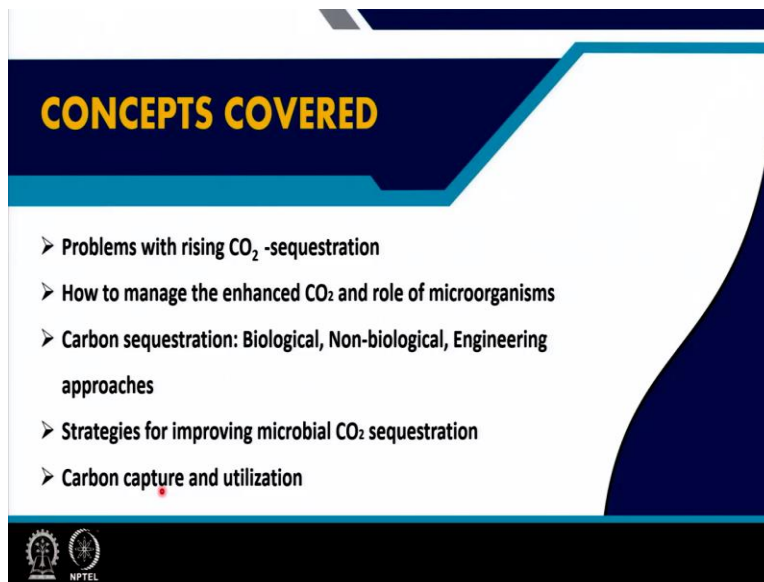


**Environmental Biotechnology**  
**Prof. Pinaki Sar**  
**Department of Biotechnology**  
**Indian Institute of Technology, Kharagpur**

**Lecture – 49**  
**Carbon Capture, Carbon Sequestration and Utilization**

Welcome to the 49th lecture of our course and in this particular lecture, we are going to talk about the carbon capture, sequestration and utilization processes and the role of environmental biotechnology and scope of environmental biotechnology in that.

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So, these are the following concepts which will be covered we will briefly discuss about the problem of rising CO concentration and then CO<sub>2</sub> sequestration and the carbon sequestration processes, particularly the biological one, will be highlighted. And strategies for improving the microbial CO<sub>2</sub> sequestration will be discussed in details and followed by these are the carbon capture and utilization processes will be are highlighted.

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**Elevated CO<sub>2</sub> is a partial cause of the complex phenomenon of climate change**

This problem urges the development of CO<sub>2</sub> sequestration techniques to capture CO<sub>2</sub> or limit its release

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Now elevated carbon dioxide is a partial cause of the complex phenomenon of climate change and these elevated CO<sub>2</sub> concentration is urging all of us towards the development of CO<sub>2</sub> sequestration techniques to capture the CO<sub>2</sub> from the atmosphere ought to reduce its release.

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**Problems with rising Carbon dioxide:**

- Carbon dioxide : Most important of
  - Absorbs less heat per molecule t
- Carbon dioxide: More abundant and
  - Increases in atmospheric carbon total energy imbalance that is ca

**COMBINED HEATING INFLUENCE OF GREENHOUSE GASES**

Reference: NOAA Climate.gov (Data from NOAA ESRL).

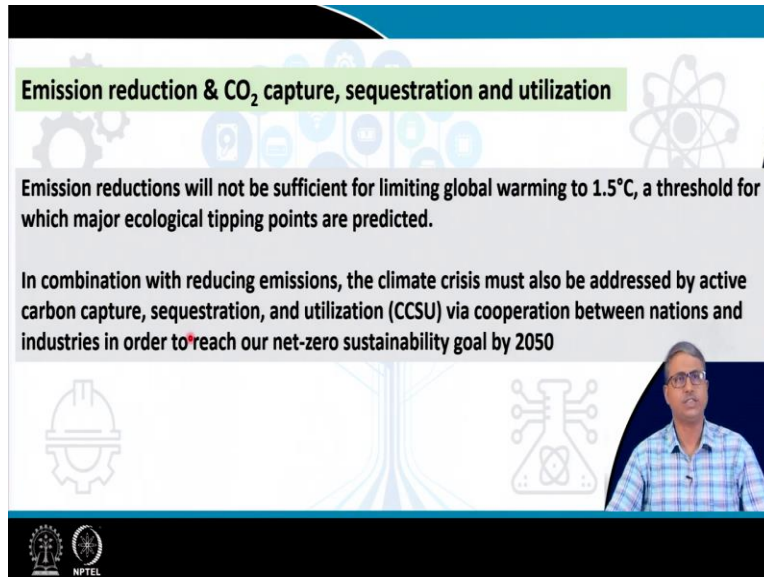
According to NOAA's Annual Greenhouse Gas Index (right axis) the combined heating influence of all major greenhouse gases has increased by 45% relative to 1990

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Now the problem with the rising carbon dioxide is multidimensional. It is considered to be one of the most important greenhouse gas it absorbs less heat part molecule than the greenhouse gases methane or nitrous oxide but it is more abundant and stays in the atmosphere a much longer. Increases in atmospheric carbon dioxide are considered to be responsible for about 2 thirds of the total energy imbalance that is causing the art temperature to rise and essentially, if you look at the data that is available for the for the NOAA's Annual Greenhouse Gas index.

The **the** combined hitting influence of all major greenhouse gases can be seen and we can identify that the role of carbon dioxide is pivotal.

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**Emission reduction & CO<sub>2</sub> capture, sequestration and utilization**

Emission reductions will not be sufficient for limiting global warming to 1.5°C, a threshold for which major ecological tipping points are predicted.

In combination with reducing emissions, the climate crisis must also be addressed by active carbon capture, sequestration, and utilization (CCSU) via cooperation between nations and industries in order to reach our net-zero sustainability goal by 2050

The slide features a background with faint icons of a gear, a lightbulb, a minus sign, a plus sign, a magnifying glass, and a molecular structure. At the bottom, there are icons of a hard hat, a tree, and a chemical flask. A small video inset shows a man in a blue plaid shirt speaking. The NPTEL logo is visible in the bottom left corner.

Now the emission reduction and show to capture sequestration and utilization is considered to be one of the priority areas of environmental biotechnology. Though physical and chemical methods are also developed, and in practice for mitigating this high carbon dioxide concentration presented the atmosphere. Now the emission reductions, who had mostly the physical and chemical technologies are more prominent.

It is found that these emissions reductions will not be sufficient for limiting the global warming to one point five degrees centigrade. A threshold which is considered and for a major ecological tipping point that is predicted. In combination with reducing emissions from the major industries who are releasing the carbon dioxide as part of their industrial processes, the climate crisis emerged due to this, rising carbon dioxide concentration must also be addressed by active carbon capture sequestration and its utilize by the cooperation between nations and industries in order to reach out to innate zero sustainability goal, which is said for the year 2050.


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**How to manage this enhanced CO<sub>2</sub> & role of microorganism:**

- Carbon Sequestration
  - Biological
  - Non-Biological/Physical
  - Engineering approach

New innovation and technology has enabled the possibility of carbon capture and sequestration (CCS), - with high investment costs and is akin to waste management.

More interest has been focused on CCSU biotechnology in order to create products that offset costs



Now how to manage this enhanced CO<sub>2</sub>. So, one idea is to reduce the emission that we talked about, that the industries are trying to develop technologies to reduce the emission, but at the other hand, we have the prospects are we have the opportunities to use technologies or develop technologies. Particularly using the micro organisms that sequestered or remove the atmospheric carbon dioxide and convert into a form which is safe and in the sequesters form a long period of time and more to that, if we can convert that carbon dioxide through biological systems, microorganisms in particular into valuable products.

So, carbon sequestration basically can be done either by biological or by physical approach or non biological approaches, and also using different tools technologies of engineering concepts. New innovation and technology which are being developed has enabled the possibility of carbon capture and sequestration, which is conventionally abbreviated as CCS with high investment cost and is akin to waste management.

That is **that is** considered to be one of the drawbacks of the non-biological processes because investment cost and also the waste management with each are likely to be generated from that. So, more interest has been focused CCSU biotechnology. Now U comes because of the utilization part. So, carbon capture and sequestration CCS and then U utilization, so, it is not only sequestering the carbon, but also converting the sequestered cardboard into some form, which is useful for the humankind or for our industry or other purposes.

