RESEARCH PAPER

Recent Advances in Porous Nanocellulose for Heavy Metals Removal

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ABSTRACT

The preservation of clean water against toxic heavy metals, such as lead and cadmium, remains a colossal global challenge. These contaminants pose severe risks to human health and cause irreversible damage to ecosystems. Plant stuff is a good solution, but to convert the simple wood thread into intelligent traps there must be a special shape with holes in it, which is called porosity. In order to create lightweight sponges out of solid fibers, intelligent designs, such as freeze-drying, salt templating, or chemical crosslinking, are used to open the inner structure and enable dirty water to infiltrate deep within the substance. Enhancing the porosity drastically increases the specific surface area, providing millions of chemical parking spots where heavy metal ions can get stuck and removed from the fluid almost instantly. Reviewing recent scientific progress confirms that combining these highly porous structures with specific chemical modifications creates a sustainable, low-cost, and reusable filter capable of solving the global water crisis effectively.

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INTRODUCTION

Water Heavy Metal Contamination Problems and Need for Advanced Adsorbents

Living on this beautiful blue planet requires drinking safe liquid every single day because no human or animal can survive without having clean fluid to drink. Although vast oceans and long rivers cover most of earth, keeping fresh water safe for drinking has become an extremely difficult job for people all over world. Huge factories and busy industries work day and night to produce modern things like fast cars and strong batteries, but making these useful items unfortunately creates massive amount of dirty waste. Dumping this black and smelly trash often happens directly into our flowing rivers and quiet lakes, carrying very dangerous poisons that human eyes simply cannot see. These invisible and silent killers hiding in water are scientifically called Heavy metals [1].

Heavy metals act very differently from normal dust or mud because these dangerous elements do not just wash away or disappear after short time passes. Strong elements like lead (Pb) and cadmium (Cd) stay inside water for many long years without breaking down into safe pieces like food or paper does. When small fish swim through this dirty liquid, dangerous poisons enter their little bodies and refuse to leave. Later, when bigger fish eat small fish, or when hungry people cook seafood for dinner, Heavy metals travel deeply into human body. The process of transferring poison in

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unclean water to the food consumed by humans is extremely dangerous since individuals begin to feel extremely ill and feeble after a certain period of time elapses [2].

Physicians who are extremely concerned with Pb and Cd raise awareness among all since the consumption or ingestion of these substances damages the most vital sections of the human body in very negative ways. Pb is a horrible poison that strikes not only brain, preventing young children learning or having clear vision and thinking, but also Cd goes to kidneys rapidly, making a very strong human bones so weak and prone to breaking. Due to the harmful nature of these metals on the human body, it is simply impossible to have them left in our drinking glasses. It needs to find strong methods of eliminating even the smallest drop of poison before it is ingested by anybody. This is a main safety task that science performs by using special cleaning materials known as Adsorbents [3, 4].

Adsorbents are like sticky sponge which attaches dirt and clings on to it so that pollution does not escape. In the dirty water, grabbing occurs and metal pieces cling to the skin and clean water comes out. Sand, charcoal, or clay, which are natural substances were in use, but cannot withstand the great dirt of modern times. Simple is slow and gets congested, unfortunately depositing bad Pb and Cd in water [5, 6]. With the factories currently dumping more waste and requiring fresh, sharper tools with greater strength than sand, it is of the essence. Cleaning materials should be able to retrieve all the pieces of metal in the quickest time without collapsing and compromising the process. These powerful new tools developed by experts are called Advanced adsorbents [7].

Searching everywhere in wide world to find perfect material for making Advanced adsorbents is big task, but best answer often comes directly from nature. Using material that is safe to touch and does not cost much money is important because cleaning water should be cheap enough for every person [8].

Using expensive items like gold or diamonds to clean water is impossible because wide rivers need huge amounts of cleaning material to be safe. Therefore, looking at green plants provides special building block that creates Advanced adsorbents effectively and cheaply. By using natural materials from earth, fighting Heavy metals contamination problems becomes much easier for protecting human health and nature. Building better traps with high porosity to catch Pb and Cd makes water safe again for all people and animals to drink [9, 10].

Why porous Nanocellulose?

When looking for very best material to build Advanced adsorbents, plants and tall trees offer great options because trees are very strong and grow almost everywhere on land. Inside every big tree and every small blade of grass, tough material called Cellulose holds plant together firmly so it does not fall down. Cellulose is most common natural material found on Earth, existing in soft cotton and hard wood, making it very Abundant [11]. Because coming from living plants makes it completely natural, scientists call it Biopolymer, which acts like good plastic that breaks down safely in soil without hurting earth [12].

Although normal cellulose from wood works well, pieces are usually too big and thick to catch tiny Heavy metals hiding in water. To solve this size problem, cutting cellulose into extremely small pieces creates material that is impossible to see without powerful microscope. These tiny pieces are called Nanocellulose also being so small makes them much stronger and more useful than big pieces of wood [13]. Nanocellulose behaves in truly amazing ways and becomes perfect for cleaning dirty water because very small things act differently than big things.

Choosing Nanocellulose happens largely because of its skin, which science calls surface area. Breaking big rock into fine dust creates huge amount of total skin on all dust particles combined compared to single rock. Nanocellulose acts exactly like that dust, possessing High specific surface area that provides giant open space to catch poisons [14, 15]. A higher surface area is a high degree of sticky places on Pb and Cd hence material is much more effective at cleaning than wood block solid [16].

The other wonderful aspect of Nanocellulose is that it is amiable to the chemical swaps, that is, one can easily dress it to perform particular tasks. This capability is referred to as Tunable chemistry that allows us to place special hooks to seize things. When it is desired to catch Pb, add lead hooks serve well and when it is required to catch Cd, switching hooks is fast [17]. The tunable chemistry brings smartness in stuff in the process of holding Heavy metals in place so that it does not escape back to water [18]. It is difficult to get other materials such as glass or metal to change but Nanocellulose does not fear water and expands to seek dirt. Since it is a bountiful natural chain there is no new poison to be created making its use safe to fish and folks. It is cheap to make because trash can be transformed into valuable Nanocellulose using farm waste [19]. This smart loop is made possible by nature to correct the mistakes we have made.

Role of Porosity in Adsorption

Big skin good, but trap deep pit and cave inside. When thing is hard such as as red brick then water strike wall and leave so bad metal on top only. To be like super sponge require open place within it known as Porosity [20], meaning blank space where water run and metal hide. When fibers cram in the form hard fence where dirt cannot enter but open make mix hole dimensions known as Microporous plus Mesoporous and Microporous [21]. They do each hole since Microporous is large hole that behaves as wide gate thus water come in fast to aid Diffusion [22]. Diffusion big hole mean travel inside and make run fast [23]. Medium tube is also Mesoporous between big door and small room as road to trap place heavy metal. In absence of road then metal crowd gate and jam entry preventing cleaning so middle hole be sure that tool remain clear and work long time.

Microporous architecture creates tiny spots or chairs where Pb and Cd atoms sit and get locked away forever. Most of cleaning power comes from these tiny Microporous spaces because they provide best grip on metals, leading to high Uptake. Uptake is measure of how much poison material can hold also having many small holes increases this amount significantly.

Therefore, perfect material needs mix of all three types: Macro, Meso also Micro pores working together as team. Big pores let water in, medium pores guide it also small pores trap poison, giving Access to internal sites deep inside particles [24]. Internal sites are hidden trapping spots that would be useless if water could not reach them. Increased Porosity enhances Uptake by using every single part of material, not just outside skin [25].

Making Nanocellulose very fluffy and full of air creates light materials like aerogels that are mostly made of Porosity. Open structure ensures that Diffusion occurs rapidly and that it can retain a lot of pollution which is very heavy. High Porosity causes the simple fiber to become complicated maze in which Heavy metals are lost and cannot re-enter clean water [26].

Arsenic is a very deceptive poison that can change the shape that it takes in water, requiring that a trap be ready to catch it in its different forms. Porosity is useful because it allows Arsenic to become trapped within the interior of a porous structure. To create a “safe house” for Arsenic to become trapped within the pore structure of a porous material, the pore interior must have some type of chemical “hook” that will hold tightly to the Arsenic ion as it moves through the water. Since the high surface area of a porous material allows for many chemical “hooks” to be placed on the walls of each pore, if one were to create a flat solid piece of material, there would only be a few chemical “hooks”, and thus, Arsenic ions would easily swim past the chemical “hooks” without being captured. However, if a porous material has a deep pore structure, millions of chemical “hooks” are created in the micropores, providing greater interaction between the Arsenic ion and the chemical “hooks»․ [24]

Mercury is a very heavy and slippery poison that will constantly attempt to escape capture. A mesoporous structure acts as a “highway” for Mercury to travel to deep in the center of the fiber. If Mercury is unable to gain better diffusion through the mesopores, it will tend to cover the surface area of the porous material and eventually cease to function effectively. Once Mercury has entered the microporous cave, it is surrounded by an enormous microporous structure and thus has an ideal area where it will bond tightly so that it can never be released back to the environment. Additionally, due to the fluffy structure of nanocellulose, Mercury will have contact with an extremely large surface area of nanocellulose, which will significantly increase the binding capacity of the nanocellulose material, thereby enabling a small amount of nanocellulose to remove a very large amount of water from a tank [27].

Hexavalent chromium (Cr) is a toxic form of Cr and requires large open areas (e.g., pores) to become chemically altered from the environment. Water containing Cr must have access to the area where it can come in contact with an active site (i.e., where it is chemically transformed to a non-toxic form). In general, a pore-filled material has more reactive surfaces compared to a flat surface; therefore, it is more effective for removal of hexavalent Cr. Pores can be thought of as prison cells for hexavalent Cr ions. Macro-sized and meso-sized pores allow rapid transport of hexavalent Cr to micropores, where ion exchange will occur, thus ensuring the hexavalent Cr is completely removed, and the water is clean and safe for life [28, 29].

Scope of This Review

Paper tell story of new science to clean water with Nanocellulose with special ways to transform so material get more holes. See Modification strategies [30] that are cook recipes to make best trap since goal is to find out whether Porosity remove Heavy metals well. Performance metrics [31] need check numbers to count the amount of dirt that has been caught plus the speed of the same. Explain Key mechanisms [32] exhibiting how catching occur inside due to metal stick similar to magnet [33] so paper read many studies using wood or grass to compare which create best Porosity [34]. But also, should speak of Challenges [35] such as it is expensive or difficult to work then check on Prospects of future dreams where smart filter clean every home [36]. Guide show path from plant to filter [37] needing mix of big and small hole [38] plus wash tool to use again [39, 40] making green way. Text put puzzle parts together to stop bad Pb plus Cd and save life [41, 42].

