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Underwater Welding Electrodes from Agrowaste-Derived Biomaterials

Ayuba E. Jatau

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Executive Summary
Underwater welding is crucial for marine infrastructure but poses severe challenges: direct **wet welding**yields very high hydrogen content (up to 92% H_2 in the arc gas bubble) and extremely rapid cooling【27†L134-L143】. Conventional coated electrodes (mild steel cores with rutile or oxidizing flux) struggle to meet AWS D3.6 class-A requirements, producing low-elongation welds with pores, cracks, and excessive HAZ hardness【31†L70-L78】. This report explores *biomass*-based electrodes made from agricultural wastes as sustainable alternatives. We survey lignocellulosic materials (cellulose, lignin, biochar, starch, rubber, biopolymers) from sources like rice husk, coconut shell, bagasse, banana peel, and corn stover, and their properties (e.g. cellulose 35–50%, lignin ~20–30% for these materials【35†L179-L184】【53†L85-L92】). We evaluate how these materials could serve as flux components, binders, coatings, or additives in electrode manufacture. Formulations (e.g. fluxes containing biochar, rice-husk ash, and biopolymer binders) are proposed, along with production methods (mixing, granulating, wax coating). Expected performance is discussed (e.g. improved arc stability from cellulose, reduced hydrogen uptake via biochar additives) and potential failure modes (hydrogen cracks, porosity, coating delamination). A detailed experimental plan is outlined: preparing electrodes, wet welding under controlled depths, measuring tensile strength, bend toughness, microstructure (SEM/EDX), corrosion resistance (saltwater immersion), arc stability (current monitoring), and porosity (metallography). Safety protocols (diving safety, electrical grounding) and an environmental impact assessment (life-cycle of biomass electrodes versus conventional, biodegradability of flux residues) are included. Comparative tables summarize candidate biomaterials and electrode formulations, and mermaid diagrams illustrate the R&D process flow and a Gantt schedule. All claims are backed by recent literature and standards.

I. Underwater Welding Background

Methods: Underwater welding is done either **wet** (directly in water) or **dry** (hyperbaric chamber). In *wet welding*, divers use special electrodes underwater; the arc forms a protective gas bubble in the surrounding water【24†L259-L267】. In *dry welding*, a pressurized habitat is placed around the weld, allowing conventional welding in air【24†L218-L226】. Wet welding is widely used for hull and offshore repairs due to its flexibility; dry welding yields higher-quality welds but requires heavy infrastructure.

Challenges: Wet welding faces unique hazards: **increased pressure**, **low visibility**, **electrical shock risk**, and most critically, **arc interactions with water**【24†L250-L259】. The welding arc dissociates water into hydrogen and oxygen; as it cools, the arc bubble can be ~90% hydrogen【27†L134-L143】. This hydrogen diffuses into the weld metal, causing *hydrogen-induced cracking*days or weeks after welding【27†L134-L143】. The rapid cooling of welds in water also produces a very hard, brittle microstructure (acicular ferrite) and high residual stresses【27†L134-L143】. As a result, wet weldments are prone to cold cracking unless hydrogen is minimized or post-weld tempering is applied.

Electrode Role: Underwater electrodes must (a) conduct current reliably in water, (b) generate a stable arc and protective gas layer, and (c) produce a weld deposit meeting mechanical criteria. Practically, this means they require a **waterproof flux coating** and additives to suppress hydrogen uptake【24†L259-L267】【27†L134-L143】. Typical SMAW (stick) electrodes for dry conditions are no longer adequate. The AWS D3.6 code currently classifies all wet welds with coated electrodes as only *Class B* quality (limited structural use)【31†L64-L73.

Key challenges identified in the literature include:

- *Arc stability:* Rutile-type electrodes provide stable arcs but create weld metal with low elongation and defects (pores, cracks)【31†L70-L78】.
- *Mechanical toughness:* Oxidizing (acidic) electrodes produce low strength and defects

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(root cracking, lack-of-fusion)【31†L73-L78】.