So, there biotechnology plays a big role, and that actually is considered to be creating a value a chain from the from the carbon which is being captured.

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**How to get these new CCSU technologies?**

An important part of the solution will be realized by innovative biotechnologies that recapitulate and tap into the large-scale ecosystems that underpin major global carbon cycles

The innovation process will be expedited by translating fundamental knowledge we already possess into technology that stores carbon within the earth's large biomes and/or delivers new value chains by harnessing unique biological functions.

The slide features a background with a stylized tree and various icons representing technology and biology. A small inset video shows a man in a blue plaid shirt speaking. Logos for NPTEL and other institutions are visible at the bottom.

Now how to get these new CCSU technologies: An important part of the solution will be realized by innovative biotechnologies that recapitulate and tap the large scale ecosystem that underpin major global carbon cycle. Now, it is important to understand that these large scale ecosystems like the soil like the ocean, like the deep earth crust they have been cycling carbon for billion years. From the very beginning of this art or the planet, they are cycling or their **their their** the house or there, the place where the carbon is being constant being recycled from different solid phase or rock hosted carbon to the **the** atmospheric carbon.

So, it is important that biotechnologist, particularly the environmental biology try to look back and see how these large scale ecosystems are functioning and what we can learn from them, the global carbon cycles and then implement those in developing the CCSU. The innovation process will also be expedited by translating the fundamental knowledge we already deposit because we have lots of knowledge information about the cardboard cycling, which are taking place in these large ecosystems.

And we need to actually translate this knowledge into technology that store carbon within the art

large biomes are delivered to new valuation like, for example soil, soil carbon cycle is known pretty well known, but if we want to develop a technology. We need to look into the soil carbon cycle into that aspect. So, that the carbon which is which is naturally sequestered within the within the soil system can be developed as a process to mitigate this high carbon dioxide into the atmosphere.

And not only that we need to also develop technology from our knowledge base. So, that is sequester carbon maybe from soil itself is converted to some kind of valuable products and for that we need to harness the unique biological functions.

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**How will this be done?**

We need to combine contemporary ideas from ecology and biotechnology associated with three major biospheres:

- Plant-soil systems
- Deep subsurface
- Marine microbial ecosystems

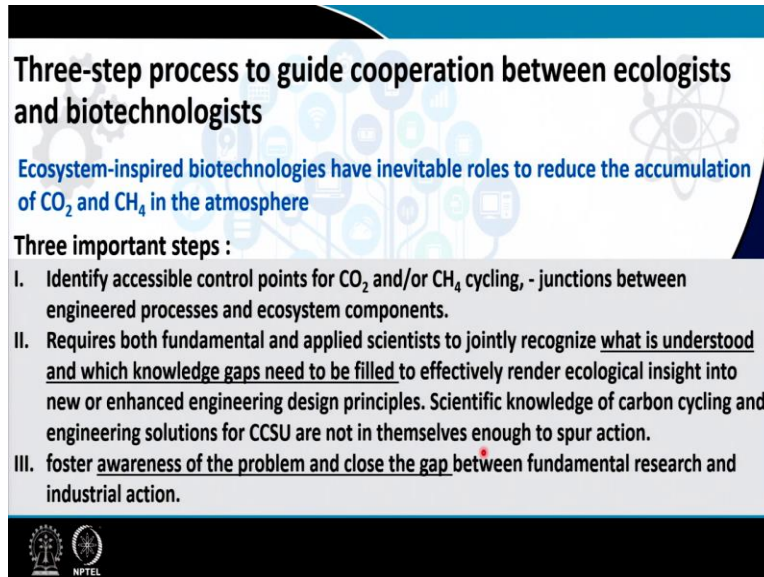
The slide features a central graphic of a tree with various icons (gears, a laptop, a microscope, a hard hat, a beaker) integrated into its branches. A small inset video of a man in a blue plaid shirt is visible in the bottom right corner. The NPTEL logo is at the bottom left.

Now how will this be done. So, we need to combine the contemporary ideas from the ecology and biotechnology, which are basically the core of the environmental biotechnology and which are associated with three major biosphere plant soil systems, deep subsurface and marine microbial ecosystems,. So, these three systems are identified because these are representing the largest ecosystems where natural carbon cycles are going on.

And so, far, we have partly understood, at least with respect to some of these systems, like a planned soil system for example to some extent the marine microbial ecosystem. Deep subsurface, however is not very well understood by the scientists, but once we identify that, that, that, that can be a large repository of the global carbon. Increased attention has been paid in last

2 decades, at least to understand the deep subsurface carbon cycling processes.

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**Three-step process to guide cooperation between ecologists and biotechnologists**

Ecosystem-inspired biotechnologies have inevitable roles to reduce the accumulation of CO<sub>2</sub> and CH<sub>4</sub> in the atmosphere

**Three important steps :**

- I. Identify accessible control points for CO<sub>2</sub> and/or CH<sub>4</sub> cycling, - junctions between engineered processes and ecosystem components.
- II. Requires both fundamental and applied scientists to jointly recognize what is understood and which knowledge gaps need to be filled to effectively render ecological insight into new or enhanced engineering design principles. Scientific knowledge of carbon cycling and engineering solutions for CCSU are not in themselves enough to spur action.
- III. foster awareness of the problem and close the gap between fundamental research and industrial action.



Now there is a three step process identified to guide the cooperation between the ecologist and the biotechnologist, more specifically for the environmental biotechnologist. So, we will see what are these three step processes? These are called ecosystem inspired by technologies, and these have inevitable roles to reduce the accumulation of CO<sub>2</sub> and methane in the atmosphere. So, what are these steps? The first step is to identify the accessible control points are for the CO<sub>2</sub> and our methane cycling.

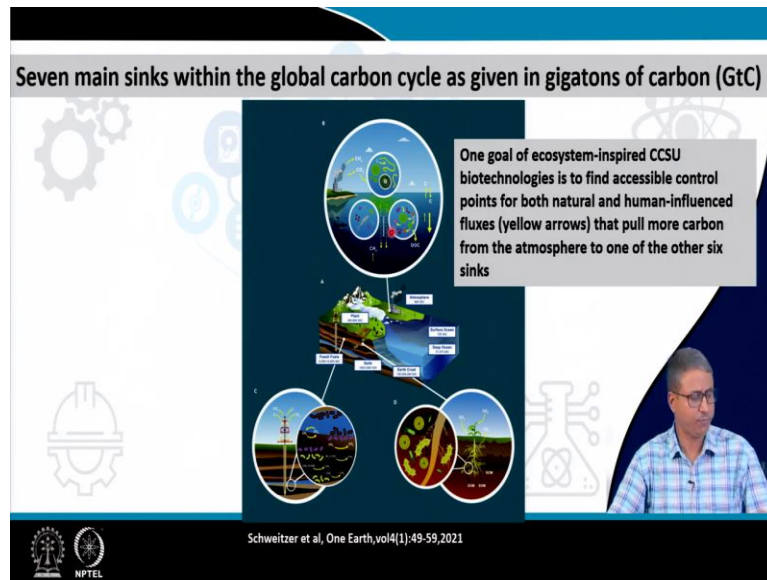
Because we know that within the soil system, this carbon and submitted are being cycled. Rather the carbon is cycled through this carbon dioxide and methane. Now what are the accessible control point what are the junctions between the engineered processes and ecosystem component and that requires possibly the fundamental and applied scientists to work jointly and recognize what is already understood and which knowledge gaps need to be filled to effectively render the ecological insights into new or enhanced engineering design principles.

So, that is something **which help** which will help us to translate the knowledge that we have about the carbon cycling into an effective technology. Now the scientific knowledge of carbon cycling and engineering solution for CCSU are not in themselves, enough to spark the action knowledge is not enough we have to actually get the **the** knowledge gaps identified and work

together so, that we can feel these gaps and developed the technologies and translate technology into effective technologies.

And this also requires the third step is fostering the awareness of the problem and close the gap between the fundamental research and industrial action.

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So, it has been clearly identified in a very recent paper in one earth. So, the references cited here is all, and also we have placed the references back of the end of the presentation that seven men sinks are there within the global carbon site. So, this has been this has been known for decades, but if we want to look very critically that the seven sinks are very well delineated like the atmosphere in the plant in the **the** problem of the fossil fuels and the soil in art craft in deep ocean and in the surface motion.

