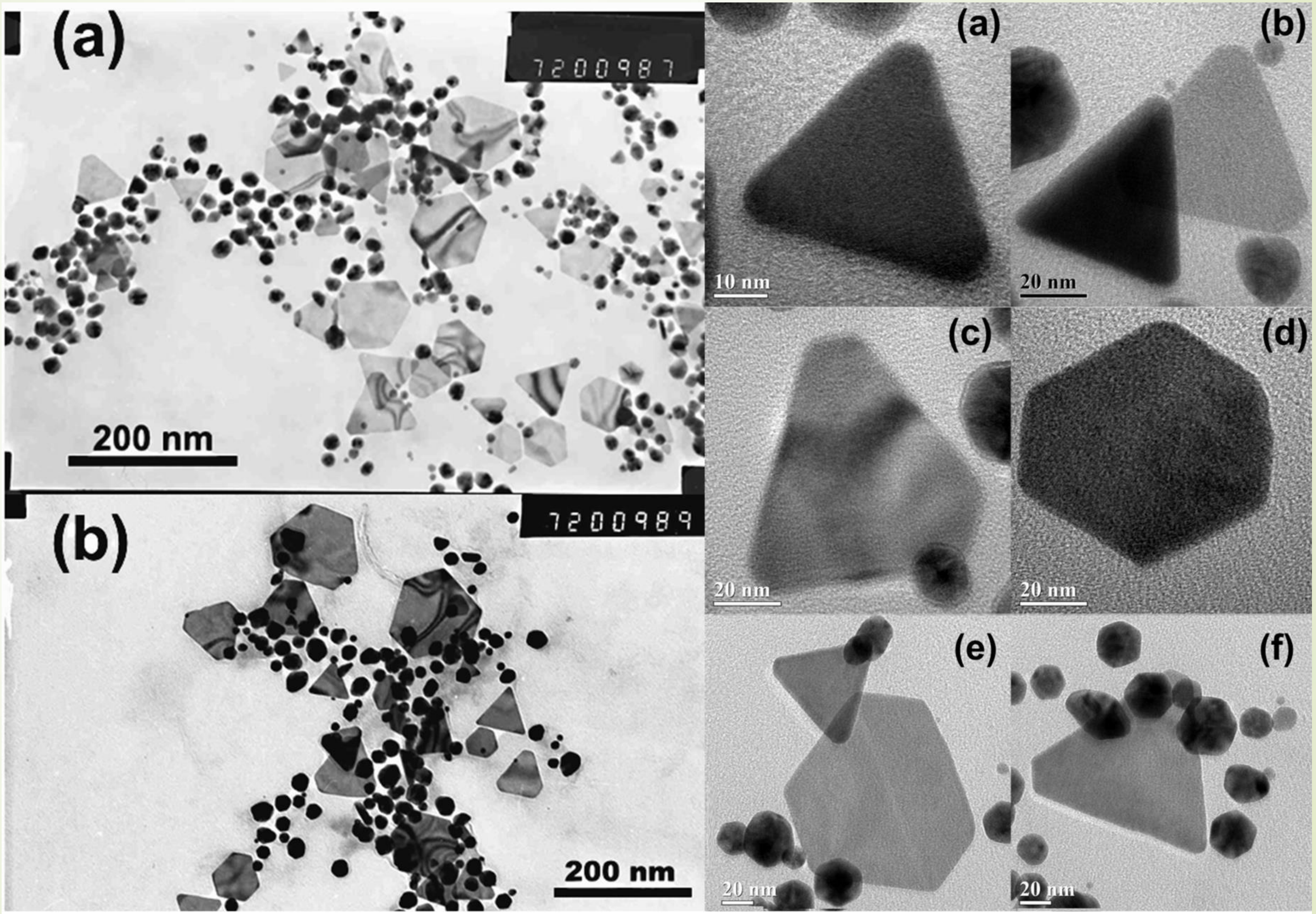
Green synthesis of Nanoparticles

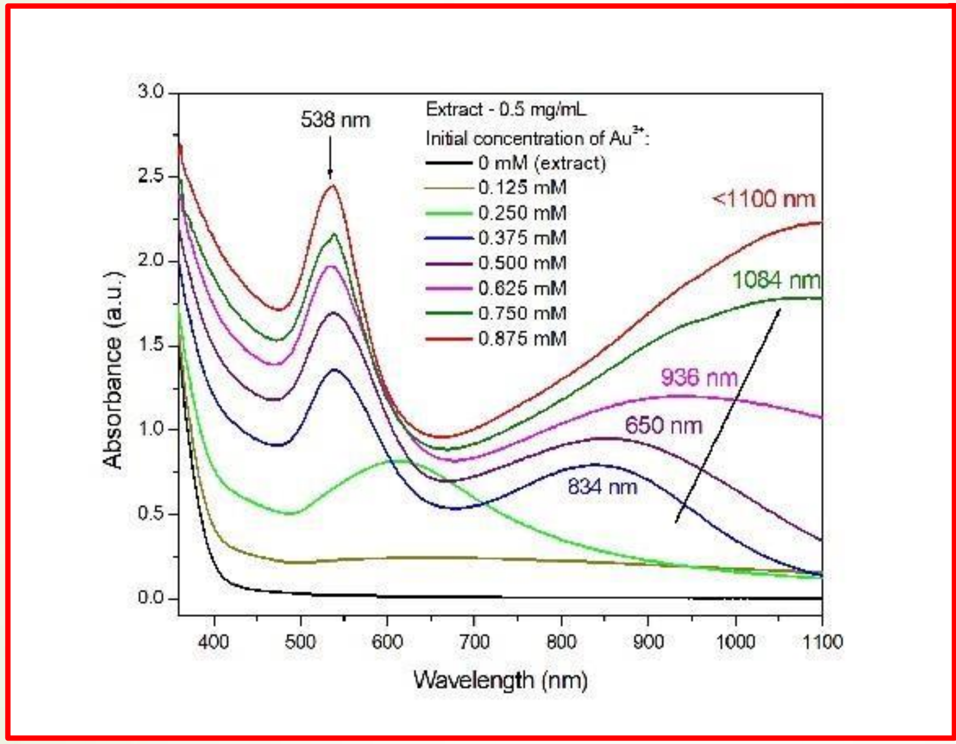


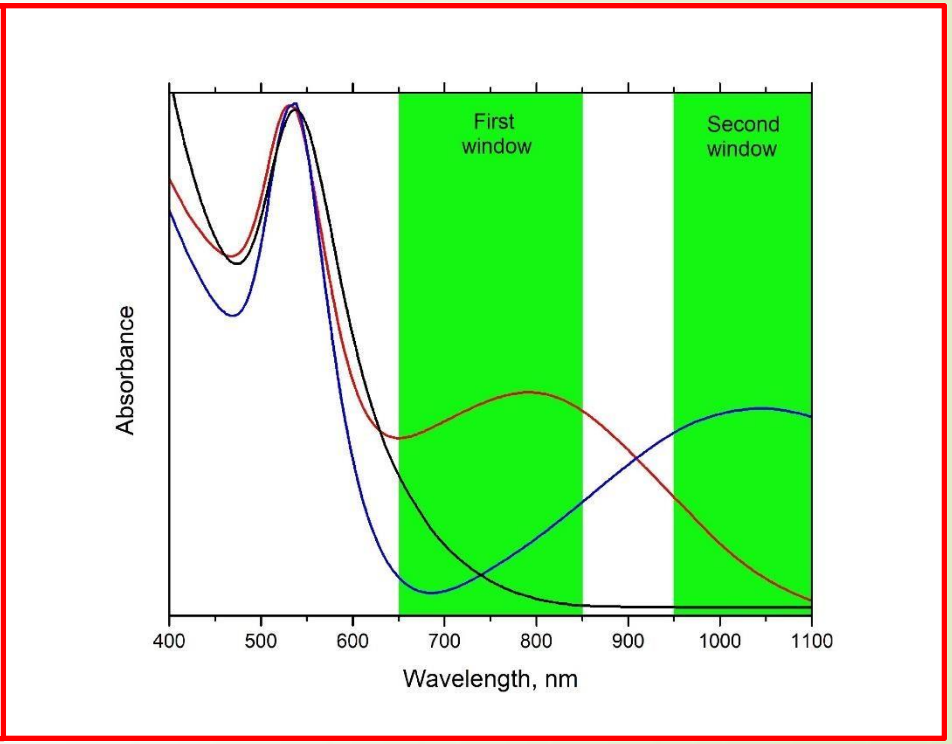
Left panel

Right panel

Green synthesis of Nanoparticles