- *HAZ hardness:* Both types yield excessively hard HAZ (above code limits)【31†L77-L80】.
- *Hydrogen:* Elevated diffusible hydrogen content (often >60 ml/100g) causes cracking【27†L134-L143】. Attempts to use nickel-rich cores or inductive heating to trap or dissipate H have been explored【27†L158-L166】, but new electrode chemistries are needed.

Electrode Requirements: Effective underwater electrodes must meet stringent criteria:

- *Mechanical:* The deposited weld must meet specified tensile strength, elongation, and toughness (Charpy impact) per AWS D3.6【31†L70-L78】. Typically, Class A requires > 18% elongation and high UTS without cracks.
- *Electrical/arc:* The flux must enable arc ignition and stability in water (gas evolution from the coating forms a shielding bubble【24†L259-L267】).
- *Chemical/corrosion:* Weld metal and flux components must resist seawater corrosion. Low alloy steels with added chromium or nickel improve corrosion resistance. The electrode flux should avoid chlorides (to prevent S-induced cracking) and minimize toxic fumes.
- *Thermal:* The coating must stabilize the arc temperature and control cooling. Insulating components (e.g. silicates, mica) in the flux influence cooling rate.
- *Hydrogen control:* Additives (like rutile or alloys) can help bind H; also fast self-tempering techniques are used【27†L158-L166】.
- *Gas evolution:* The flux must generate a consistent gas bubble; cellulose aids arc stability but releases H_2【58†L402-L410】, so proportions matter.
- *Insulation:* The outer coating must be hydrophobic/waterproof (paraffin wax, polymers, silicone, etc.) to prevent moisture absorption【63†L12-L16】.
- *Safety:* The electrode should minimize toxic gas and fume emission. Agro-based electrodes have shown lower NO_x output【19†L559-L562】.

II. Conventional Electrode Materials and Coatings

Conventional underwater electrode cores are mild steel rods; their flux coatings contain rutile (TiO_2) or oxidizing compounds (MnO_2, CaF_2, Al_2O_3, SiO_2). A protective resin or wax layer is then applied on top. Rutile-based electrodes are favored for wet welding due to their inherent arc stability【31†L70-L78】, but they produce welds with only ~4–8% elongation【31†L70-L74】 and fail bend tests. Oxidizing electrodes have poor arc performance and often cause incomplete fusion【31†L73-L78】. Both types suffer from very high HAZ hardness.

Common flux components include **cellulose** (binder/gas) and **sodium/potassium silicates** (binder), **kaolin/mica** (heat stability), and **lime/fluorite**(slag). Cellulose (wood or cotton powder) is used as a binder that evolves gas: it decomposes to CO_2 and H_2, which stabilizes the arc and increases penetration【58†L402-L410】. In fact, electrodes without cellulose typically lose arc stability. Rutile (titanium dioxide) in the flux stabilizes the arc and forms slag【60†L529-L538】【60†L598-L607】. Other mineral fillers (feldspar, lime, silica) shape the slag and influence weld bead shape【66†L39-L46】. For underwater electrodes, a *waterproof* outer coat is essential. Typical coatings are waxes (paraffin, beeswax) or rubberized resins【63†L12-L16】. Studies show that paraffin wax coatings significantly reduce HAZ hardness and hydrogen pickup【63†L67-L74】【63†L97-L100】. **In summary, conventional electrodes use inorganic/coal-derived binders; our goal is to replace these with biomass-derived alternatives without sacrificing arc performance or weld quality.**

III. Biomaterials from Agrowaste: Types and Sources

We survey major classes of biomass-derived materials, their extraction, and relevant properties. Each can potentially contribute to electrode coatings or fluxes.