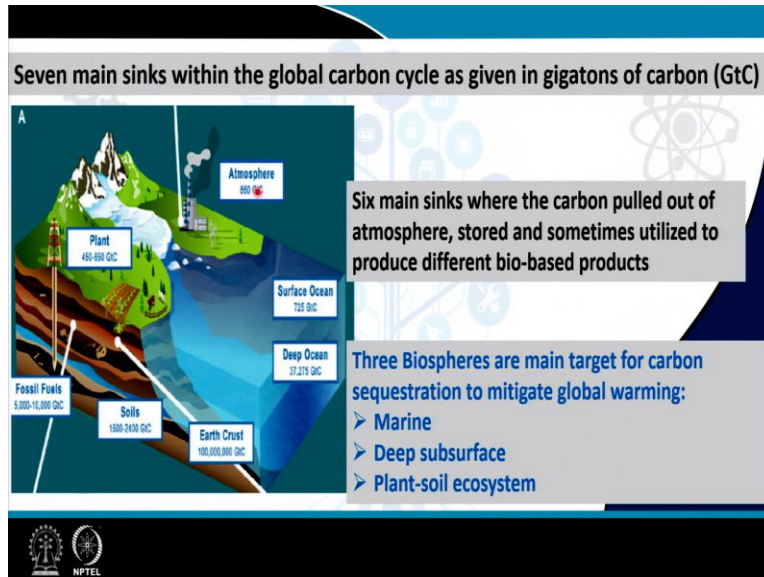
So, these are the seven things identified. Now one goal of ecosystem inspired CCSU related biotechnologies is to find the control points. Control points in order to party both natural and human influenced fluxes. So, how natural carbon flux, like the yellow arrows are indicating the carbon movement how the entrepreneurial activities and how the natural activities are responsible for controlling the carbon fluxes within the seven sink.

And that possibly will be important to identify the point that pulls more carbon from the



atmosphere to one of the other six sinks. So, one is the atmosphere, but the other six sinks are there where the carbon can be sequestered and possibly they can be converted to useful product also. Now the points of control are very important.

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Now these are the six sinks that could be potentially utilized except the seventh one that is the atmospheric one because we want carbon to move from atmosphere to rest of the six sinks. Now these six main sinks where the carbon pulled out atmosphere stored, and sometimes it can be utilized to produce defined bio based products the second interesting aspect of the entire story of the environmental biotechnology based carbon sequestration.

Because there we think of the **the** circular economy or maybe halogen system that we convert the carbon not only remove the carbon, but also try to convert the carbon into some valuable products and the three biosphere,. So, these six things together, we can actually converge, we can think of converging them into three biospheres, which are considered to be the main targets for carbon sequestration to mitigate the global warming.

And these are the marine system that is, oceanic both the surface ocean and the deep ocean deep subsurface of the terrestrial crust or **or** the earth crust, plant soil ecosystem which is where the entire soil is found to be the major part of the biome where the carbon can be sequestered and can be utilized or can be converted to sample now.

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The deep subsurface: One of the largest human-caused releases of carbon into the atmosphere due to the extraction of fossil fuels

although the microbial functional capacity for the turnover of deep carbon is still unknown and has great potential for influencing geologic storage

The plant-soil ecosystem/rhizosphere: primary producer plants that are able to pump CO<sub>2</sub> from the atmosphere into the soil.

C- can be stored in soils depending on the root system and how it interacts with the rhizosphere and soil microbiome that can convert soil organic matter

Schweitzer et al, One Earth, vol4(1):49-59,2021

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Let us see these parts in little more details. Now the deep subsurface, particularly, is less known but in recent past, as I mentioned last 2 decades, we see very, very interesting observations are coming and people are gaining interest in this particular domain of the earth that this is considered to be one of the largest human caused releases of carbon into the atmosphere due to the instruction of fossil fuel.

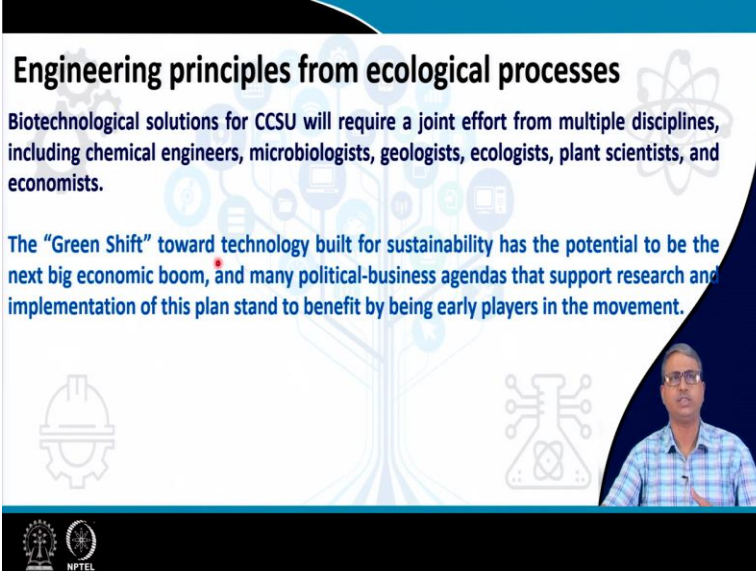
So, we have been continuously dragging the fossil fuels from these deep subsurface, but how about returning this carbon dioxide back to this deep subsurface, because naturally, we the call the fossil fuel, the natural gases, these are the source of all the carbons that we are using today. And most of the carbon dioxide present in the atmosphere is actually coming from the particularly the anthropogenic release component.

But how about this, that developing technologies particularly biotechnologies; where the microbial functional capacity can be enhanced. So, that the turnover of the deep carbon can be reversed so, that the carbon can be stored instead of the carbon is lost as a gaseous form. And it is interesting that this microbial functional capacity within the deep subsurface of the earth crust remain largely unknown and it has shown great potential for influencing with the geological carbon storage.

The second aspect is the **the** plant soil ecosystem or the we conventionally call the rhizospheric region because the primary producer are the plants who are naturally able to capture the atmospheric carbon dioxide and during their photosynthetic convert this carbon dioxide into complex organic molecule. And part of these molecules are being continuously pumped into the soil system because the plants are having profuse route system and through the routes, they release a large amount of carbon.

Now carbon can be stored in soil depending on the root system and how it interacts with the rhizosphere that the root associated soil zone and the soil microbiome. So, there are actually three components one is the plant root system, another is the plant root **root** system associated soil system, and then the rhizospheric and the soil bulk microbiome, which are actually responsible for controlling the fate of the organic matter, which is being released or produced by these green plants within this soil. So, this needs to be looked into in detail.

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**Engineering principles from ecological processes**

Biotechnological solutions for CCSU will require a joint effort from multiple disciplines, including chemical engineers, microbiologists, geologists, ecologists, plant scientists, and economists.

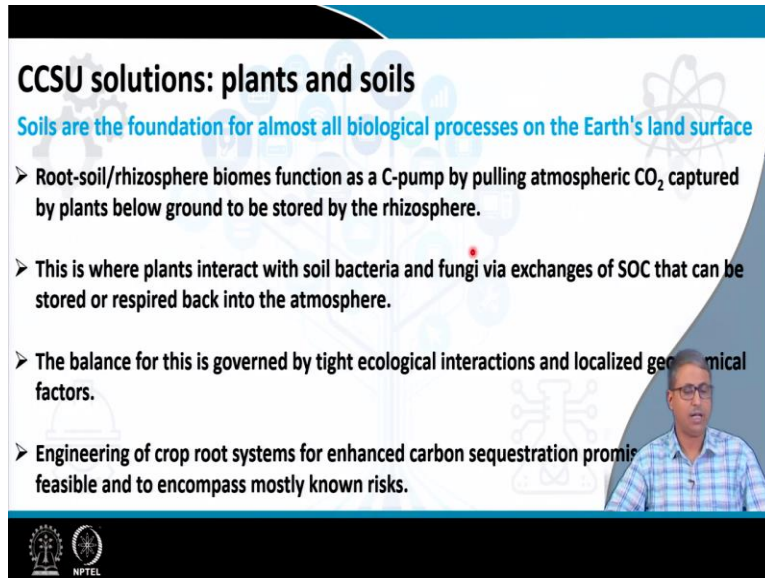
The “Green Shift” toward technology built for sustainability has the potential to be the next big economic boom, and many political-business agendas that support research and implementation of this plan stand to benefit by being early players in the movement.