Optical properties management

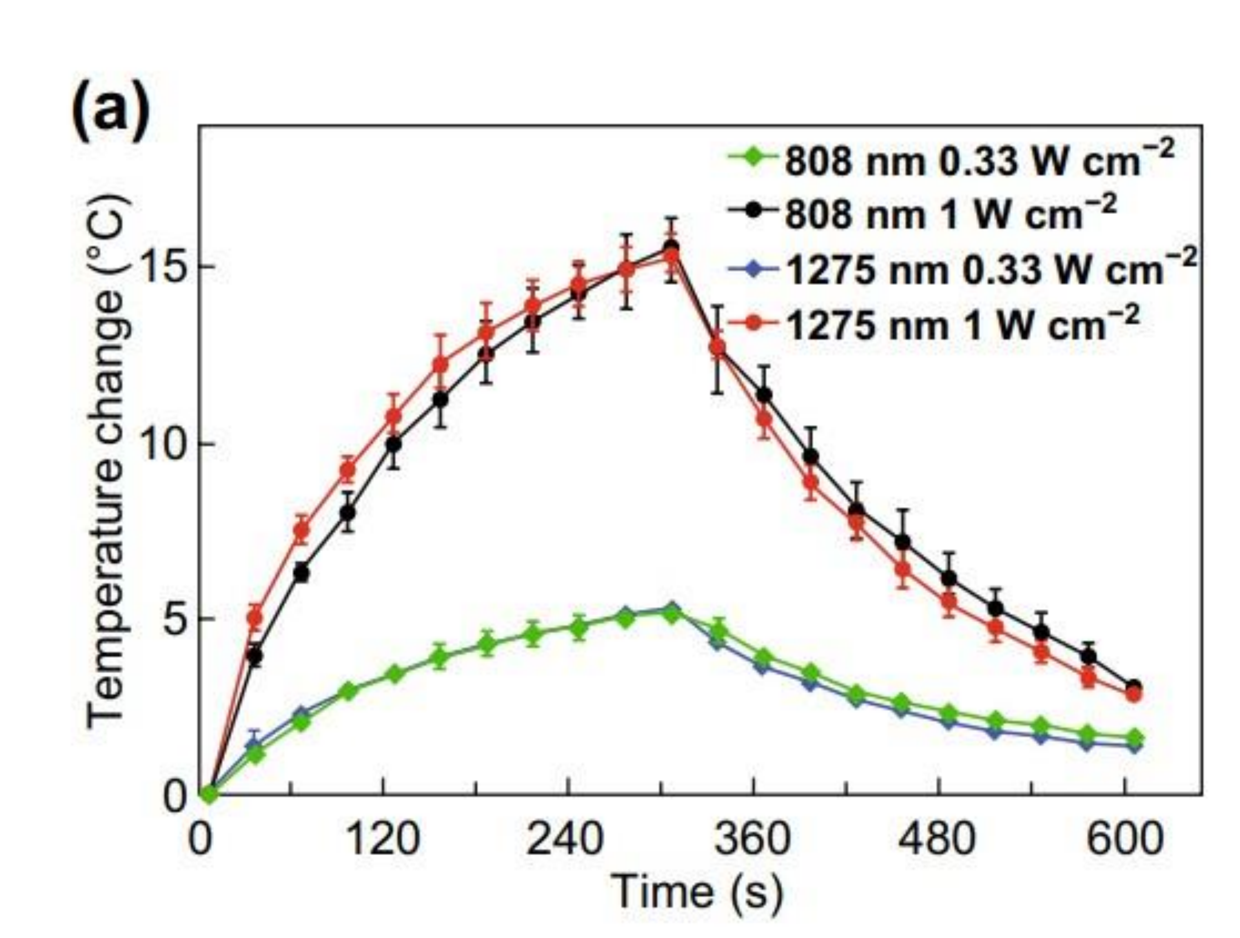




Mariychuk, R., Smolková, R. et al. The regularities of the ***Mentha piperita*** L. extract mediated synthesis of gold nanoparticles with a response in the infrared range (2022) Applied Nanoscience (Switzerland), 12 (4), pp. 1071-1083. DOI: 10.1007/s13204-021-01740-8

Green synthesis of Nanoparticles

Temperature rising experiments in vitro. Heating effects of 808 and 1275 nm laser.