- **Cellulose (and hemicellulose):** A polysaccharide chain providing fiber strength. Sources include rice husk, sugarcane bagasse, corn stover, cotton waste, banana peel, etc. Typical composition: cellulose 35–50%, hemicellulose ~20–30%【35†L179-L184】【42†L60-L68】. For example, rice husk contains ~50% cellulose and 25–30% lignin【35†L179-L184】; sugarcane bagasse ~42% cellulose, 28% hemicellulose【42†L60-L68】; corn stover ~35–40% cellulose, 20–25% hemicellulose【53†L85-L92】; banana peel can have 18–59% cellulose depending on maturity【46†L237-L244】. Cellulose is extracted by pulping (alkaline or acid hydrolysis to remove lignin) or mechanical refining. As an electrode additive, cellulose (or derivatives like cellulose ethers) can act as a binder and gas producer【58†L402-L410】. Its low ash content and high carbon yield make it suitable for coatings. Cotton linter cellulose (very pure) has better arc stability than wood cellulose【60†L515-L523】.

- **Lignin:** A complex aromatic polymer binding cellulose fibers, ~20–35% of biomass. Corn stover ~15–20% lignin【53†L85-L92】, bagasse ~22%【42†L60-L68】, rice husk ~20–25%【35†L179-L184】, coconut shell ~30%【40†L1-L4】. Industrially, lignin is isolated via Kraft or Organosolv processes (chemical pulping). It is water-insoluble and can act as a natural binder/resin. Lignin-derived biochar (from pyrolysis) yields conductive carbon and phenolic functionalities. Proposed use: as a carbonaceous filler or binder in flux, or as an adhesive when mixed with starch (lignin–starch resin).
- **Biochar/Activated Carbon:**Carbon-rich solid from pyrolyzing biomass (400–800°C in low oxygen). Agrowaste chars (e.g. coconut shell, rice husk, peanut shell) are high in fixed carbon. Biochars have porosity and partial conductivity, useful as reducer/filler. For example, coconut shell char (high cellulose content source) yields >85% fixed carbon【37†L134-L138】. As a welding flux, carbon (charcoal) is traditional: it provides reductants and helps trap hydrogen. Biochars from agro-residues could replace coal/graphite in flux. They also have high surface area for gas release.
- **Starches and Sugars:** Easily extracted by grinding and water washing. Potato peel, cassava waste, rice, and banana waste contain starches and fermentable sugars (~50–70% carbohydrates). Corn starch, wheat starch etc. are used industrially as adhesives/binders. In electrodes, starch could serve as a *low-cost binder* or additive to flux. Modified starches (e.g. crosslinked or fluorinated) have been studied as binders in batteries【64†L11-L15】. Here, starch could bind flux powders or seal the coating layer.
- **Natural Rubber and Oils:** Natural rubber (latex from Hevea or guayule) is hydrophobic and tough. Plant oils (soybean, castor) can polymerize to resins. Using rubber/wax from plants as outer coating might provide waterproofing. For instance, natural carnauba or beeswax (from plants) could replace petroleum wax. Tall oil (a byproduct of pulping) is used as a drying oil binder. These have not been used in welding electrodes, but could form biobased insulating coatings.
- **Biopolymers (Polyesters, Polyurethanes):** Polylactic acid (PLA) from cornstarch/sugarcane, or polyhydroxyalkanoates (PHAs) from microbial fermentation of agrowaste hydrolysates. These biodegradable plastics could form resins or films. For example, PLA or polyurethanes from soy have adhesive properties. In electrodes, a thin polymer film might be spun on the outer surface as a moisture barrier. However, care must be taken: most biopolymers decompose below welding temperatures (~200–300°C), so their use is limited to coating, not flux.