The slide features a background with a stylized tree and various icons representing engineering and biology. A small inset video shows a man in a blue plaid shirt speaking. The NPTEL logo is visible in the bottom left corner.

Now with respect to the engineering principle from ecological processes, the biotechnological solutions for CCSU will require the joint effort from multiple disciplines, including the chemical engineers, microbiologist. geologist, ecologist, plant scientist and also economist. And the green shift concept has emerged, which is basically green sipped we call towards technology built for sustainability that has shown the potential to be the next big economic boom.

And many political business agendas that support research and implementation of this plan stand to benefit by being early players in the movement.

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**CCSU solutions: plants and soils**

Soils are the foundation for almost all biological processes on the Earth's land surface

- Root-soil/rhizosphere biomes function as a C-pump by pulling atmospheric CO<sub>2</sub> captured by plants below ground to be stored by the rhizosphere.
- This is where plants interact with soil bacteria and fungi via exchanges of SOC that can be stored or respired back into the atmosphere.
- The balance for this is governed by tight ecological interactions and localized geochemical factors.
- Engineering of crop root systems for enhanced carbon sequestration promises to be feasible and to encompass mostly known risks.

The slide includes a video inset of a man in a plaid shirt speaking, and logos for CCSU and NPTEL at the bottom.

Now first, we will see the plants and soil soils are the foundation, as I mentioned. for almost all biological processes on the earth land and root soil rizhosphere function as a carbon pump by pulling the atmospheric carbon dioxide captured by the plants and then below the ground, transferred it and stored in the rizhospheric region and in this region. The plants interact with soil bacteria and fungi via the exchange of SOC that is, the soil organic carbon that can be stored or respired back into the atmosphere.

So, basically the root system is delivering the carbon which is originally fixed from the atmospheric carbon, and then they are releasing the SOC's. These SOC's are being metabolized by the organisms, presenting the rizhosphere in the carbon dioxide, and this SOC organic carbon is getting converted into carbon dioxide and the carbon dioxide or methane it is been coming out into the atmosphere.

Now the balance for this, that how much carbon will be assimilated by the plant and released into the soil as a SOC and then how much SOC will be oxidized by just file microorganisms, and they will be converting them into gaseous form. So, there must be a balance, and this balance for adequate carbon sequestration is governed by the tight ecological interactions and localized

geochemical factors.

The engineering of the crop root systems for enhanced carbon sequestration promise basically to be to be feasible and to encompass mostly known risk.

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The slide is titled "CCSU solutions: plants and soil". It features a diagram on the left showing two plants with roots extending into the soil. Yellow arrows indicate the transfer of carbon from the plants to the soil. A magnifying glass highlights a section of the soil labeled "Suberin". To the right of the diagram is a graph showing the "Rate of Decomposition" on the y-axis and depth on the x-axis. The graph shows a downward-sloping curve, indicating that the rate of decomposition decreases as depth increases. Below the diagram, there is a caption: "Atmospheric carbon drawdown from an engineered plant-soil ecosystem Schweitzer et al, One Earth, vol4(1):49-59, 2021". To the right of the diagram, there is a list of bullet points explaining the concepts.

The yellow arrows represent the transfer of carbon.

- Plants can be selected or designed to have deeper root systems, -creates better C sink potential in the localized soil.
- This is because the rate of soil organic matter decomposition decreases with depth.
- Plants can also be selected or designed to produce biopolymers that resist decomposition (e.g., suberin (black dots), which is a major component of cork and able to resist decomposition)- presenting an opportunity for crop-based CCS

Atmospheric carbon drawdown from an engineered plant-soil ecosystem Schweitzer et al, One Earth, vol4(1):49-59, 2021

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Now in case of plant system with a league, see there are actually 2 aspects. One aspect is the plants can be selected to design having a very deep root system, creating the better carbon sink potential in the localised soil. So, the deposit route, more carbon will be sequestered in the soil zone because the rate of soil organic matter decomposition decreases with get deeper, it will be less will be the oxygen level available, and the activity of the aerobic heterotrophic microorganisms oxidizing the organic card, would it be less.

Plants can also be selected or designed to produce biopolymers that resist the composition, for example, the suberin type of molecules, which are represented here as the which is a major component of cork and able to resist decomposition. So, so plants can be selected who are able to naturally produce more suberin type of molecules, and these molecules will stop the ready decomposition of this organic material that would possibly present an opportunity for crop based CCS.

So, on the above ground we can grow the crop harvest the fruits, vegetables, flowers, leaves,

etcetera, but at the same time, we can allow more carbon to be sequestered safely within the soil.

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**The deep biosphere**

- ❑ The deep subsurface is largely unexplored and remains a mysterious environment.
- ❑ “deep” subsurface refers to the biomes below the soil and ocean floor sediments where community composition and/or function is distinct from those inhabiting the overlying organic soil layers or sediments interfacing with water columns
- ❑ Complex microbial communities dominate these environments and have a high functional capacity for the turnover of CO<sub>2</sub> and CH<sub>4</sub>
- ❑ The deep subsurface is spatially heterogeneous, and microbial functions change depending on location, which also affects long-term geological storage of carbon

The slide features a blue header and footer. The footer contains the NPTEL logo and a small video inset of a man in a blue plaid shirt speaking. The background of the slide is white with faint icons of a hard hat, a tree, and a beaker.

Second is the deep biosphere, the deep subsurface is largely unexplored and remains a mysterious environment. And when we say it is a deep surface, it is a few meters below the top surface and it is referring to the biomes below soil ocean floor sediment where community composition, microbial community composition and the functions microbial community functions and are found to be different from those inhabiting the overlying organic soil layer or sediment interfacing the water columns in place of the **the** oceanic system.

So, the both oceanic deep subsurface and the terrestrial deep sub surfaces are found to play very important role in sequestering the carbon. Complex microbial communities are found to dominate these environments both the oceanic crust, as well as the terrestrial crust and these organisms, as I mentioned, are not very well characterized, but they show potential high functional capacity for the turnover of carbon dioxide and methane.

Deep subsurface is specially heterogeneous from place to place because of the composition of the rock crust and microbial functions also will change depending upon the data, depending upon the location, availability of different substrate, etcetera which also affects long term geological storage of the carbon.

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## Microbial biotechnologies

Microbial biotechnologies have been developed to prevent CO<sub>2</sub> leakage from wells and adjacent geological formations in the deep subsurface

These innovations harness naturally occurring microbial processes associated with the attachment, biomineralization, and formation of biofilms

The naturally occurring processes will precipitate CO<sub>2</sub> into a carbonated sediment over very long time periods (tens of thousands of years), demonstrating deep subsurface sequestration potential.

Innovations in microbial biotechnologies have shown that it is possible to enhance the carbonate precipitation (calcium carbonate) and biomineralization process using several microbial biofilm-forming species.



One of the approaches was the injection of the carbon in the basaltic crust, where you can see that there are several efforts are being internationally done where we can see that the water and carbon dioxide is injected into the basaltic rock crust so, that long term storage of carbonate minerals can be achieved. So, this is how to be an attractive strategy, it is called geo sequestration of carbon dioxide, particularly in the basaltic crust.

Because the technology for injecting something into the underground system is already existed because of the microbial enhanced oil recovery or something similar, and it has already been applied for **for** example, the oil recovery although geologic CO<sub>2</sub> sequestration has a key role to play in managing atmospheric carbon dioxide. And already, as I mentioned, being practiced in several countries and several places, many current technologies are viable only for temporary storage.

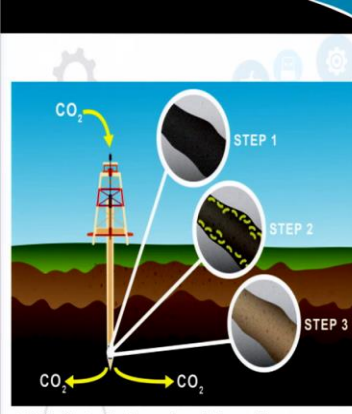
Meaning; that more innovation is required to fully understand the carbon dioxide sequestration and long term storage of the carbon, particularly considering the leakage factor. Hence, while the deep subsurface represent a major scene for CO<sub>2</sub> more knowledge need to be gained or you should understand the resident microorganisms present in the this **geogenetic** geological startup where the carbon dioxide is stored.