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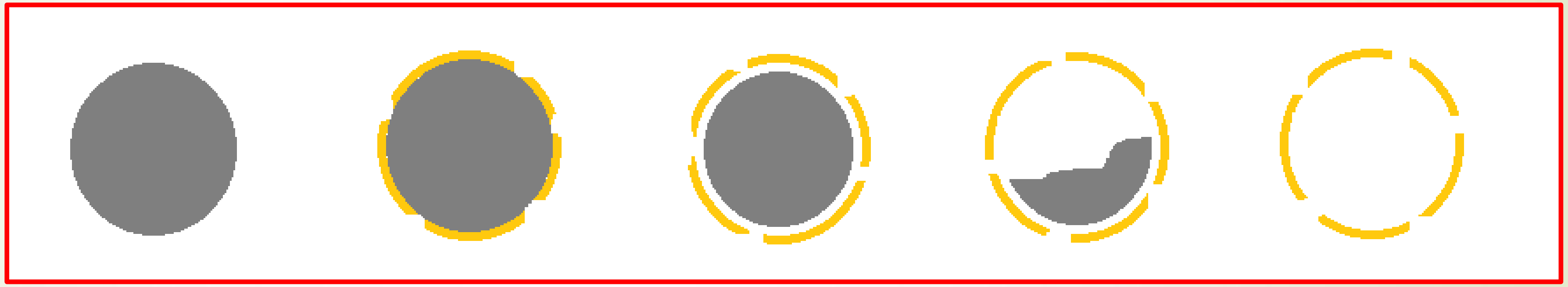
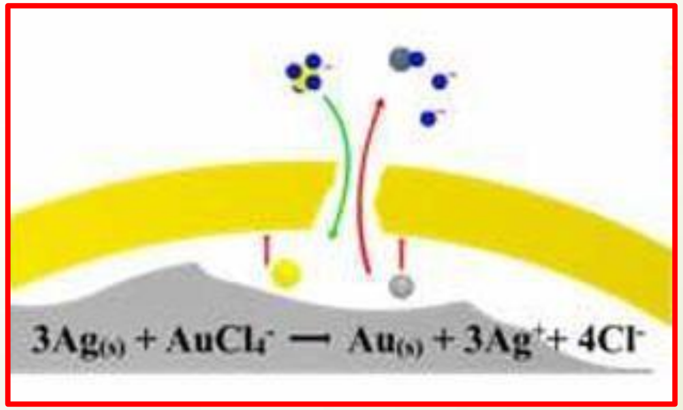
Green synthesis of Nanoparticles