Table 1. Comparison of Nanocellulose Types (Based on References).

Nanocellulose Type	Where it Comes From	How it is Created	Shape Under Microscope	Why it is Good for Filters	Reference
General Nanocellulose	Plants & Biomass	Various methods	Varies	Very versatile and safe for nature.	[43]
Cellulose Nanocrystals (CNCs)	Wood / Cotton	Acid burning (Hydrolysis)	Short, hard needles	High strength; acts like skeleton.	[44, 45]
Cellulose Nanofibrils (CNFs)	Wood Pulp	Mechanical grinding	Long, flexible ropes	Forms messy net to trap dirt.	[46, 47]
Bacterial Nanocellulose (BNC)	Bacteria	Bacterial growth	Pure, fine mesh	Extremely pure; holds lots of water.	[48, 49]

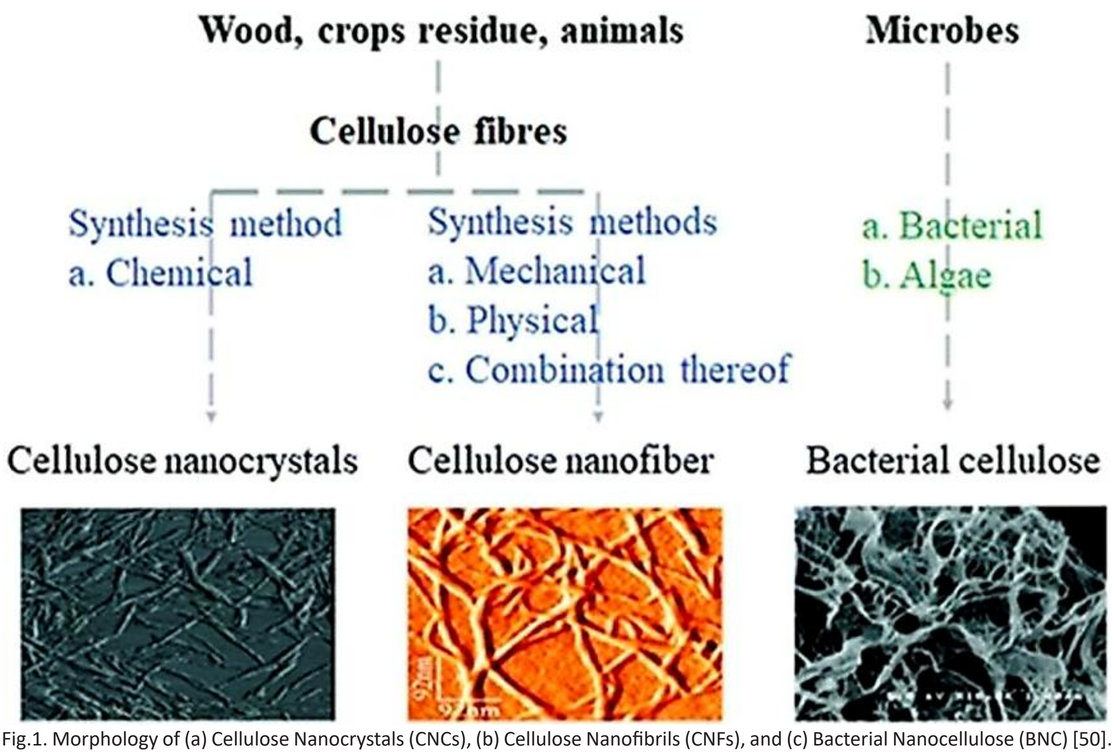

Fig.1. Morphology of (a) Cellulose Nanocrystals (CNCs), (b) Cellulose Nanofibrils (CNFs), and (c) Bacterial Nanocellulose (BNC) [50].

FUNDAMENTALS OF NANOCELLULOSE AND ADSORPTION OF HEAVY METALS

Types of Nanocellulose: Cellulose Nanocrystals (CNCs), Cellulose Nanofibrils (CNFs), Bacterial Nanocellulose (BNC)

Nature hides amazing building blocks inside ordinary plants and trees that scientists call Nanocellulose, but finding these tiny pieces requires understanding that they come in three very special and different shapes that act like distinct tools for specific cleaning jobs. Understanding these three shapes helps people choose exactly right tool for cleaning dirty water because each type acts differently when swimming in fluid to catch poison [43].

First among these important types is strong and short rod known as Cellulose nanocrystals (CNCs), which looks exactly like stiff grain of rice or tiny needle when viewed under very powerful microscope. Making CNCs involves using strong acid to burn away soft and messy glue-like parts of wood, leaving only extremely hard and crystal-like parts behind to do heavy work [44]. Because CNCs are so stiff, straight also highly organized, they act like tiny hard sticks that do not bend easily, making them perfect for building strong frame inside water filter that does not collapse under pressure [45].

Unlike short and stiff crystals, Cellulose nanofibrils (CNFs) act more like long and tangled strings of spaghetti that twist around each other to make very strong and messy net. Producing CNFs usually happens by grinding wood pulp with heavy machines until fibers rip apart into long, flexible also hairy threads that hold together very well due to mechanical force [46]. CNFs contain both hard crystal parts and soft messy parts on same string, which allows them to bend, twist also wrap around dirt particles like spider web catching fly. Using CNFs creates very thick network that is excellent for trapping things because long strings create many layers of protection and entanglement [47].

Tiny living creatures called bacteria also make their own special version known as Bacterial nanocellulose (BNC), which is extremely pure because it does not have other sticky plant parts like lignin or hemicellulose found in trees [48]. BNC grows as thick, wet skin on top of sugar water where bacteria live, forming ready-made sponge that holds huge amount of water inside its belly. Because BNC comes from bacteria and not plants, fibers are extremely thin and woven together very tightly by germs themselves, creating material that is very strong even when it is wet and holding its shape perfectly [49] (Table 1, Fig. 1).

Physicochemical Properties

Functioning as good trap requires having special chemical hands-on surface also Nanocellulose possesses millions of these tiny hands called Surface hydroxyl groups [51]. Surface hydroxyl groups act like sticky chemical glue that loves to grab onto water and dangerous metals, making material perfect for hunting poison in river. Having so many Surface hydroxyl groups means material is never lonely in water because it always pulls liquid and metal ions towards itself very quickly to hold them tight [52].

Looking deep inside fiber reveals that some parts are organized like soldiers standing in perfect, straight line, which is called Crystallinity, while other parts are messy and soft, known as Amorphous portions [53]. Soft part allow water to enter and swell like balloon and hard part Crystallinity ensure that fiber is strong such that it does not melt like sugar [54]. Require combination of hard as well as soft to endure then fiber is long and thin with high Aspect ratio behaving like rope to wrap things not like ball [55]. This make tight net small make huge Surface area meaning total skin giant [56]. Big skin is a secretive one as it gives million parking spot to Heavy metals to rest (Table 2).

Conventional Adsorption Mechanisms of Heavy Metal Ions

Table 2. Important Properties for Cleaning Water.

Property Name	Simple Explanation	How it Helps Cleaning	Reference
Surface Hydroxyl Groups	Chemical "hands" on skin.	Grabs metal poison chemically.	[51, 52]
Crystallinity	The hard, organized parts.	Stops filter from dissolving in water.	[53, 54]
Amorphous Portions	The soft, messy parts.	Let's water soak in like sponge.	[53]
Aspect Ratio	Length vs. Width (Long rope).	Makes tangled web to catch dirt.	[55]
Surface Area	Total amount of skin exposed.	More skin = More spots for metals to stick.	[56]

Smart trick of catch bad metal as nature is clever and first trick name Ion exchange where tool swap safe bit bad bit in place of lead [57]. Ion exchange are as market trade such as tool give safe thing and take danger thing then next way call Complexation or Chelation acting like crab claw grab ball because arm wrap round metal and hold tight [58].

Poison not fall back by strong lock by complexation make things fall back plus water run fast and adding stuff make claw stronger hunter and also work like magnet via Electrostatic attraction where minus charge pull plus charge metal [59]. Electrostatic attraction happen because opposite side pull each other so wood fiber drag metal out of water fast before touch however sometimes metal just get stuck in hole or sit on top without glue named Physical adsorption [60]. Physical adsorption is like dust settling on table, where metal just rests on vast Surface area of nanomaterial. Although this hold is weaker than Complexation, it still helps remove lot of dirt when combined with other stronger mechanisms (Table 3).

Observing the top Fig. 2 labeled (a) reveals the clever trick called ion exchange where the material acts like a trading post. Dangerous heavy metal particles shown as blue circles swim towards the surface and swap places with safe red sodium

Table 3. How Material Traps Poison.