So, that we can enhance or limit the long term storage maybe the leakage can be controlled or the

enhanced CO<sub>2</sub> carbonate formation or mineralization can be far formed. Now microbial biotechnologies have been developed to prevent CO<sub>2</sub> leakage from example from the oils and adjusted geology formation in the deep subsurface. These innovations harnessed naturally occurring microbes microbial process associated with the attachment, bio, mineralization. and formation of biofuel underground where the CO<sub>2</sub> is being injected.

The naturally occurring process will precipitate CO<sub>2</sub> into the carbonate or carbonated sediment over a very long period of time tens of thousands of years, demonstrating deep surface sequestration potential. However, innovations in microbial biotechnology has to be done more has to be done because we have seen that it is possible to enhance the carbonate precipitation and by mineralization, but more research and development of technologies are required.

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These microbial biofilms have been shown to be effective at plugging pore channels or creating reactive biofilm barriers, which can reduce flow or mass transport through porous geologic formations, thereby helping prevent well leakage.

More recently, a biofilm barrier technology was applied by harnessing microbially induced calcite precipitation which can be applied to a range of geoscience and engineering applications (CCS biotechnology), including sealing leaky wells, amending or improving construction materials, cementing porous media, environmental remediation, and containment of nuclear waste.

CCS biofilm technology using existing well infrastructure to inject CO<sub>2</sub> into the deep subsurface  
Schweitzer et al, One Earth, vol4(1):49-59,2021

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So, some of the aspects like the CCS biofilm technology, which helped in three steps like the microbial biofilm can actually allow in **in** effective plugging up the pore channels over there.

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## The deep subsurface contains high microbial functional capacity for cycling of C compounds

The three steps depict the use of biocement to seal cracks, leaks, or channels in the deep subsurface, specifically of a wellbore

Step 1 represents the crack in the wellbore to seal

Step 2 represents the injection or stimulation of microbial communities that form biofilms and produce an extracellular polymeric substance, which will attach and stimulate growth along cracks within geologic formations

Step 3 represents bacterially induced biomineralization, specifically calcium carbonate precipitates that can act as a biocement sealant.

Schweitzer et al, One Earth, vol4(1):49-59,2021

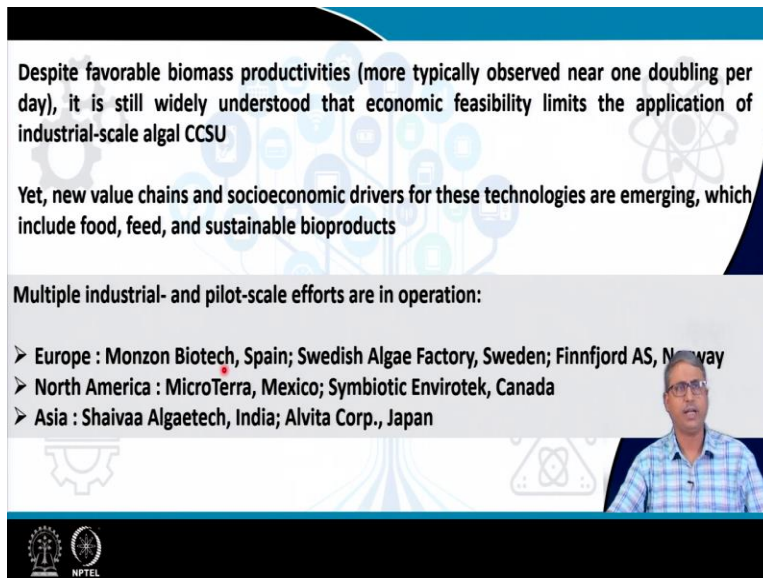
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And we can see that there are definite advantages for this. The deep subsurface contains high microbial functional capacity for cycling carbon compound. And biotechnologies that seal the wellbore to reduce the leaking of CO<sub>2</sub> or methane are being developed to manage the carbon storage. Now there are three steps into this. These three steps are used to biopsy meant the seal cracks, leaks or channels in the deep surface specifically of the well bore.

Step one in this case represent the crack in the wellbore to seal. So, the microbes form by a film and help in selling this wellbore. Crack in the wellbore. The second step is injection or stimulation of the natural microbial committee that form biofilm and produce an extracellular polymeric substance EPS material, which will attach and stimulate growth along the cracks within the geologic formation.

So that is the step 2 and in step three bacteria bio mineralization process can be induced, specifically the carbon calcium carbonate precipitation that can act as a bio cement or sealant to seal the leakage, thereby allowing the long term of sequestration and innovating the leakage of the carbon dioxide underground of mosquito studying startup.

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A presentation slide with a blue and white background. The text is as follows:

Despite favorable biomass productivities (more typically observed near one doubling per day), it is still widely understood that economic feasibility limits the application of industrial-scale algal CCSU

Yet, new value chains and socioeconomic drivers for these technologies are emerging, which include food, feed, and sustainable bioproducts

Multiple industrial- and pilot-scale efforts are in operation:

- Europe : Monzon Biotech, Spain; Swedish Algae Factory, Sweden; Finnjord AS, Norway
- North America : MicroTerra, Mexico; Symbiotic Envirotek, Canada
- Asia : Shaivaa Algaetech, India; Alvita Corp., Japan

The slide also features a small inset video of a man in a blue plaid shirt speaking, and logos for a university and NPTEL at the bottom left.

Similarly, the marine microbiomes and microbial biotechnology are also gaining importance because the photosynthetic microbes specifically, the algae and cyanobacteria, they have shown enormous potential marine phytoplankton, benthic microalgae, the atoms they are showing huge potential because they can contribute to the 20% of the global primary productivity, for example, and despite the favorable biomass productivities it is still widely understood that economic feasibility limits the application of industrial scale algal CCSU.

It new values value and socioeconomic drivers for these technologies are emerging, which includes the food, feed and sustainable bioproducts, particularly from the marine organisms. And multiple industrial and pilot scale efforts are in operation, particularly with respect to the marine carbon sequestration and utilization, including Europe, North America and Asia.

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## Marine microbial ecology offers multiple roadmaps for new CCSU technologies

Our oceans play a critical role in global carbon sequestration by exerting control over atmospheric carbon concentrations

Marine microbiomes help facilitate this through photosynthetic primary productivity, resulting in large amounts of dissolved organic matter (DOM) being stored in our oceans.

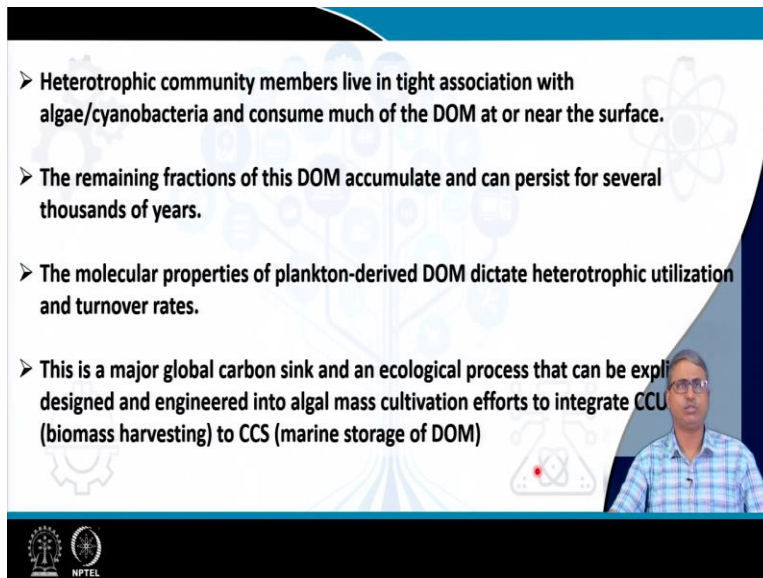
A marine microbial ecology offers actually multiple roadmaps for new CCSU technology because our oceans play critical role in global carbon sequestration particularly, the many microbiomes help facilitate to the photosynthetic primary productivity and resulting in large amount of dissolved organic matter DOM being stored in our ocean.