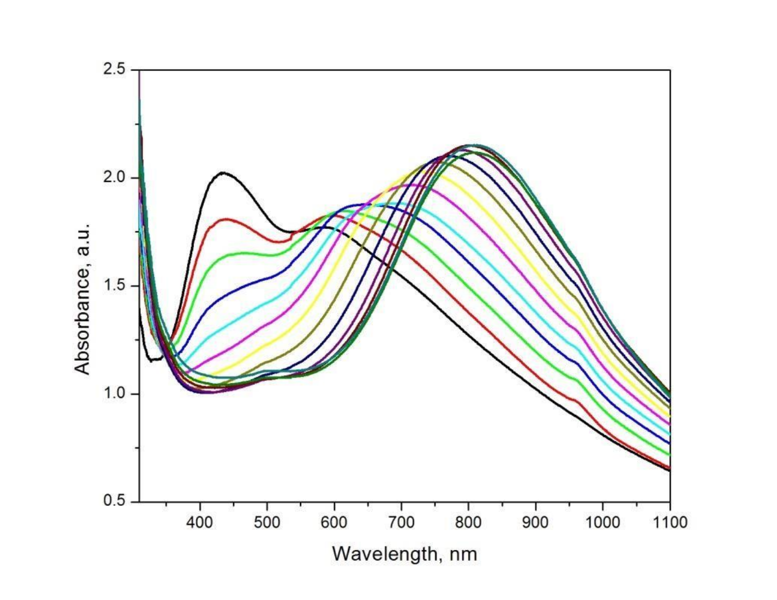
Galvanic exchange

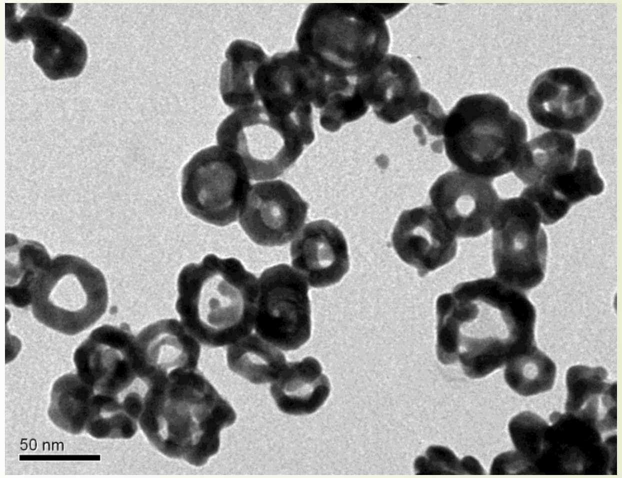
$3\,Ag^0 + Au^{3+} = 3\,Ag^+ + Au^0$

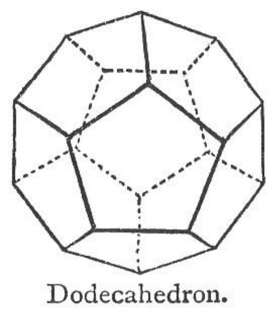


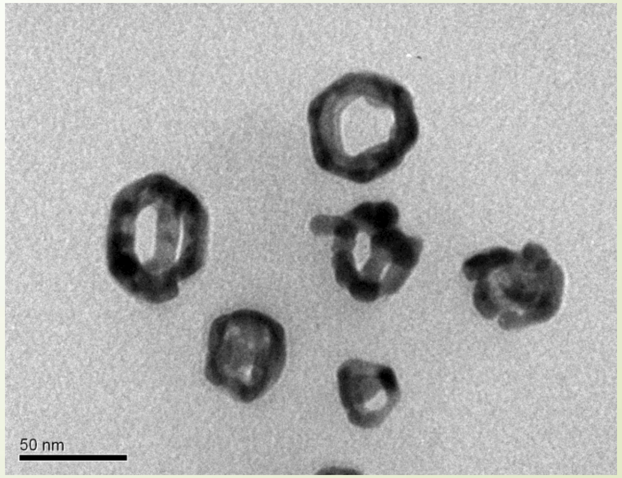


Green synthesis of Nanoparticles



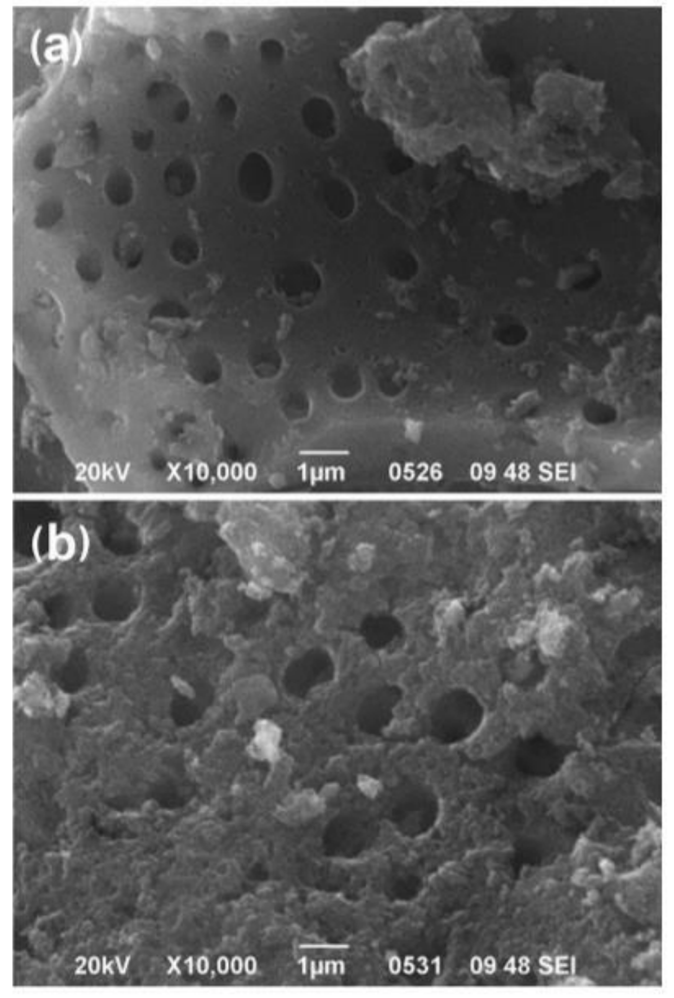






Nanomaterials

The active carbon was obtained from ***Prunus armeniaca*** fruit pits by physical activation with steam.