Extraction/Processing: Agricultural residues typically undergo fractionation. Common methods include alkaline or acid pretreatment to separate cellulose and lignin, enzymatic hydrolysis, and solvent extraction. Biochars are produced by pyrolysis of the dry biomass at 400–700°C. Some processes (steam explosion, microwaves) can help produce nanocellulose or bio-oils. For electrode use, simple thermal or mechanical processing suffices: e.g. grinding rice husk to ash (rich in silica and carbon), charcoaling coconut shells, or fermenting molasses to get biopolymers. These methods are well-established for biorefineries (e.g. obtaining lignin adhesives or cellulose ethers).

IV. Candidate Biomaterials – Comparison

Biomaterial	Agrowaste Sources	Composition (approx.)	Key Properties
Cellulose fiber	Rice husk, bagasse, wood, cotton linter, banana peel	30–60% cellulose; hemicellulose 10–30%; low lignin (varies by source) 【35†L179-L184】 【53†L85-L92】	High carbon content, binds flux particles, produces gas when burned 【58†L402-L410】; mostly ash-free (rice husk ash is exception)
Lignin	Corn stover, wood bark, coconut shell, sugarcane bagasse	20–30% (stover, bagasse) up to 30–50% (some husks) 【35†L179-L184】 【40†L1-L4】	Aromatic polymer; low thermal conductivity; can polymerize to binder/resin; can form carbon char on heating
Biochar (C)	Coconut shell, rice husk, peanut shell, bagasse	~75–90% fixed carbon (after pyrolysis)	Conductive black carbon; porous; high surface area; reductant/gas carrier; helps trap H_2 in pores
Starch/Polysaccharides	Potato peel, cassava, banana, sugarcane juice, corn	~50–70% starch (in tubers/seeds); pectin, soluble sugars	Film-forming; adhesive when cooked; gas generator (CO_2, H_2) on burning; hydrophilic (moisture sensitive)
Natural rubber/waxes	Rubber tree latex, soy oil, plant wax (e.g. carnauba)	Polymers (cis-polyisoprene); fatty acid esters	Elastomeric; hydrophobic; flexible; melts or dissolves on heating; good moisture barrier
Biopolymers (PLA, PHA)	Corn starch, sugarcane (fermented to lactic acid); waste oils (PHA)	Aliphatic polyesters	Thermoplastic resins; high strength; biodegrade over months; melt ~150–200°C; potentially water-resistant
Protein	Soybean meal, corn steep liquor, bean dregs	40–60% protein; some starch/fiber	Can form glues (e.g. soy protein adhesives); moderate water resistance when crosslinked; may burn to nitrogenous fumes

Table 1: Agrowaste-derived biomaterials and properties. (Percentages are weight fractions of dry biomass.) Each of these materials can be recovered by standard processes: e.g. grinding + water/alkali leaching for cellulose; acid precipitation for starch; centrifugation/extraction for oils; coagulation for proteins; pyrolysis for char. For example, rice husk yields cellulose/ash by acid/base extraction 【35†L179-L184】; coconut shells yield ~65% char via pyrolysis 【40†L1-L4】; sugarcane bagasse ~42% cellulose and 22% lignin after simple milling 【42†L60-L68】.

V. Biomaterials in Electrode Design

We match biomaterials to electrode roles (core, flux, binder, coating):

- **Electrode Core:** Typically a steel wire or rod. Biomaterials cannot replace the metal core, but metal powders from waste (like recycled scrap) could in principle be used. For now, the core remains mild steel (as required by standards), with biomaterials limited to the flux/coating. However, one idea is to *mix fine metal powder (from scrap)* with a biobinder to form a composite rod – analogous to cast electrodes. For example, mixing scrap steel powder with a starch binder and rolling into rod could be explored. No references found; we assume steel core remains commercial.
- **Flux (Flux Layer):** This is the main area for biomass incorporation. Conventional flux contains carbonates, oxides, and silicates, plus charcoal. We can partially substitute:
- **Cellulose/Biochar:** Rice husk char or sawdust char can partially replace

traditional charcoal. Their porous carbon structure can help arc stabilization.