Mechanism	Simple Analogy	Description	Reference
Ion Exchange	Trading cards.	Giving good atom to take bad atom.	[57]
Complexation / Chelation	A crab claw.	Wrapping around metal tightly.	[58]
Electrostatic Attraction	A fridge magnet.	Negative fiber pulls positive metal.	[59]
Physical Adsorption	Dust on shelf.	Metal sits in hole without bonding.	[60]

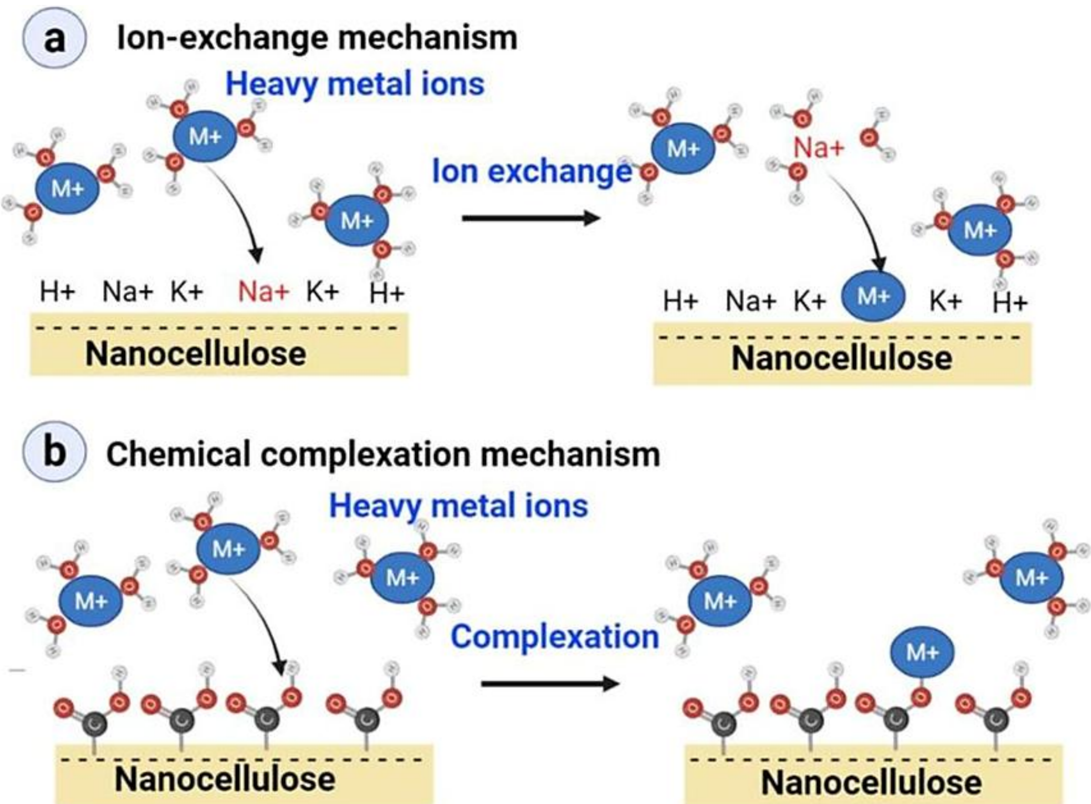

Fig. 2. Schematic illustration of heavy metal adsorption mechanisms on nanocellulose. (a) Ion-exchange mechanism where a safe ion (like Na+) is swapped for a heavy metal ion (M+). (b) Chemical complexation mechanism where surface functional groups strongly grab and hold the heavy metal, Ion [61].

particles. Trading a harmless salt atom to catch a harmful metal atom allows the filter to clean the water without losing its balance.

Looking at the bottom Fig. 2 labeled (b) demonstrates the strong gripping method known as chemical complexation. Red and white chemical hooks on the surface reach out to grab the blue metal ions and hold them very tightly. Locking the poison onto the surface creates a strong bond that prevents the metal from escaping back into the clean water.

Importance of Porosity and Internal Architecture

Having sticky surface is good, but truly great trap needs complex system of tunnels and rooms inside, which is Internal architecture [62]. Creating material full of empty space is essential because Porosity allows dirty water to travel deep into center of trap instead of just hitting outside wall. Without Porosity, inside of cleaning bead would be wasted space because water could never reach hidden Surface hydroxyl groups located there [63].

Having holes of many different sizes is important, so scientists study Pore size distribution to ensure there are big doors for entering and small chairs for sitting (Table 4) [64]. Big pores act as highways that let water rush in quickly, while small pores act as tiny jails that lock metal away. Link hole makes Interconnectivity a bit like hall system so metal move room to room not hit wall [65] making all

Table 4. Importance of Holes and Structure.

Structural Feature	What it is	Why it is Necessary	Reference
Internal Architecture	The design of inside.	Allows water to reach center.	[62]
Porosity	Amount of empty space.	Stops filter from being solid wall.	[63]
Pore Size Distribution	Big and small holes mixed.	Big holes for speed; small holes for trapping.	[64]
Interconnectivity	Connected tunnels.	Prevents dead ends so water flows.	[65]
Aerogel Structure	A 3D sponge of air.	Highly porous and very lightweight.	[66, 67]

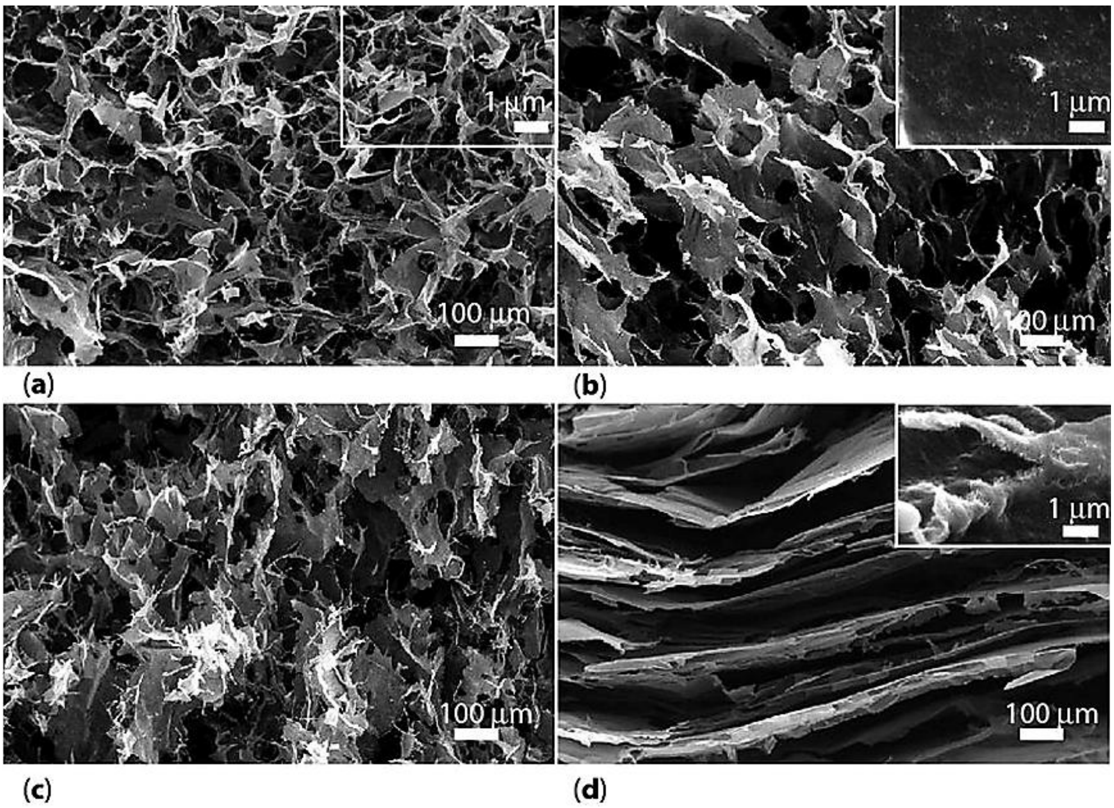

Fig. 3. SEM images of porous nanocellulose aerogel showing interconnected network structure and high porosity [68].

sponge work without dry place. Build shape give rise to Aerogels that are dry light sponge full of air or Hydrogels that behave as wet jelly full of water [66] whereby the aerogel displays high Porosity that behaves light as feather and strong cages to carry stainless heavy poison within the empty space. Use Network structure make thing float on water and suck dirt like vacuum [67] since structure keep little bundles of fiber tight in order to keep road open to flow.

Metrics/Figures of Merit in Heavy Metal Adsorption

Measure work check number to show it beat old way [69] most key number is Adsorption capacity that indicates how much heavy metal tool carry before full stop [70]. High Adsorption capacity small bit clean big tank then checks speed name Kinetics since slow filter not useful to thirsty man [71]. Good Kinetics have metal stick fast and clean water in minute by means of Porosity and then pick only poison and leave safe mineral is skill name Selectivity [72].

High Selectivity fill useless thing with a fill of useless stuff so Adsorbent save space to bad Pb plus Cd again use so test Regeneration meaning wash dirty sponge for new job [73]. Washing wash tools clean so good thing works many cycles not break [74] and comparing metric showing whether Modified nanocellulose beat sand. Objective is to achieve high capacity and high speed and Selectivity and easy regeneration [75] such that modify shape change number [76] proving tiny fiber solve big problem [77]. Going dust to Aerogels is giant leap [78] and Regeneration retain solution inexpensive in the future [79, 80] (Table 5).

STRATEGIES FOR ENHANCING POROSITY IN NANOCELLULOSE ADSORBENTS

Template and Scaffold-Based Approaches

Make perfect trap need to build thing with empty space inside such as house use smart way call Template-based approaches where science use temp object to hold space [80]. Well-known one Salt templating whereby grains of salt are placed in wet material until they become solid [81] and washed out with water, dissolving all the salt and leaving behind the shape of the grain perfectly clean. Pick salt size determine hole size to make water run easy making structure appear like sponge to allow Centre to conceal Heavy metals [82].

Also, can apply Sacrificial templates such as plastic bead or oil drop that wash away [83] in ghost shape plus tunnel pattern [84]. This process prevents tight fiber sticks in order to adjust and control the amount of mean control total Porosity as greater the amount of salt more the holes [85]. The best option is salt as cheap and safe and cost-effective with water elimination making green filter [86] (Table 6).

Fig. 4 Schematic diagram showing the salt-templating technique used to create porous structures. The process involves grinding salt crystals, mixing them with the polymer (like nanocellulose), drying the mixture also finally washing away the salt with water to leave behind open pores [87].

Fig. 4 reveals the clever step-by-step recipe used to create a sponge-like material full of holes using simple table salt. Mixing solid salt crystals into the liquid material creates a temporary solid block where the salt grains act as placeholders sitting inside the drying polymer. Washing the final dry sheet with water dissolves the salt completely, leaving behind empty spaces that match the exact shape and size of the original crystals, which creates the perfect porous structure needed for filtering dirty water.

Freeze-Drying, Supercritical Drying also Aerogel Formation

Removing water from wet Nanocellulose without crushing delicate structure requires special drying tricks that prevent walls from collapsing inward. Drying wet fibers in sun usually makes them stick together like glue, forming hard and useless plastic-like film that cannot hold water or dirt [88]. Preventing this collapse involves using

Table 5. Measuring Success (Performance Metrics).