Diyuk, V.E., Mariychuk, R.T. & Lisnyak, V.V. J ***Therm Anal Calorim*** (2016) 124: 1119. https://doi.org/10.1007/s10973-015-5208-6

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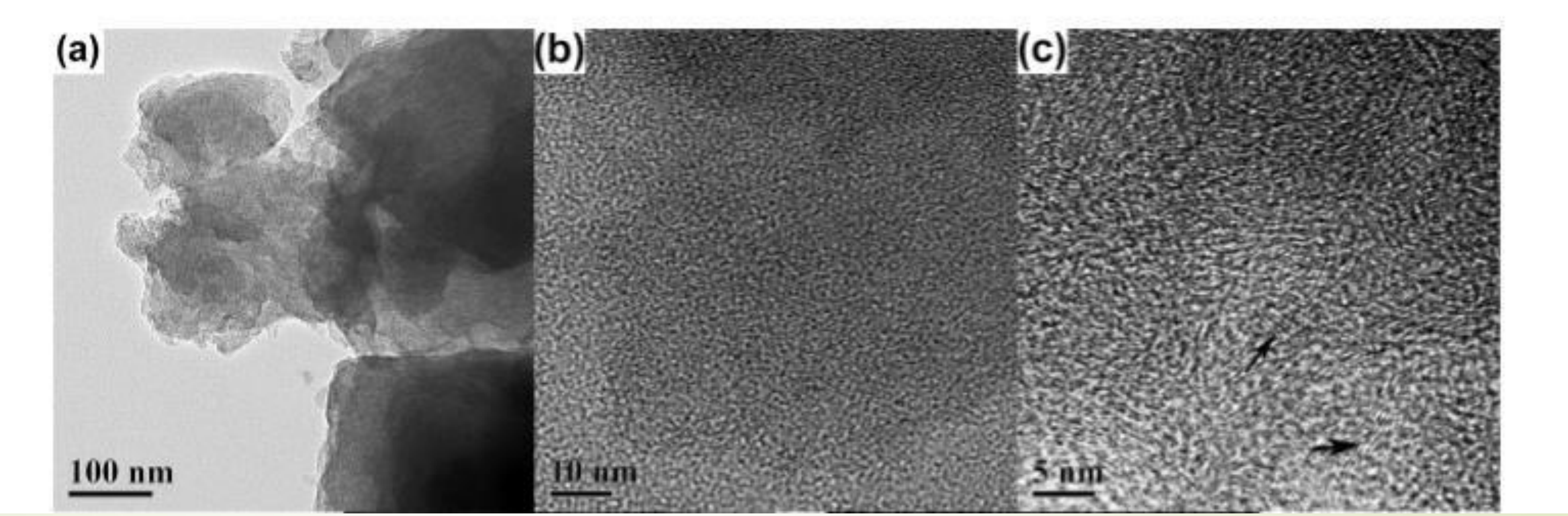
Nanomaterials

Nanoporous carbon materials from food waste



Grishchenko L.M., Diyuk VE., Mariychuk R.T. Et al. Surface reactivity of nanoporous carbons: preparation and physicochemical characterization of sulfonated activated carbon fibers. ***Applied Nanoscience*** **2020**. https://doi.org/10.1007/s13204-019-01069-3

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ВИСНОВКИ

IN SUMMARY,

GREEN CHEMISTRY IS…

- **Saving companies money by using less energy and fewer/safer chemicals, thus reducing the costs of pollution control and waste disposal.**

BECAUSE,

GREEN CHEMISTRY IS…

- Scientifically sound,
- Cost effective, and
- Leads toward a sustainable civilization.

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4. McKenzie, Lallie C., Lauren M. Huffman and James E. Hutchison. (2005) The Evolution of a Green Chemistry Laboratory Experiment: Greener Brominations of Stilbene. Journal of Chemical Education. 82(2). ISSN 0021-9584. DOI: 10.1021/ed082p306.

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5. Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., & Ludwig, C. (2015). The trajectory of the Anthropocene: The Great Acceleration. The Anthropocene Review, 2(1), 81–98. DOI: 10.1177/2053019614564785.
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7. Mariychuk, R., Porubská, J., Ostafin, M., Čaplovičová, M., Eliašová, A. (2020) Green synthesis of stable nanocolloids of monodisperse silver and gold nanoparticles using natural polyphenols from fruits of *Sambucus nigra* L. (2020) Applied Nanoscience. 10 (12), pp. 4545-4558. DOI: 10.1007/s13204-020-01324-y.

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ДЯКУЮ ЗА УВАГУ!