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## Industrial carbon capture, utilization, and storage via marine microorganisms

So, this **this** can be harnessed, so, that the more and more carbon dioxide can be converted into DOM by the microorganisms, which are present in the ocean.

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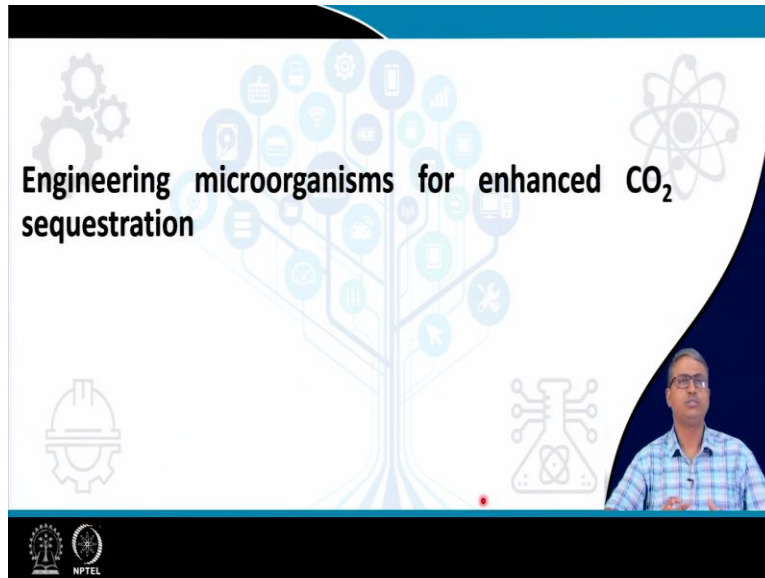
A presentation slide with a blue header and footer. The main content area is white with a faint background of molecular and biological icons. A small video inset in the bottom right shows a man in a blue checkered shirt speaking. The slide contains four bullet points.

- Heterotrophic community members live in tight association with algae/cyanobacteria and consume much of the DOM at or near the surface.
- The remaining fractions of this DOM accumulate and can persist for several thousands of years.
- The molecular properties of plankton-derived DOM dictate heterotrophic utilization and turnover rates.
- This is a major global carbon sink and an ecological process that can be explicitly designed and engineered into algal mass cultivation efforts to integrate CCU (biomass harvesting) to CCS (marine storage of DOM)

It could be by the heterotrophic community member, the remaining fraction of the DOM accumulates because heterotrophic community live in tight association with the algae and consume much of the DOM produced. And the remaining fraction of the DOM basically accumulates and persists for several thousands of years. The molecular properties of this plankton derived DOM dictate the heterotrophic utilization and turnover rates and it is found to be a global carbon sink.

And an ecological process that can be explicitly designed and engineered into algal mass cultivation effort to integrate the CCUS that is, the biomass harvesting to CCS that is, the marine storage of dissolved organic matter. And both the algae and other organisms can be utilized for that.

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Now in the second part of this we will talk briefly about the engineering the microorganism specifically to enhance the CO<sub>2</sub> sequestration because we can understand that the microorganisms, whether they are in the soil. Whether they are in a deep terrestrial crust or oceanic crust or in the marine micro environment marine environment, they play huge role in sequestered in the carbon dioxide.

So, enhanced research interest increased research interest has been shown to engineer the microorganism for enhance your CO<sub>2</sub> sequestration.

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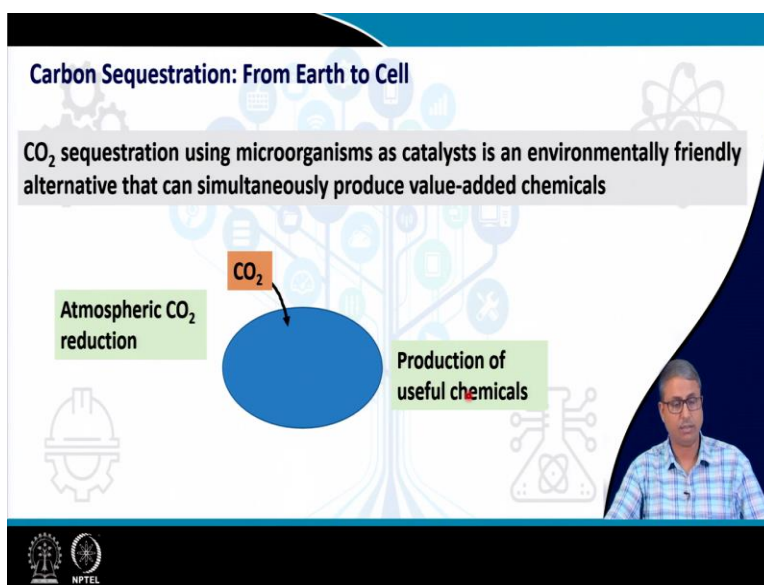
A presentation slide with a white background and a blue header. The title "Microbial CO<sub>2</sub> sequestration not only provides a green and sustainable approach for ameliorating global warming but also simultaneously produces biofuels and chemicals" is centered. Below the title, the text "Limiting factors" is followed by two bullet points: "The efficiency of microbial CO<sub>2</sub> fixation is very low" and "Concomitant microbial CO<sub>2</sub> emission decreases the carbon yield of desired chemicals". Below this, the text "Strategies to combat these issues:" is followed by two bullet points: "Engineering CO<sub>2</sub>-fixing pathways and energy-harvesting systems have been developed to improve the efficiency of CO<sub>2</sub> fixation in autotrophic and heterotrophic microorganisms" and "Metabolic pathways and energy metabolism can be rewired to reduce microbial CO<sub>2</sub> emissions and increase the carbon yield of value-added products". The NPTEL logo is in the bottom left corner.

Now, because microbial CO<sub>2</sub> sequestration is one part which not only provides the green and

sustainable approach for mitigating this globe climate challenge but also it provides the opportunity to produce useful molecule ID, biofuels and chemicals. however, it is facing some challenges and these factors challenging factors are the efficiency of microbial CO<sub>2</sub> fixation is found to be quite low and concomitant microbial CO<sub>2</sub> emissions decreases the carbon yield of desired chemical.

And therefore, the strategies are identified to combat these issues. So, one aspect is engineering the CO<sub>2</sub> fixation pattern and energy harvesting systems have been developed to improve the efficiency of shelter fixation in both autotrophic and heterotrophic microorganisms. On the other hand, metabolic pathways and energy metabolism engineered can be reviewed to reduce the microbial CO<sub>2</sub> emission and increasing the carbon yield of the value added products.

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Now carbon sequestration from earth to sell is catalyzed by these microorganisms, where microbes can actually remove the carbon from the atmosphere and can simultaneously converted into the valuable useful chemicals and some of them can be resources as good as to be used in bioenergy.

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**Strategies for improving microbial CO<sub>2</sub> sequestration focus on both enhancing microbial CO<sub>2</sub> fixation and reducing microbial CO<sub>2</sub> release**

The slide features a central graphic of a tree where the branches are represented by various icons related to technology and science, such as gears, a smartphone, a Wi-Fi symbol, a document, and a microscope. The background is a gradient from light blue to dark blue. In the bottom right corner, there is a small inset video of a man in a blue and white checkered shirt. The NPTEL logo is visible in the bottom left corner.

Now strategies for improving the microbial CO<sub>2</sub> sequestration focus therefore, on both aspect. One is enhancing the microbial CO<sub>2</sub> fixation and second is the reducing CO release. So, we will look into these 2 aspects briefly.

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**CO<sub>2</sub> Sequestration: From Earth to Cell: Two methods and Two strategies**

The slide contains two diagrams. The left diagram, labeled 'Earth', shows 'CO<sub>2</sub> sequestration at the level of earth macroscopical'. It depicts a globe with 'Ocean' and 'Fossil fuel' sources, and arrows indicating CO<sub>2</sub> emissions and capture. The right diagram, labeled 'Cell', shows 'CO<sub>2</sub> sequestration at the level of cell microscopical'. It illustrates a cell with internal organelles and a 'CO<sub>2</sub> fixing pathway' shown as a series of steps. Below the diagrams are citations: 'Hu et al, Trends Biotechnol. 37(5):532-547,2019' and 'Trends in Biotechnology'. A text box at the bottom states: 'Two methods might be able to mitigate global warming: developing CO<sub>2</sub> capture techniques and limiting CO<sub>2</sub> release. Similarly, two strategies for improving microbial CO<sub>2</sub> sequestration can be developed: enhancing CO<sub>2</sub> fixation and reducing CO<sub>2</sub> release.' An inset video of the same man from the first slide is in the bottom right corner. The NPTEL logo is in the bottom left.