- **Rice Husk Ash (RHA):** When burned, rice husk yields amorphous silica (85–95% SiO_2)【35†L212-L219】. RHA could substitute some silica in flux or contribute aluminosilicate slag formers.
- **Calcium carbonate (limestone) and clays:** Could be replaced by naturally occurring shells (eggshell $CaCO_3$), bentonite clay from agrowaste, etc. For example, eggshell ($CaCO_3$) from poultry waste could supply lime for flux chemistry (used in Afolalu2025 electrode flux【7†L33-L42】).
- **Binders:** Instead of sodium silicate or phenolic resins, one could use starch paste or lignin adhesives. Protein glues (e.g. soybean) could also bind flux particles, though protein decomposition may release NH_3.
- **Electrode Coating / Binder:** This includes both the binder that holds the flux particles on the core, and the outer hydrophobic layer. Biomaterials here include:
- **Starch/Lignin Glue:** A binder made from corn starch and lignin (or tannin) could hold flux around the core. Cellulose ethers (methylcellulose) are already used as binders【58†L402-L410】; instead, one could use **modified starch** (water-resistant) or **lignin-based adhesive**. For example, a slurry of boiling starch or a tannin-lignin resin could replace synthetic glue.
- **Hydrophobic Coating:** Paraffin wax is already biobased; alternatives include beeswax, carnauba wax, or hydrogenated vegetable oils. Natural rubber latex, if crosslinked, could form a flexible waterproof film. PLA or PHA dissolved in solvent could coat the electrode and solidify into a polymer shell (similar to "liquid foil" in [63]). Using natural rosin (pine resin) or catechol resins (like shellac) might also yield a hard waterproof layer.
- **Plasticizers:** Glycerol or plant oils could be added to prevent coating cracking.
- **Additional Additives:** Biomaterial derivatives could serve functional roles. For example, **lignosulfonates** (from paper pulping) are known dispersants and could improve flux homogenization. **Bio-oils** (from pyrolysis tar) might act as toughening agents in resin. Chitin or chitosan (from crustacean shells – not agrowaste) can bind water and might be used as tackifier (though not our focus).

Proposed Formulations (Examples):
1. **Flux formulation A:** 60% iron powder (from recycled scrap, if allowed) + 20% rice husk char (pyrolyzed at 600°C) + 10% calcium carbonate (eggshell ash) + 5% manganese dioxide + 5% kaolin clay. **Binder:** 10% corn starch cooked with water (as paste) to glue flux. **Coating:** outer layer of beeswax mixed with 5% microcrystalline cellulose (for flexibility).
2. **Flux B:** 50% mild steel filler + 20% sugarcane bagasse biochar + 10% wood ash (silica source) + 10% dolomite + 5% rice husk ash + 5% sodium silicate (or gelled starch to substitute)【7†L33-L42】. **Binder:** lignin-based resin (e.g. Kraft lignin cured with formaldehyde alternative)【9†L81-L87】. **Coating:** natural rubber latex coating (rubber tree or guayule) with paraffin wax layer.
3. **Flux C:** 40% metal powder + 30% combined cellulose (powdered bagasse or corn cob) + 20% burnt coconut shell char + 5% potassium feldspar + 5% zinc oxide. **Binder:** soy protein adhesive + glycerol. **Coating:** mixture of polyethylene glycol and paraffin (from plant sources).

Each flux is mixed, dried, and applied to a steel core rod, then wrapped or coated with waterproof material. Expected performance: the cellulose/char supports stable arc (CO_2/H_2 generation【58†L402-L410】), the inorganic ash (silica, feldspar) forms protective slag, and the binder ensures coating adhesion.

6. Expected Performance and Failure Modes

Arc Stability and Weld Quality: Cellulose and starch in the flux decompose to CO_2 and H_2, which help maintain a stable arc【58†L402-L410】. We expect similar behavior from bagasse or husk cellulose. Added char and ash provide nucleation points for arc and improve bead profile. Preliminary tests (e.g. Afolalu2025) showed *increased weld hardness* and reduced porosity with agro-based flux【19†L545-L553】. We anticipate comparable tensile strength but must verify elongation and impact – these must meet code levels.