Metric Name	What it Measures	Why We Need High Numbers	Reference
Adsorption Capacity	Total load of poison held.	Cleans more water with less material.	[69, 70]
Kinetics	Speed of cleaning.	Provides safe water quickly (minutes).	[71]
Selectivity	Choosing bad metals only.	Does not waste space on safe minerals.	[72]
Regeneration	Ability to wash and reuse.	Saves money and reduces trash.	[73, 74]

Freeze-drying, process where water inside material freezes into solid ice crystals that act as pillars to hold structure up [89]. Removing air pressure causes ice to turn directly into gas without ever becoming liquid water again, leaving behind dry skeleton that keeps its original fluffy shape.

Resulting materials from this process are called Aerogels, which feel like solid smoke because they are mostly made of air and are incredibly light [90]. Nanocellulose aerogels have large volumes of empty space within and hence are able to absorb heavy metal such as super-vacuum cleaner. Supercritical drying is another advanced technique, where special liquid gas is used to wash away the water in the gentle manner and leaving even the smallest holes open and not to shrink [91]. Using Supercritical drying creates highest quality aerogels with finest network of pores, although it costs more money than freezing.

converting Nanocellulose suspensions into these porous 3D architectures transforms simple liquid slime into high-performance filter that can stand on its own [92]. Creating these Aerogels is essential for heavy metal adsorption because open structure allows huge amounts of polluted water to pass through quickly [93]. Studies show

Table 6. Creating Holes Using Templates (Sacrificial Methods).

Template Strategy	What is Used as Placeholder?	How Hole is Made	Resulting Structure	Reference
Salt Templating	Solid salt grains (like table salt).	Washing with water dissolves salt.	Large, defined holes matching salt shape.	[80, 81]
Ice Templating	Frozen water crystals.	Turning ice directly into gas (sublimation).	Long, tunnel-like channels.	[82]
Polymer Beads	Tiny plastic spheres.	Burning or melting plastic away.	Perfectly round, uniform holes.	[83]
Emulsion Templating	Oil droplets in water.	Washing away oil.	interconnected bubbly foam structure.	[84]
Role in Research	Cheap materials (Salt).	Easy removal creates high porosity safely.	Essential for letting dirty water enter deep sites.	[85, 86]

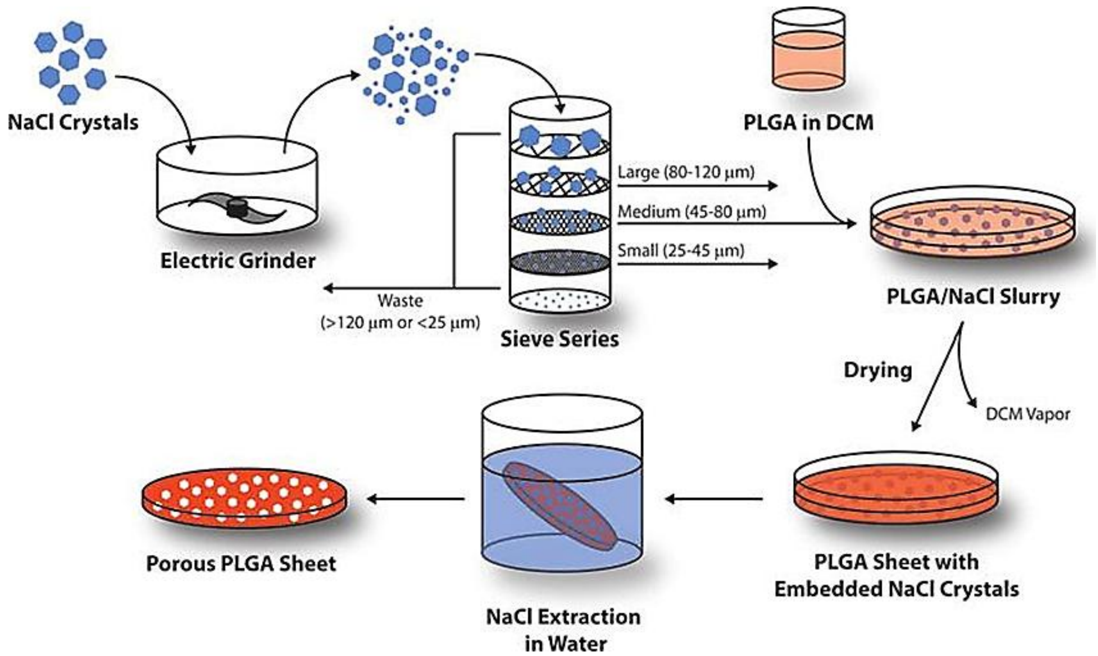

Fig. 4. Schematic diagram showing the salt-templating technique used to create porous structures. The process involves grinding salt crystals, mixing them with the polymer (like nanocellulose), drying the mixture also finally washing away the salt with water to leave behind open pores [87].

that aerogels made this way can hold hundreds of times their own weight in water, making them some of most porous materials on Earth [94] (Table 7).

Fig. 5 observing the middle images labeled as films reveals a very smooth and solid surface that looks like hard plastic because the internal walls collapsed completely during normal drying. Comparing those dense films to the fluffy aerogels shown in the top and bottom rows proves that using special freezing methods keeps the tiny holes open and distinct like a sponge. Seeing these deep holes and rough textures confirms that the porous material stays ready to soak up dirty water, whereas the smooth film acts like a closed wall that blocks everything from entering.

Chemical Crosslinking and Network Creation

Hold tiny fiber together require glue named Chemical crosslinking [96] so add bridge part

Table 7. Drying Methods to Create Aerogels.

Drying Method	Process Explanation	Effect on Porosity	Quality of Aerogel	Reference
Air Drying	Letting water evaporate naturally.	Bad; structure collapses into hard film.	Low porosity; useless for filtering.	[88]
Freeze-Drying	Freezing water, then turning ice to gas.	Good; ice crystals hold pores open.	High porosity; sponge-like structure.	[89, 90]
Supercritical Drying	Using high-pressure liquid gas (CO2).	Best; preserves extremely tiny holes.	Highest surface area; very fine mesh.	[91]
Aerogel Result	Final dry material is mostly air.	Allows massive uptake of heavy metals.	Ultra-lightweight and highly effective.	[92, 94]

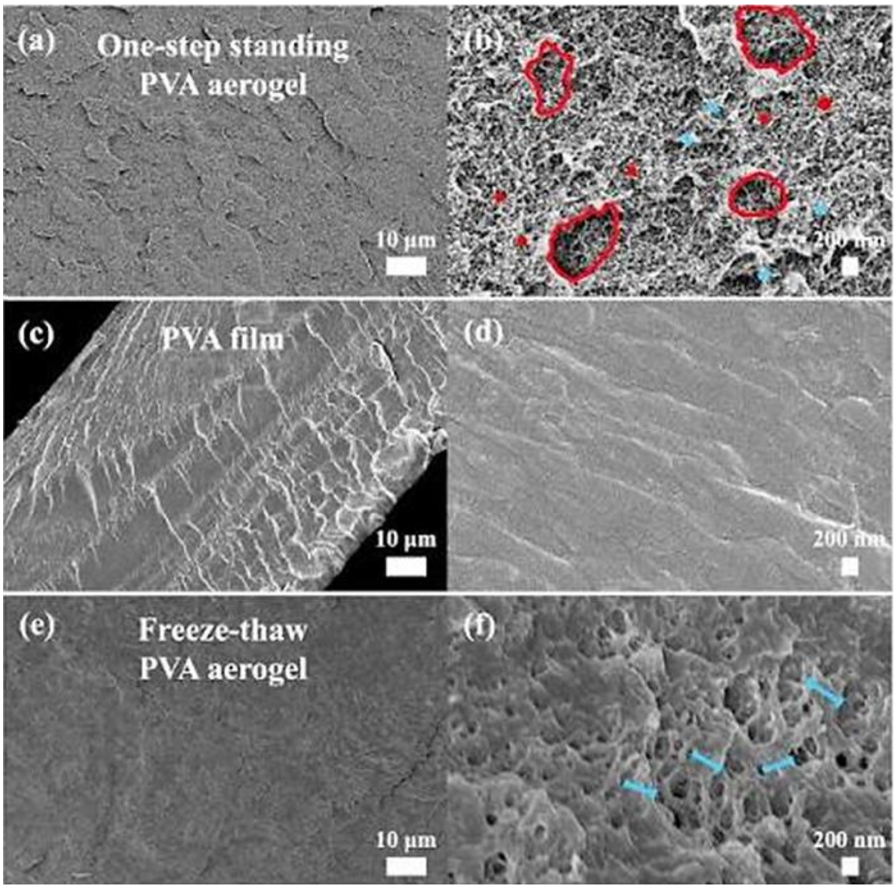

Fig. 5. SEM comparison showing structural collapse in air-dried films versus the open porous network in freeze-dried aerogels [95].

to connect fiber to fiber making strong Network that stay open forever. Without Crosslinking then fiber float away or close hole needed for clean [97] but use Crosslinker make hard 3D scaffold that not shrink even if wet or dry. Link fiber create strong house for metal to enter ensuring Macropore formation stay safe over time [98]. Polymer grafting involves growing new chemical branches on surface of cellulose, which push fibers apart and create more space between them [99]. Creating these chemical bridges allows material to act like stiff sponge that can be squeezed and used many times without losing its shape [100].

Introducing porous networks through chemistry ensures that material has both large holes for water flow and small holes for trapping poison [101]. Making structure strong through Crosslinking allows it to survive in harsh river conditions where water flows fast and might contain acid or salt (Table 8).

Fig. 6 Observing the bottom section labeled chemical crosslinking shows exactly how strong covalent bonds act like permanent knots tying the long fiber strings together into a safety net. Comparing this stable net to the loose physical tangle shown above proves that using chemical glue creates a rigid structure that refuses to break apart or dissolve when placed in water. Building such a strong 3D cage ensures that the internal pores remain open and ready to trap heavy metals without collapsing under pressure.

Composite and Hybrid Approaches

Mixing Nanocellulose with other strong materials creates super-material that has best qualities of both ingredients, known as Composite approach [103]. Combining wood fibers with Graphene oxide sheets builds structure that is

Table 8. Building Strong Networks (Crosslinking).