So, one aspect is that 2 methods up there and 2 strategies up there. So, what are these methods and strategies? 2 methods might be able to; so one is reduce the emission another is convert the carbon dioxide into valuable products. The 2 methods might be able to mitigate the global warming, developing CO<sub>2</sub> capture technology and limiting CO<sub>2</sub> release. And the strategies would be improving the microbial CO<sub>2</sub> sequestration and enhancing through enhancing the CO<sub>2</sub> fixation and reducing the CO<sub>2</sub> release.

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**Both autotrophic and heterotrophic microorganisms fix CO<sub>2</sub>**

Autotrophic microorganisms can use CO<sub>2</sub> as their sole carbon resource to directly produce various value-added chemicals, including biodiesel, biofertilizers, antioxidants, and bioactive compounds

However, the titer and rate of chemical production from autotrophic microorganisms need to be improved (e.g., the highest rate of lipid production from microalgae is ~5 g/m<sup>2</sup>/d, while ~30 g/m<sup>2</sup>/d is required to make commercialization of algal-lipid biofuels economically feasible)

The slide features a blue and white color scheme with icons of a microscope, a gear, and a chemical flask. A small video inset in the bottom right corner shows a man in a blue plaid shirt speaking. The NPTEL logo is visible in the bottom left corner.

And as I mentioned, both autotrophic and heterotrophic microorganisms, they can fix carbon dioxide. Autotrophic microbes they use the CO<sub>2</sub> as the sole carbon source to directly produce the various value added chemicals. So, they convert CO<sub>2</sub> to value added chemicals the molecules which are useful in biodiesel production, bio fertilizer production, antioxidants, and bioactive compounds. On the other hand, the titer and the rate of these chemicals, which are produced out of the carbon dioxide which is fixed by these autotrophic organisms need to be improved.

That is, for example, the highest rate of lipid production from microalgae is around 5 gram per meter square per day, while it is 30 gram per meter square per day is required to make commercialization of the algal lipid biofuel which is considered to be economically feasible.

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## Both autotrophic and heterotrophic microorganisms fix CO<sub>2</sub>

Heterotrophic microorganisms can generate chemicals with much higher productivity (e.g., lactate and ethanol) and genetic tools for heterotrophs are more advanced (e.g., CRISPR-based technologies)

Nevertheless, CO<sub>2</sub> fixation in heterotrophic microorganisms is based on using organic substrates to provide energy (with CO<sub>2</sub> release), and net CO<sub>2</sub> gain by microorganisms is achieved only when some specific products (e.g., malate and succinate) are generated

The key challenge for CO<sub>2</sub> fixation is to provide an alternative energy source to the cells



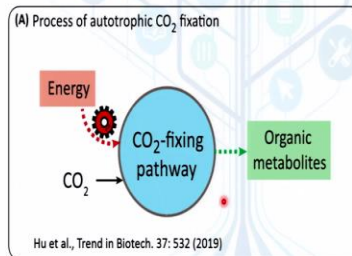
On the other end the heterotrophic microorganisms they can also generate chemicals with much higher productivity, for example lactated ethanol and genetic tools for heterotrophic organisms are more advanced, including decreased per gas systems. Nevertheless, this year to fixation in heterotopic organisms is based on using organic subjects to provide the energy, which actually leads to a release of carbon dioxide.

And net CO<sub>2</sub> gain by microbes is achieved only when some specific products like malate or succinate are generated, otherwise, there will be a substantial CO<sub>2</sub> release. Now the key challenge for CO<sub>2</sub> fixation in case of heterotrophic organism is to provide an alternative energy source to the cells.

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## Reinforcing CO<sub>2</sub> Fixation in Autotrophic Microorganisms

CO<sub>2</sub> fixation in autotrophic microorganisms can be simply described as a pathway driven by cell energy (ATP and reducing power) that transforms nonbiogenic carbon compounds (HCO<sub>3</sub><sup>-</sup>/CO<sub>2</sub>) into organic metabolites (e.g., acetyl-CoA and pyruvate)

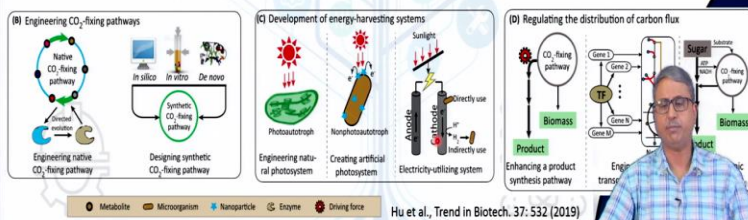


Now the reinforcing the CO<sub>2</sub> fixation by autotrophic microorganism, as I mentioned the CO<sub>2</sub> fixation in autotrophic microbes can be simply described as a pathway which is driven by cellular energy by the ATP and the reducing power and that transform non biogenic carbon, carbon dioxide into some kind of a complex organic molecules through the CO<sub>2</sub> or the bicarbonate which is taken in the cell is converted into acetyl-CoA and pyruvate.

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CO<sub>2</sub> fixation in autotrophic microorganisms can be reinforced by :

- Improving the efficiency of the CO<sub>2</sub>-fixing pathway
- Developing more efficient energy-harvesting systems to improve the supply of ATP and reducing power
- Regulating the distribution of carbon flux to optimize the utilization of cell resources



Now, CO<sub>2</sub> fixation can be reinforced by improving the efficiency of this CO<sub>2</sub> fixation pathway. The way this CO<sub>2</sub> fixation pathway operate, we can increase their efficiency by different engineering approaches developing through developing more effective energy harvesting system that improves the supply of ATP and reducing power and also regulating the distribution of

carbon fluxes to optimize the utilization of cell resources.

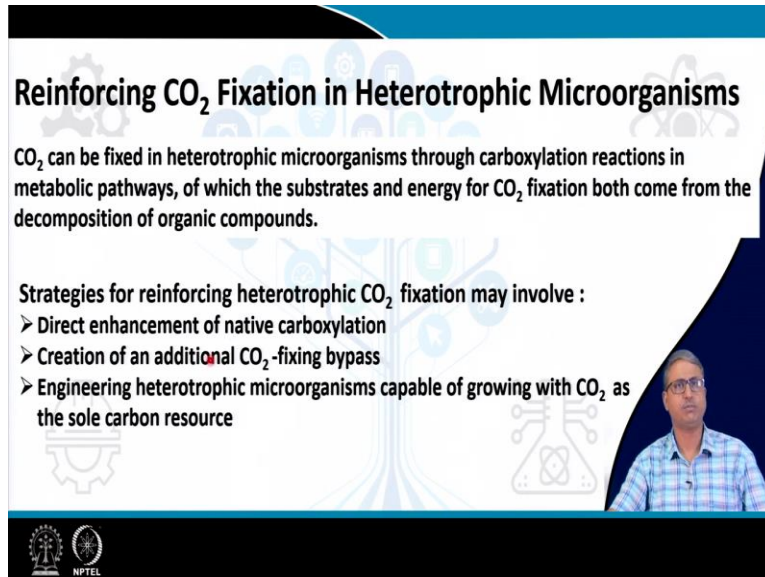
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### Reinforcing CO<sub>2</sub> Fixation in Heterotrophic Microorganisms

CO<sub>2</sub> can be fixed in heterotrophic microorganisms through carboxylation reactions in metabolic pathways, of which the substrates and energy for CO<sub>2</sub> fixation both come from the decomposition of organic compounds.