Strategy	Simple Definition	Role in Porosity	Reference
Chemical Crosslinking	using molecular “glue” or bridges.	Locks fibers in place so pores don’t close.	[96, 97]
Polymer Grafting	Growing plastic branches on fibers.	Pushes fibers apart to create more space.	[98]
Network Creation	Building 3D spider web.	Ensures continuous paths for water flow.	[99]
Macropore Stability	Keeping big holes open.	Prevents collapse when wet; improves reuse.	[100, 101]

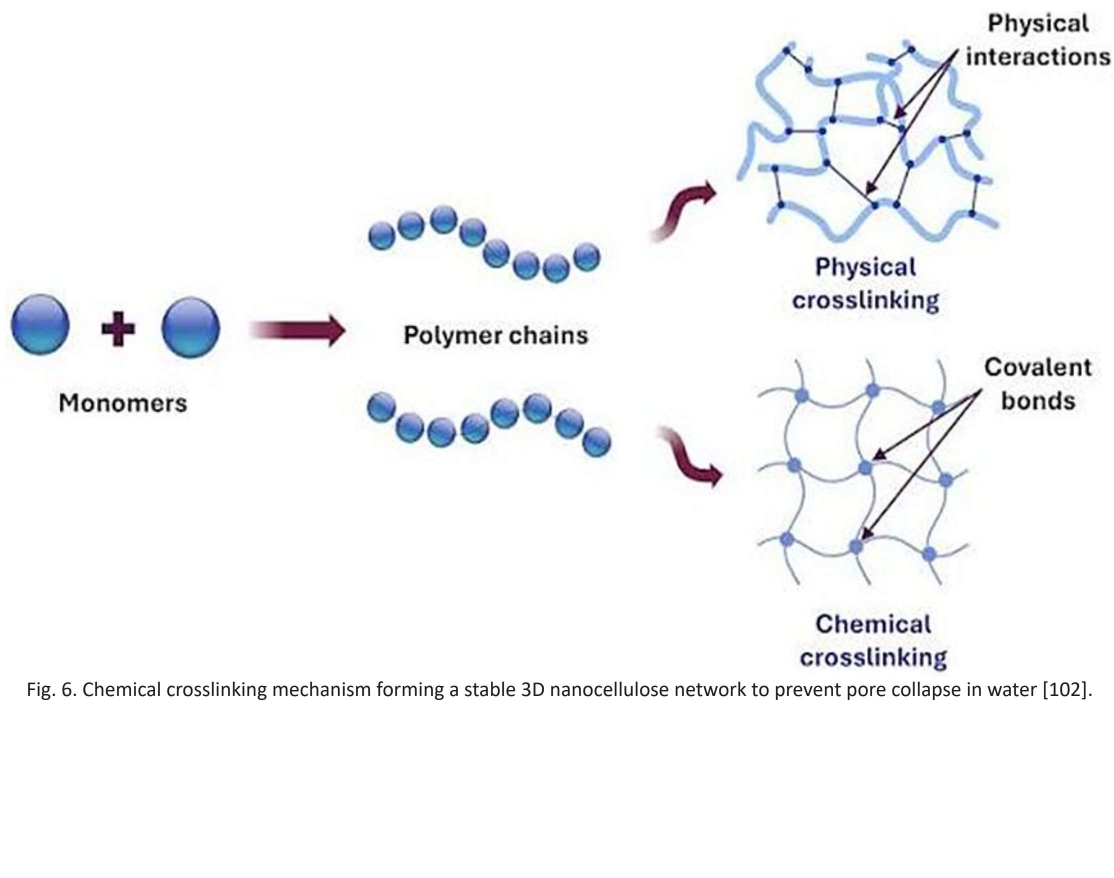

Fig. 6. Chemical crosslinking mechanism forming a stable 3D nanocellulose network to prevent pore collapse in water [102].

not only porous but also very strong and capable of catching different types of poisons [104]. Graphene oxide adds extra walls and rooms inside sponge, increasing Hierarchical porosity by adding different sizes of holes [105].

Adding tiny metal cages called Metal-organic frameworks (MOFs) introduces millions of extremely small holes that are perfect for catching gas or tiny metal ions [106]. MOFs act like high-tech traps that sit inside larger cellulose net, creating double-trap system where cellulose catches big dirt and MOF catches small poison [107]. Incorporating Magnetic nanoparticles allows filter to be pulled out of water using simple magnet, which makes cleaning water much easier [108].

These Hybrid methods provide Functional adsorption sites which are absent in normal wood, which is why filter is smarter and powerful [109]. The blending of materials is used to maintain pores open since hard particles do not allow soft cellulose fibers to squeeze [110] (Table 9).

Functionalization for Porosity

Change fiber skin chemistry Change hole shape named Functionalization for porosity [111] so modifying surface via Oxidation add oxygen making fiber push each other like magnet [112]. Push make Swelling open network for water [113]. Add acid group via Carboxylation make surface want water so sponge get big [114] plus Amination add nitrogen acting like spacer to keep Network spacing wide for metal [115]. Chemical change do two job meaning make better hook plus open door wide [116]. Tune Pore structure use chemistry not machine [117] so fiber push apart naturally making open house perfect for Heavy metal adsorption [118] (Table 10).

Tuning Pore Size Distributions

Design filter mean finding mix of big plus medium plus small hole named Tuning pore size distributions [119]. Mostly big hole call Macropores let water run fast but bad at grab tiny metal [120] while mostly tiny hole call Micropores trap poison well but water flow slow plus clog easy [121]. Middle hole named Mesopores is bridge joining fast road to parking spot [122]. Every size has good and bad so aim for Hierarchical structure having all three work together [123]. Big hole is door plus medium is hall and small is trap [124]. Balance size boost Heavy metal removal efficiency because trap fill fast and hold tight [125] so need adjust freeze speed or glue or salt size to get it right [126] (Table 11).

MODIFICATION OF NANOCELLULOSE FOR HEAVY METAL REMOVAL: LINKING POROSITY WITH FUNCTIONALITY

Surface Chemical Modifications of Nanocellulose

Change skin of wood fiber turn it to magnet for poison using chemical trick to add hook so Oxidation processes using TEMPO method [127] put oxygen on skin making negative charge to pull positive lead plus cadmium. Fiber push away each other with negative charge which make Swelling to open big pore [128]. Carboxylation put acid mouth on the skin to bite metal a lot more Adsorption capacity [129] and Amination add nitrogen hook metal that hate oxygen making trap clean many waters type [130]. Cover sulfur called Thiol group take hold of mercury since sulfur love mercury

Table 9. Mixing Materials (Composites).

Added Material	Why Mix it with Nanocellulose?	Effect on Porosity	Reference
Graphene Oxide	Adds strength and extra surface area.	Creates layers and spaces between sheets.	[103, 104]
MOFs (Metal Cages)	Adds millions of tiny, specific holes.	Drastically increases micro-porosity.	[106, 107]
Magnetic Particles	Makes filter magnetic.	Spacers that keep fibers apart; easy removal.	[108]
Hierarchical Effect	Combining big and small traps.	Ensures both fast flow and deep trapping.	[105, 109]

Table 10. Chemical Changes to Open Pores.

Chemical Method	What it Does to Fiber	Effect on Pore Structure	Reference
Oxidation	Adds negative charges (Oxygen).	Fibers repel each other, opening gaps.	[111, 112]
Carboxylation	Adds acidic groups.	Causes swelling, increasing internal volume.	[113, 114]
Amination	Adds nitrogen groups.	Acts as spacer to keep network open.	[115]
Swelling	Soaking up more water.	Expands whole sponge like balloon.	[116, 118]

and keep him there forever [131]. Experiment demonstrates chemical change not only add hook but alter Structure of pore to prevent fiber turn to solid block when dry [132] thus how to keep fiber apart keep fluffy network allowing dirty water to reach all hooks inside [133].

Grafting and Polymerization Strategies

Strategy that is used to grow long chemical hairs or branches on surface of Nanocellulose is referred to as Grafting which forms thick forest of active sites which are able to trap much more pollution than bald fiber. Grafting-to is the process of stealing long plastic chains which are already synthesized and attaching them on cellulose backbone, which serves as gluing the artificial leaves on the tree branch [134]. Grafting-from begins growth on the surface of the fiber, whereby plastic chains grow away as in the case of natural hair, and this results in very dense and bushy coating that entraps metals well [135].

The generation of porous networks occurs since these new branches repel the adjacent fibers and leave empty spaces or rooms between fibers that are not sealed even when the material is squeezed [136]. Polymerization enables the scientists to determine precisely what type of branch to develop, that is, the scientists can create smart branch where only one type of metal is captured but safe minerals are ignored [137]. These strategies are converted into high-tech sponge by using simple cellulose as precursors, where the grafted polymers are the long arms that reach out in water to collect passing poisons [138].

These polymer bridges connect fibrils in the whole house, so that the roof cannot collapse down and the Macropore formation is to be maintained in the same condition during a long period of time [139]. It is possible to create such 3D network so that the water passes through the grafted hairs forest without becoming clogged, and heavy metals are trapped and adhered to branches [140] (Table 13).

Porous Architectures Built from Nanocellulose

The creation of useful shapes out of tiny fibers involves assembly of these fibers into 3D structures such as Aerogels which are super-light solids that are filled with air which perform the role of super-sponge that can absorb vast amounts of water [141]. The porosity of all types of aerogels is the largest, and they can be 99% empty space, which serves as an interminable maze of tunnels that heavy metals can lose their way through [142]. Hydrogels are wet equivalents to aerogels that remain soft and wet with water like jelly and can therefore be used instantaneously without the need to be wetted [143].

The process of Membranes is to press fibers against the thin skin or sheet which is used as a sieve to allow the clean water to pass through and block the huge particles of dirt and collect the metals on the surface [144]. Microspheres are shaped like small beads or pearls with holes that are highly easy to pour into tanks and filters since they roll and fit easily into each other [145, 146]. With such applications of Example systems, engineers can select appropriate shape to be used in a job, be it floating sponge to be used in a lake or packed tube to be used in a factory pipe [147,

Table 11. Balancing Hole Sizes (Tuning).

Pore Type	Size Description	Main Advantage	Main Disadvantage (Trade-off)	Reference
Macropores	Big holes (>50 nm).	Fast water flow; easy access.	Low surface area; weak trapping.	[119, 120]
Mesopores	Medium holes (2-50 nm).	Good transport; connects layers.	Hard to control exact size.	[121, 122]
Micropores	Tiny holes (<2 nm).	Huge surface area; strong trapping.	Slow flow; gets blocked easily.	[123]
Hierarchical	Mix of all three.	Best of all worlds (Fast & Strong).	Complex and harder to make.	[124, 126]

Table 12. Chemical Changes to Surface Hooks.

Modification Type	Chemical Added	Effect on Porosity	Target Metal Behavior	Reference
TEMPO Oxidation	Oxygen (Carboxyl groups).	Causes swelling; opens pores wide.	Attracts positive metals strongly.	[127]
Alkaline Treatment	Base (OH groups).	Removes glue; exposes more surface.	Increases access to internal sites.	[129]
Thiolation	Sulfur (SH groups).	Minor swelling; high specificity.	Grabs Mercury and Lead tightly.	[131]
Amination	Nitrogen (Amine groups).	Acts as spacer between fibers.	Catches Copper and Chromium well.	[130, 132]

148].

Different water environments require different kinds of shapes to efficiently combat certain types of enemies (pollutants). Lead (Pb) can be best removed from static bodies of water, like reservoirs and settling ponds, using Aerogels as the shape, which simply float on top and will soak up an incredible amount of lead into their open caverns like a sponge (as described in [149]), to aid in capturing heavy metals. Cadmium (Cd) is a different story, as when it is dissolved in flowing water, it is best to remove it using Microspheres that have been assembled into filter columns, where the spheres themselves allow for high volumes of water to flow through, but catch cadmium ions in the syringe-like holes of the spheres, acting as a trap to prevent cadmium from going downstream (as discussed in [150]). In the case of Chromium (Cr), Membranes are used as barriers to prevent chromium from entering waterways. The Membranes themselves are composed of sheets that contain reduced iron and allow only the reduced form of chromium to interact and neutralize the chromium through a series of chemical reactions taking place inside the column's membrane (described in [151]).

Iron nanoparticles infused into Hydrogels are used as a solution to treat groundwater sources contaminated with Arsenic (As), as the Hydrogels' swollen with moisture allow for the fast and efficient diffusion of complex arsenate species into and through the Hydrogels without holding them up, thus causing them to become dry [152]. Lastly, the use of Thiol modified three-dimensional scaffolds provides the structural integrity needed to permanently bind Mercury (Hg) to the surface of a stable solid substrate due to their high surface area and sulfur content [153].

Performance of Modified Nanocellulose Adsorbents

To determine the effectiveness of these new materials, one can look at the Adsorption capacity, which has risen from the low values in plain wood to gigantic values in modified aerogels [149]. Adjusted nanocellulose is much more effective since added chemical hooks are taken violently, whereas open depressors make sure that no hook is concealed behind the wall [150]. The removal time has reduced to only a few hours to just a few minutes in certain instances due to high porous structure where the water is able to flow into the active site as soon as possible [151].

Selectivity has been enhanced, such that now intelligent materials can be used to select dangerous atoms of lead, despite the presence of non-dangerous atoms of sodium or calcium in sea [152]. In conclusion of the results of recent works, it is possible to state that high porosity and certain chemical grafting yield super-absorbent, which surpasses virtually all other materials such as charcoal or sand [153]. It is possible to compare studies that indicate that structure is as significant as chemistry; there is no use to have best chemical hooks when door to room is locked and metal cannot enter.

The effectiveness of advanced composite materials is further demonstrated by their ability to

Table 13. Growing Chemical Branches (Grafting).

Strategy Name	Simple Explanation	Impact on Structure	Reference
Grafting-From	Growing hair from skin.	Creates dense, bushy surface.	[135, 137]
Grafting-To	Gluing wigs onto skin.	Adds specific, pre-made functions.	[134]
Polymerization	Building plastic chains.	Pushes fibers apart to keep pores open.	[136]
Network Formation	Linking branches together.	Stops structure from collapsing.	[138, 139]

Table 14. 3D Shapes for Cleaning Water.

Architecture	Description	Porosity Type	Best Use Case	Reference
Aerogel	Dry, frozen smoke.	Extremely high (99% air).	Floating on dirty lakes; high capacity.	[141, 142]
Hydrogel	Wet, soft jelly.	High (swollen with water).	Treating water without drying out.	[143]
Membrane	Thin paper-like skin.	Dense with small holes.	Filtering pipes under pressure.	[144]
Microsphere	Tiny round beads.	Medium porosity; easy to handle.	Packing into large cleaning columns.	[145, 146]

remove low-level arsenic, mercury, and chromium from contaminated waters using a single product. For example, the ability to chemically modify the surface of the composites allows for the rapid capture of various ionic forms of arsenic, thus preventing the re-release of arsenic back into the water due to the spontaneous release of ions associated with conventional filter materials. Mercury is trapped within the mesopores of the composite materials by chemical hooks made up of sulfur atoms (the sulfur-containing groups), which keep the mercury from being released back into the water. In addition, the porous structure of the composites also serves to both trap and fix chromium within the mesopores in order to neutralize it and render it non-toxic. The combination of the access to the composite's wide-mouthed pores and the chemically modified surfaces of nanocellulose provides for a unique opportunity to simultaneously remove three types of highly toxic contaminants from an industrial liquid waste stream [154] (Table 15).

Case Studies of Heavy Metals

To thoroughly assess the adsorption capabilities of these enhanced materials, it will be important to test their interaction with actual "enemy" ions. Each metal has its own distinct chemical challenge. Nanocellulose's porosity and surface modification should be uniquely tailored to fit each metal like a glove [156].

Lead (Pb) is an example of an ion that has a high electrostatic charge since Pb is a large and heavy divalent cation (Pb^{2+}). Porous aerogels and carboxylated nanocellulose contain a high density of negatively charged carboxylic (-COOH) and hydroxyl (-OH) functional groups on the surface. These negatively charged groups strongly attract the positively charged lead ions [154]. The lead atom's large mass makes it imperative that the adsorbent's porosity is very high, so that the bulkier hydrated lead ions may easily travel through the adsorbent into the interior of the adsorbent without obstruction. The lead ions can be entrapped in the mesopores of the aerogel via bidentate bridging or chelation; thus, once the lead ions are trapped in the aerogel, they are effectively isolated within the aerogel lattice due to the large surface area created by the porosity of the aerogel [155].

Cadmium (Cd) is considered to be comparable to Lead; however, its negative effects are often much greater and more difficult to remove from the human body than Lead due to the presence of competing ions for excretion. Standard Cellulose has been shown to be ineffective in the case of Cadmium, and therefore, an innovative solution using Aminated Nanocellulose Beads has been developed as a viable option. Aminated Nanocellulose Beads are created by applying Amine Functional Groups ($–NH_2$) to the porosity of Nanocellulose Beads. This configuration utilizes the "Soft Acid-Soft Base" principle: The soft Acid (Cadmium) has a strong affinity for the Nitrogen Atoms associated with the Amine Groups (soft Bases). The porous nature of the Nanocellulose ensures that the Amine Hooks remain exposed on all sides, allowing for rapid rates of complexation,

Table 15. Improvements in Performance.

Performance Metric	Old Material Result	New Modified Material Result	Reason for Improvement	Reference
Capacity	Low (hooks hidden).	Very High (hooks accessible).	Porosity exposes internal sites.	[149, 150]
Removal Time	Slow (hours).	Fast (minutes).	Open tunnels allow fast flow.	[151]
Selectivity	Grabs everything.	Grabs only poison.	Specific chemical grafting.	[152]
Efficiency	Wasted space inside.	100% usage of volume.	Interconnected porous network.	[153, 155]

Table 16. Success Stories by Metal Type.

Metal Poison	Best Modification Strategy	Role of Porosity	Reference
Lead (Pb)	Carboxylation (Acid groups).	Allows large Pb ions to enter deep sites.	[154]
Cadmium (Cd)	Amination (Nitrogen groups).	Fast diffusion through mesopores.	[154]
Chromium (Cr)	Magnetic/Iron composites.	Supports iron particles that react with Cr.	[131, 155]
Arsenic (As)	Iron/Sulfur doping.	Prevents clogging; allows flow to active iron.	[155]

and allowing for the rapid removal of Cadmium from solution, even when the concentration of Cadmium is low, through the formation of Stable Coordinate Covalent Bonds.

Chromium (Cr) represents a notable challenge in the realm of environmental remediation due to its primary existence as Hexavalent Chromium (Cr(VI)), which is one of the few metals that can exist in anionic (negative) ionic form, and that can undergo changes in oxidation state. Using standard Negative Cellulose to remove Chromate from solution would not be an option, as the Negative Charge of Chromate would repel the Negative Charge of Cellulose. Therefore, a Sophisticated Approach Using Magnetic Nanocomposites and Protonated Nanocellulose was developed. These materials effectively electrostatically attract the Chromate Ion at low pH values.

One mechanism for removing chromium from contaminated water involves what is called "adsorption coupled reduction." In this method, porous materials adsorb toxic Cr(VI) from solution, then chemically reduce it to the much less toxic Cr(III) state using the electron-donor functionality of the cellulose matrix. As a result of the chemical reduction, a Trivalent Mercury Cation (TMC) is immobilized in the cellulose matrix during the chemical reduction process. This can be accomplished via a multi-step process that requires a highly porous structure to facilitate the transfer of electrons and ions deep into the porous network of the cellulose [153].

Arsenic (As) also presents a unique challenge because it exists primarily as oxyanions (either arsenate or arsenite) and does not readily form bonds with organic carbon chain molecules. To overcome this problem, nanocellulose can act as a porous, scaffold-like matrix material that is capable of supporting inorganic materials that can remove arsenic, like either iron oxide or thiol-based compounds, for example, [153]. Nanocellulose effectively prevents the agglomeration of Fe-nanoparticles and provides increased surface area on which to bind the As using the mechanism of ligand exchange—namely, the As displacing hydroxyls on the iron surface to create an inner-sphere complex and thus allow the flow of arsenic-contaminated water through the nanocellulose scaffold to promote the formation of the As and Fe (or S) complex in the cellulose matrix, thereby effectively locking the As up in that strong cellulose matrix [156].

Role of Porosity in Regeneration and Reusability

Toilet technology clean filter to use again make Regeneration [153]. Porosity has major role when open tunnel allows cleaning acid in and heavy metal out within seconds like rinsing sponge [156] and Desorption is the opposite process whereby when hole is too small then metal stick and tool remain dirty [153]. Reuse cycles depend on strong wall because weak wall make structure fall apart

Table 17. Washing and Reusing (Regeneration).