Strategies for reinforcing heterotrophic CO<sub>2</sub> fixation may involve :

- Direct enhancement of native carboxylation
- Creation of an additional CO<sub>2</sub>-fixing bypass
- Engineering heterotrophic microorganisms capable of growing with CO<sub>2</sub> as the sole carbon resource



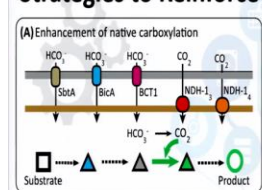
NPTEL

On the other hand, the reinforcement of the CO<sub>2</sub> fixation in heterotrophic organism can also be done through carboxylation reaction in metabolic pathway, in which the substantial energy for CO<sub>2</sub> fixation both come from the decomposition of the organic compound. And the strategies for reinforcing the heterotrophic you to fixation may involve direct enhancement of native carboxylation creation of an additional CO<sub>2</sub> fixation bypass and engineering the heterotrophic microorganisms we are capable of growing with CO<sub>2</sub> as the sole carbon source.

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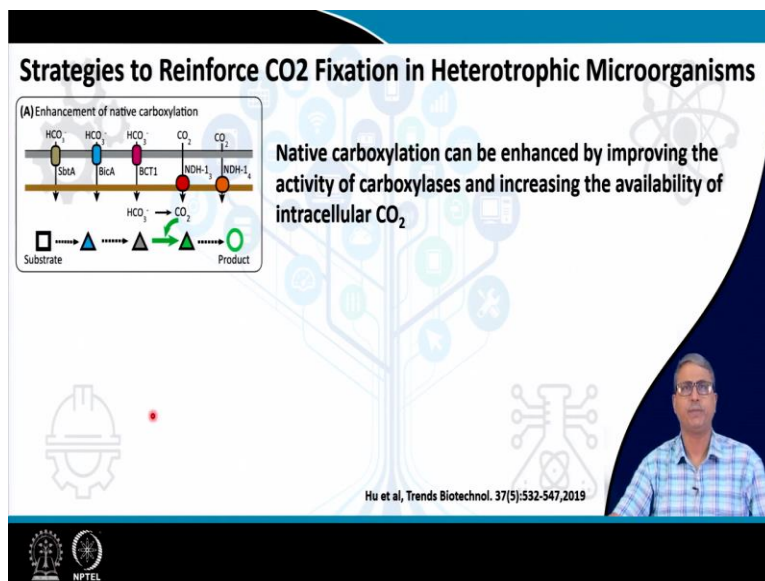
### Strategies to Reinforce CO<sub>2</sub> Fixation in Heterotrophic Microorganisms

(A) Enhancement of native carboxylation



Native carboxylation can be enhanced by improving the activity of carboxylases and increasing the availability of intracellular CO<sub>2</sub>

Hu et al, Trends Biotechnol. 37(5):532-547,2019



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Now these are the strategies one strategy could be the native carboxylation, which can be

enhanced by improving the activity of carboxylase and increasing the availability of the intracellular CO<sub>2</sub>.

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### Strategies to Reinforce CO<sub>2</sub> Fixation in Heterotrophic Microorganisms

(B) Establishing non-native CO<sub>2</sub>-fixing bypass

**A CO<sub>2</sub>-fixing bypass from an autotroph**  
R5P → Ru5P → RuBP → 3-PGA  
Glucose → G6P → F6P → G3P

**A synthetic CO<sub>2</sub>-fixing bypass**  
CO<sub>2</sub> → For → FoCoA → FALD → DHA → DHAP  
Glucose → G6P → F6P → G3P

**Building a synthetic CO<sub>2</sub>-fixing bypass efficiently improves heterotrophic CO<sub>2</sub> fixation when the product synthesis pathway for desired chemicals does not contain a carboxylation reaction**

Hu et al, Trends Biotechnol. 37(5):532-547,2019

And the other could be building CO<sub>2</sub> fixing bypass efficiently that will improve the heterotrophic CO<sub>2</sub> fixation.

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### Strategies to Reinforce CO<sub>2</sub> Fixation in Heterotrophic Microorganisms

(C) Engineering heterotrophs into autotrophs

**Complete CO<sub>2</sub>-fixing pathway**  
**Energy module**  
**Introduce!**  
**Adaptive evolution**

**A fully artificial autotroph may be constructed by building a complete CO<sub>2</sub>-fixing pathway and an energy-harvesting system in a model heterotrophic microorganism by harnessing the power of modular optimization and adaptive evolution**

Hu et al, Trends Biotechnol. 37(5):532-547,2019

And the other one is a fully artificial autotrophy may be constructed by building a complete CO<sub>2</sub> fixation pathway and an energy harvesting system in a model heterotrophic E.coli by harnessing the power of modular optimization, adaptive evolution and other approaches of metabolic engineering and synthetic biologist.

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**Reducing CO<sub>2</sub> release from microorganisms**

During microbial fermentation, CO<sub>2</sub> is released in three ways:

1. **Decarboxylation reactions in product synthesis pathways** (e.g., through pyruvate and acetoacetate decarboxylation during the production of acetone)
2. **Redox imbalance, by two routes:**
  - when NAD(P)<sup>+</sup> is overproduced, NAD(P)H needs to be regenerated via the TCA cycle and pentose phosphate pathway, which produce large amounts of CO<sub>2</sub>
  - when NAD(P)H is overproduced, oxygen is required to regenerate NAD(P)<sup>+</sup>, thus enhancing oxidative phosphorylation and further increasing CO<sub>2</sub> release
3. **ATP generation:** to maintain cell function, ATP need to be produced by burning organics to CO<sub>2</sub> and H<sub>2</sub>O

The last one is the reducing CO<sub>2</sub> release from the microorganisms. Now during microbial metabolism CO<sub>2</sub> releases are there because of the decarboxylation reaction because of the redox imbalance and also because of the ATP generation to maintain the cell function.

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**Strategies for reducing microbial CO<sub>2</sub> release can be divided into three categories:**

1. **rewiring metabolic pathways**
2. **improving redox balance**
3. **decreasing respiratory ATP production**

There have been defined processes or strategies through which the microbial metabolism derived CO<sub>2</sub>, which is **which is** actually releasing CO<sub>2</sub> into the atmosphere can also be controlled, and this can be done using three categories. One is the rewiring of metabolic pathways improving the redox balance and decreasing the respiratory ATP production.

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- Capturing atmospheric carbon: biological and nonbiological methods, Nogia et al, International Journal of Low-Carbon Technologies,11(2):266-274,2013
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So, overall, for these 2 aspects of the carbon sequestration that the first one was a general aspect of the sequestration capture utilization, and the third one more like how do we engineer or what are the options to engineer microorganisms for better CO<sub>2</sub> fixation and reduced CO<sub>2</sub> emissions. These are the references.

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## CONCLUSION

- Innovating carbon-capture biotechnologies through ecosystem-inspired solutions are discussed
- Biotechnology and innovation efforts that are inspired and/or connected directly to three major biomes (plant-soil, deep biosphere, and marine) are introduced
- It is important that biotechnologists and engineers seeking to build ecosystem-inspired solutions will depend on fundamental expertise for a given ecosystem to understand which processes, species, and genetic parts can be rendered into controllable modules or, perhaps more importantly, those that cannot.
- The other message for fundamental scientists is to help identify value-chain opportunities. Innovation requires capital investment from the public and/or industry, and both are often motivated by clear value-chain perspectives such as CCSU aiming to convert factory emissions of CO<sub>2</sub> and/or CH<sub>4</sub> into food, feed, and sustainable bioproducts from algae



And in conclusion the innovating carbon captures of our technologies to ecosystem inspired solutions are discussed, and biotechnology innovation efforts that inspired and are connected directly to the three major biomes are introduced. It is important that biotechnologists and engineers seeking to build ecosystem inspired solutions will depend on fundamental expertise for a given ecosystem to understand which process species genetic parts can be rendered into

controllable module perhaps more importantly those that cannot.

The other message of the fundamental scientists is to help identify the value and opportunities. How do we convert identify the roots through which the products can be synthesized. And again, in a deeper understanding of these processes, biologically catalyzed processes into carbon cycling will guide towards innovation industrial developments. It must be emphasized that better communication and cross disciplinary innovation will motivate future investments into science and industrial action to consider the benefit of ecosystem in the CCSU.

Microbial CO<sub>2</sub> sequestration is a promising approach for closing this carbon cycle of earth using current particle level strategies, the efficiency of CO<sub>2</sub> fixation in autotrophic and heterotrophic, organisms can be increased, and the problem of microbial CO<sub>2</sub> release can be partly sought. Finally, the improvements of microbial CO<sub>2</sub> sequestration often result in a higher level of chemical production, which emulates the energy and resource shortage simultaneously. Thank you.