Factor	Why Porosity Matters	Result of Good Porosity	Reference
Desorption Speed	Cleaning fluid must reach inside.	Fast washing; metals release easily.	[153]
Reuse Cycles	Filter must handle stress.	Can be used 5-20 times.	[156]
Structural Integrity	Walls must not collapse.	Filter keeps its shape after acid wash.	[137]
Cost Efficiency	Reuse means buying less material.	Cheaper water treatment.	[137, 153]

Table 18. Linking Holes to Performance.

Property	Simple Definition	Effect on Capacity (Amount Held)	Effect on Kinetics (Speed)	Reference
Specific Surface Area	Total skin available to touch water.	High area = High capacity (More spots).	Does not change speed much.	[157, 161]
Pore Volume	Total empty space inside.	High volume = High capacity (More room).	Helps water enter faster.	[158]
Pore Size Distribution	Mix of big and small holes.	Needs small holes to lock metals in.	Needs big holes to let metals enter fast.	[159]
Interconnected Pores	Tunnels that connect rooms.	Uses all internal space efficiently.	Very fast speed (No dead ends).	[160]

during wash [137] so maintain Structural integrity need crosslinking fiber to build tough 3D skeleton surviving harsh acid without shrink [156, 137] (Table 17).

KEY RELATIONSHIPS: POROSITY/STRUCTURE–FUNCTION–PERFORMANCE

How Porosity Correlates with Adsorption Capacity and Kinetics

Understanding how well material cleans water requires looking at relationship between empty space and cleaning power, because having more holes usually means having more room to trap dirt. Specific surface area acts like giant unfolded map where every inch of space provides parking spot for dangerous atoms, meaning that material with high Specific surface area can hold huge number of heavy metals before it gets full [157]. Pore volume is a measure of total amount of empty space in sponge as well as having large Pore volume enables the material to absorb more dirty water simultaneously, which enhances a greater Adsorption capacity [158].

Pore size distribution defines the size of holes to be large enough to allow metals to enter but it should be small enough to ensure they are trapped to serve as filters to ensure that only things of the right sizes are caught. Having only tiny holes might trap metals tightly but makes process very slow, while having only big holes makes process fast but might let metals escape back into water [159]. Kinetics describes speed of cleaning process also studies show that materials with many medium-sized pores clean water much faster because metals can travel deep inside particle without getting stuck in traffic [160].

Connecting Porosity to performance proves that best materials are those that balance huge skin surface with deep, open tunnels, allowing them to catch lot of poison in very short time [161].

Influence of Morphology, Network Connectivity also Mass Transfer Pathways

Shape matters just as much as chemistry because physical form of material decides how easily water can flow through it to reach cleaning sites. Morphology refers to shape and texture of Nanocellulose also having rough, 3D shape like flower or sponge works better than flat, smooth shape because it catches water from all directions [162]. Network connectivity ensures that every tunnel inside material leads to another tunnel instead of hitting dead end, which allows heavy metals to travel deep into center of trap without stopping [163].

Mass transfer pathways are invisible highways that atoms travel along to get from dirty water to sticking point on fiber also open pathways make this journey very short and easy. Designing materials with wide and clear Mass transfer pathways prevents outside of filter from getting clogged, which would stop cleaning process even if inside is still empty [164]. Using Aerogels or Hydrogels creates perfect 3D web where water can flow freely, ensuring that every single fiber gets used to catch pollution [165].

Improving Heavy metal removal performance relies on creating these open networks because

Table 19. Shape and Movement.

Feature	What it Means	Why it Improves Removal	Reference
Morphology	The 3D shape (sponge vs. sheet).	Rough shapes catch more flowing water.	[162]
Network Connectivity	All tunnels touching each other.	Metals don't get stuck in dead ends.	[163]
Mass Transfer Pathways	Highways for atomic movement.	Allows deep penetration into filter.	[164]
Open Architecture	A loose, fluffy structure.	Prevents clogging on outside surface.	[165, 166]

Table 20. Balancing Good and Bad Qualities (Tradeoffs).

Conflict	The Problem	The Solution	Reference
Stability vs. Porosity	More holes make it weaker.	Adding crosslinkers (glue) to strengthen walls.	[167]
Robustness vs. Collapse	Wet sponges can get crushed.	Using composite materials for support.	[168, 169]
Performance vs. Scale	Complex filters are hard to make big.	Finding simpler ways to make porous structures.	[170]
Cost vs. Quality	Best filters are expensive.	Using waste biomass to lower costs.	[171, 172]

even best chemical magnet cannot work if metal ion cannot swim close enough to touch it [166] (Table 19).

Tradeoffs: Structural Stability vs. High Porosity

Make space with nothing in it cause trouble since slim walls are uneliminated thus easily crushed by the weight of water. Structural stability used to be hard and grow more porous to clean it to make it weak like dry leaf [167]. Mechanical robustness is capability to work with rough flow but porous aerogel tends to mush up when wet [168, 169] whereas Porosity failure occurs when wall adhesive to one another during dry closing hole [170].

Modeling Considerations: Adsorption Isotherms and Kinetics

It is important to predict the behavior of materials precisely unless special math tools known as Predict behavior need special math tool namely model are used to draw picture with number so that Adsorption isotherms graph may tell how much metal remain on filter assisting in locating max Capacity [173]. Kinetics theory calculate velocity with math to demonstrate whether metal stick slow or fast [174] whereas Transport in porous networks is difficult to enumerate thus advanced model predict how atoms swim through tunnels [175]. Nanocellulose systems usually can be used in Langmuir model with metal form single layer or in Freundlich model with rough pile [176] so utilize this model aid engineer pick right tank size [177]. Recent research indicate that combination of Thermodynamics and Kinetics modeling provide optimum perspective of how Porosity changes actual work of filter [178].

Challenges in Relating Porosity Metrics to Real-World Performance

Clean lab Test material is simple but dirty river show hard challenge because Real-world performance decline as dirty water contain Complex wastewater matrixes filled with dirt as well as oil and bacteria blocking pore [179]. Competing ions such as calcium and sodium are present in such large quantities competing to get the parking spot [180] and Scale-up problems occur due to the easy formation of tiny cup but hard to form ton due to its huge size [181]. It is difficult to relate Porosity values of dry air to wet water since thing swell and alter shape [182] hence Complex matrices reduce Adsorption capacity meaning filter require swap frequently [183] making it essential to test in actual sewage to observe how Porosity manage nature mess [184, 185].

Artificial Intelligence and Machine Learning in Adsorbent Design

Historically, developers of heavy-metal adsorbents relied on traditional trial-and-error approaches, a process both tedious and costly. The advent of Artificial Intelligence (AI) and Machine Learning (ML) has revolutionized the development of adsorbents, enabling a fundamental change

Table 21. Math Models for Prediction.

Model Type	What it Predicts	Common Nanocellulose Result	Reference
Adsorption Isotherms	Maximum holding capacity.	Fits Langmuir (single layer sticking).	[173, 176]
Kinetics Models	Speed of cleaning.	Fits Pseudo-second order (chemical sticking).	[174]
Transport Models	Movement inside tunnels.	Shows diffusion is slow step.	[175]
Thermodynamics	Energy changes.	Shows process releases heat (exothermic).	[177, 178]

Table 22. Real-World Problems.

Challenge	Why it Happens	Impact on Filter	Reference
Complex Matrices	Water has oil, dirt also bacteria.	Pores get clogged; capacity drops.	[179, 183]
Competing Ions	Safe minerals fight for space.	Filter fills up with useless Calcium/Sodium.	[180, 186]
Scale-up Issues	Making big batches is hard.	Quality drops; pores collapse in big tanks.	[181]
Lab vs. Reality	Lab water is too clean.	Real performance is always lower than lab results.	[182, 184]

in the way adsorbents are evaluated. Instead of relying primarily on empirical observations, novel modelling techniques can be used via advanced computational algorithms (Artificial Neural Networks (AWN), Genetic Algorithms (GA) and Random Forest (RF)), allowing researchers to simulate complex interactions that occur between metal ions and nanocellulose surfaces prior to producing even one gram of material for laboratory testing.

As with most cationic contaminants (e.g., lead (Pb) or cadmium (Cd)), there are several variables (e.g., pH, initial concentration and/or temperature) that govern their adsorption. The non-linear nature of the relationships among these parameters and the amount of Pb and Cd that are adsorbed onto the adsorbing agent (q_{max}) are mapped by AI models. Recent work indicates that AWN models can predict the performance of Pb and Cd removal with a more than 99% accuracy rate ($R^2 > 0.99$) and therefore outperform traditional statistical techniques [187]. Novel computational technologies provide the opportunity for researchers to determine experimentally-proven optimal parameters such as: (1) Porosity, and (2) Distributed functional groups (carboxyl or amine) and to experimentally determine the ideal conditions under which to create a specific nanocellulose/metal adsorbent combination [187].

Due to the complexity in removal pathways, the importance of implementing AI increases exponentially as Cr is a complex ion. Cr is a common contaminant in many industries, and its removal from an aqueous solution often relies on the combined processes of chemical reduction (reducing Cr VI into Cr III) and adsorption. The underlying mechanism of action for the combined processes described above is influenced by factors such as the protonation state of the active site of the adsorbent, as well as the degree of accessibility between pores and molecules. Because of this, most standard linear interpolation models (best fit equations) fail to adequately represent the kinetic behaviour of Cr adsorption/removal from contaminated aqueous solutions.

Deep learning architectures are being used to model these multiple kinetic steps, leading to the development of "smart" nanocellulose composites that adjust their surface charge according to the acidity of the wastewater [188]. This means that the composite material would have been designed specifically to bind to anionic species of chromium (chromate).

When it comes to the threat of chronic exposure to toxins such as arsenic (As) and mercury (Hg), the challenges will be a little different in terms of reducing selectivity with regard to other ions found in the same environment. For this reason, AI-driven "inverse design" strategies are being employed to evaluate thousands of different chemical changes and which one yields the optimal mass ratio of iron oxide nanoparticles for As or thiol functional groups for Hg [189]. By training the AI on large datasets with many examples of competition that occur in actual adsorption experiments, it is possible to guide the selection of the correct molecular structure that would preferentially

Table 23. Making it Big (Scalability Issues).

Challenge	Why it is Hard	Possible Solution	Reference
High Energy Cost	Freezing and drying huge tanks takes too much electricity.	Using ambient drying or salt templates.	[142, 160]
Quality Control	Big batches often have uneven or collapsed holes.	Better mixing machines and automated control.	[119]
Water Usage	Washing out templates wastes clean water.	Recycling wash water or using meltable templates.	[85, 172]
Raw Material Supply	Getting enough clean bagasse or pulp is logistical work.	Building factories near sugar farms.	[81, 108]

Table 24. Keeping it Strong (Stability).

Problem	What Happens	Why it Matters	Reference
Pore Collapse	Holes shrink after drying.	Material cannot catch metals next time.	[156, 169]
Swelling	Fibers get too fat in water.	Tunnels get blocked; flow stops.	[137]
Breakage	Flowing water tears filter.	Filter pieces contaminate clean water.	[168]
Acid Damage	Cleaning acid dissolves glue.	Filter falls apart during regeneration.	[96, 167]

bind to As or Hg, while ignoring the competitive elements of safe minerals, such as calcium and magnesium. This type of computational prediction has the benefit of reducing the amount of chemical waste generated during experimentation while providing high-performance filters capable of functioning in a true to life setting.

CURRENT GAPS, CHALLENGES ALSO RESEARCH OPPORTUNITIES

Scalability and Cost

Producing tiny amounts of porous nanocellulose in small glass beaker works perfectly every time, but trying to manufacture tons of this material for big city remains very difficult and expensive problem to solve [142]. Making material in laboratory allows scientists to control every single ice crystal and pore, yet doing this in giant factory often results in uneven holes and poor quality [119]. Scalability refers to ability to make huge quantities without losing quality also currently, methods like Freeze-drying take too much time and electricity to be used for treating all water in river [160].

Cost remains major barrier because even though wood waste is cheap, machines needed to make it into Nanocellulose and dry it into Aerogels are very expensive to run [84]. Using chemical templates like salt helps reduce cost, but washing away salt requires huge amounts of clean water, which adds another cost to process [85]. Reducing price of these Advanced adsorbents requires inventing new drying methods that do not use expensive freezing or dangerous chemicals [172].

Manufacturers face challenge of turning delicate, fluffy lab sample into strong commercial product that can be sold in bags or blocks to water treatment plants [108]. Further studies need to be done to identify low-cost methods of producing Controlled porosity in large scale such that poor countries can afford using such smart filters [144].

Structural Stability and Durability

Spongy sponge after wash ten time is hard work because acid weaken wall [156] such Structural stability mean filter not turn to dust in fast water but high porous substance such as aerogel is weak just like dry toast [167]. Durability mean thing last long time but lots of Nanocellulose shape swell and lose shape when wet [137] plus keep Porosity during Adsorption/desorption cycles is tough because hole close or shrink when dry so-called pore collapse [169]. It is important that mechanical integrity in Flow systems since with a broken filter the tiny bits fly off creating new pollution [168] but make it hard with glue like plastic but not too hard like a crosslinker or it may block its hole and prevent it getting dirty [96] therefore engineer needs to make skeleton like plastic but skin soft like cotton to grab metal [166].

Selectivity in Complex Effluents

There are mud, oil and harmless salt struggling ill bad lead inside the river water [179]. Selectivity means smart filter to grab only dangerous Heavy metals but most tool grab everything [152].

Table 25. Picking Right Poison (Selectivity).

Obstacle	Description	Impact on Performance	Reference
Competing Ions	Safe salts (Na, Ca, Mg).	They fill up trap, leaving no room for Lead.	[179, 180]
Organic Matter	Slime, oil, dirt.	Clogs surface pores physically.	[164]
Ionic Strength	High salt levels in water.	Weakens magnetic pull of filter.	[183]
Mixed Metals	Soup of many poisons.	Hard to remove all types at once.	[152, 175]

Table 26. Measuring Correctly (Standardization).

Current Issue	Why it is Confusing	Needed Solution	Reference
Dry vs. Wet Testing	Materials shrink when dry.	Test porosity in wet state (NMR or cryo-SEM).	[100, 127]
Different Timings	1 hour vs. 24 hours.	Set standard testing times.	[68, 174]
Varying Conditions	Different pH or temperatures.	Standardize pH and temp for all tests.	[109]
Unclear Metrics	mg/g vs. % removal.	Report both capacity and efficiency always.	[161, 178]

Massive effluents are actual dirty water of high Ionic strength implying complete of salt that prevent magnetic attraction of Nanocellulose [180], whereas Organic matter such as rot leaf form slime on filter skin obstructing hole [164]. Remedy these Real wastewater conditions are not easy test since filter working in clean lab fail in dirty sewer [183] and therefore improve selectivity must make special chemical hand fitting only lead shape such as key fit lock [175]. Other competing ions such as calcium are ubiquitous and filter should be intelligent to locate rare lead such as needle in hay [186].

Standardization of Porosity Characterization and Performance Reporting

Measure hole size varies widely in lab making hard to find best one [100] so Standardization means make one rule to all but now some measure dry and other measure wet giving mix result [109]. In water, gas is commonly used to characterize porosity by filtering the water and is used to identify the presence of holes but not the actual story [127] (Tables 26 and 27).

Environmental/Sustainability Aspects

Make green filter should not make black smoke signify energy to freeze or dry low to save earth [115]. Lifecycle analysis is the examination of things since their inception to death to ensure that Nanocellulose does not employ a greater number of chemicals than it eliminates [12]. Good feature is biodegradation as it turns into soil but bad if the rots when containing toxic lead releasing poisonous leads back to the ground [181]. Regeneration energy must be low because if need boil acid to clean then better make new one [153] and Secondary pollution happen when wash chemical become waste making new toxic puddle [172]. Solve problem need safe way to burn or bury dirty filter so poison never return [156] while True sustainability mean use farm waste to clean factory waste closing loop without add new trash [144].

Future Directions

Design next filter use computer to draw perfect hole shape before make it so every atom do job [178] and Design of hierarchical absorbent materials aim to build big road for water plus tiny alley for trap acting like nature lung [20]. Integration with targeted binding groups let science program filter to catch only gold or mercury making it mine tool plus clean tool [137]. Sensing/monitoring coupling turn filter to smart device changing color when full telling worker when to swap [175] so Intelligent control systems use color to switch flow automatically making plant run alone [168]. Computational design of Porosity/absorption let science test million structure in second to find best one [185] meaning Future research stop guess work and move to smart engineering where porosity is plan perfect [162] (Table 29).

Specific Prospects for Heavy Metal Removal Using (Melamine-Modified Laminated Nanocellulose,

Table 27. Fitting into Machines (Integration).

System Type	Challenge	Required Form of Material	Reference
Fixed-Bed Column	Soft materials get crushed by water weight.	Hard beads or pellets.	[160, 176]
Continuous Flow	High pressure breaks filter.	Strong, crosslinked scaffolds.	[144]
Membrane Filter	Surface gets clogged with dirt.	Anti-fouling coating.	[91]
Hybrid System	Connecting different technologies.	Multi-functional composites.	[131, 157]

Table 28. Protecting Earth (Sustainability).

Aspect	The Risk	The Goal	Reference
Production Energy	Making it burns too much coal.	Low-energy production methods.	[115]
Biodegradation	Rotting filter releases trapped poison.	Safe disposal or metal recovery.	[12, 181]
Secondary Pollution	Washing chemicals become toxic waste.	Green washing fluids (like citric acid).	[153, 172]
Raw Material	Cutting forests to make filters.	Using agricultural waste (bagasse).	[144, 156]

Table 29. What Comes Next (Future Directions).

Future Idea	What it Does	Benefit	Reference
Hierarchical Design	Mimics nature (lungs/leaves).	Perfect flow and trapping balance.	[20, 162]
Smart Sensing	Color change when full.	Easy maintenance; no guessing.	[175, 168]
Computational Design	Computer simulation of pores.	Saves time; finds perfect structure.	[178, 185]
Metal Recovery	Mining gold/silver from water.	Turns waste into money.	[137]

Table 30. Specific Contribution (Melamine & Salt).

Component	Function	Gap it Solves	Reference Context
Melamine	Adds Nitrogen hooks.	Solves Selectivity (grabs metals well).	[130, 137]
Laminated Structure	Layers provide strength.	Solves Stability (won't collapse).	[80]
Salt Casting	Creates controlled holes.	Solves Porosity/Cost (cheap holes).	[81, 85]
Combined System	Strong, porous, & sticky.	Addresses Real-world performance.	[129]

Salt Casting)

Combine Melamine adjustment with Salt casting to come up with special tool with nitrogen hook to hold metal and flawless hole to allow water in [130]. Melamine is rich in nitrogen which may serve as super-magnet to lead and cadmium, and hence it renders Nanocellulose skin very active [137] and Laminated nanocellulose make page-like layer to provide strength. Then Salt punch hole through page so water flow between them [81].

The emphasis on this particular combination brings up gap in Selectivity since Melamine is highly specific also it brings up gap in Scalability since Salt casting is cheap and easy [85]. My work helps fill these gaps by showing that cheap chemical (melamine) and cheap template (salt) can create high-performance filter which is not only strong but also porous [80].

The future of this particular material is imminent since it addresses the trade-off of the strength and porosity producing porous scaffold that is rigid and starving of metals [129] (Table 30).

CONCLUSION

The examination of hundreds of different studies makes it obvious that the transformation of ordinary plant debris into Nanocellulose is one of the most promising substances to clean dirty water in case scientists can introduce changes to it both chemically and physically and make holes. Surface chemistry modification makes lazy fibers aggressive hunters by being modified with hooky sticky groups such as carboxyl or amine groups that are like magnets to attract the dangerous Heavy metals like lead and cadmium. Porosity improvement in order to ensure that the fiber is not packed like tight wall, but sit like open sponge allowing dirty water to penetrate deep to reach each hook, combination of two way is good to make great improvement in the removal of Heavy metals. Open pore allow water in fast indicating fast kinetics and chemical hook hold mean poison tight indicating high capacity and Aerogels and Hydrogels are preferred shape since light 3D structure offer high surface area that offer most parking spot to metal. Simple template such as grains of salt allow science to determine how large the placing of the science hole is ideal formation of balance that water travel rapidly yet metal trap in place when formed properly with high Porosity.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript.

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