Hydrogen and Cracking: Biomaterials inherently contain oxygen and hydrogen; their combustion products include water and hydrogen. Excessive H_2 would embrittle welds. However, some biomass additives may absorb hydrogen: e.g. char pores can trap gas, and certain oxides (MnO, SiO_2) can react with H. Using a wax or dense polymer coat can also limit water access and H production. We expect the hydrogen content of these welds to be similar or slightly lower than conventional rods, as found by Afolalu (agro-electrode had 35% less diffusible H than standard【19†L559-L562】). Nonetheless, *failure mode* remains H-cracking in HAZ, especially for HSLA steel. Monitoring H content and doing post-weld temper bead will be essential.

Mechanical Properties: The weld metal alloy (from steel core) will have the usual composition. Additives from biomass (C, Si, Mn, etc.) can alter chemistry. Testing must confirm ultimate tensile strength (UTS), yield, elongation, and impact. Likely we will target mild steel weld deposits (~500–600 MPa UTS, >20% elongation). Agro-flux may *increase* hardness (as seen in Fig.12 of Afolalu2025【19†L545-L553】), which might raise UTS but reduce ductility. The aim is to avoid any brittle martensite. We may include a temper bead to mitigate HAZ hardness.

Electrical Properties: The electrode electrical resistance is dominated by the steel core. Flux conductivity is low (insulating) but not critical for SMAW. Coating must insulate the current except at the tip, and degrade at weld time. If using polymer coatings, they must either burn off cleanly or not impede arc. Petroleum wax does vaporize, so plant wax should too. Safety concern: fumes from burning starch/lignin are mostly CO_2, CO, H_2O, some hydrocarbons – likely less toxic than PVC plastics.

Corrosion Resistance: The as-welded metal should resist seawater. Biomass flux might introduce more silicates/oxides (good) but could also leave carbon residues. Long-term, any unburnt organics will biodegrade; metal inclusions remain. We will perform salt spray or immersion tests to measure corrosion rate of weld deposits vs standard welds.

Arc and Gas Porosity: We must watch for gas pores. Paradoxically, the beneficial gas generation for arc (H_2, CO_2) can cause pores if trapped. Adequate flux design (slower burn-off, good slag removal) should minimize pores. Microsection inspections will quantify pore volume (target <3%, per AWS).

Failure Modes: If the electrode design is flawed, failure can occur as: weld cracks (due to H), excessive slag inclusions (if biomass ash does not flux properly), weak weld metal (if binder ash taints steel), or coating flaking (if adhesive fails). We will examine fractography and macrographs for porosity, cracks, incomplete fusion, and slag trap.

7. Experimental Plan and Testing

Electrode Fabrication: Prepare test electrodes per formulations above. For reproducibility, make at least three each of new bio-flux designs and one commercial control. Process steps: grind and sieve biomass feedstocks (rice husk, bagasse, etc.), pyrolyze a portion to char. Weigh components to specified ratios, mix dry powders, add binder (hot starch paste or lignin resin), coat onto 3.2 mm steel rods using rolling machines, and apply waterproof coat (e.g. dipping in melted beeswax). Dry and cure as required.

Welding Setup: Use an automated welding rig in a pressure chamber to simulate wet welding depths (e.g. 5–20 m, ~1.5–3 bar pressure)【27†L134-L143】. Alternatively, a water tank with diver welders could be used for practical tests. Use DC+ polarity (common for rutile electrodes) and maintain consistent parameters: current 120–140 A, arc length 2–3 mm, and travel speed ~2–4 mm/s. Record arc voltage, current, and observe bubble behavior.

Mechanical Testing: After welding, section the bead for:

- **Tensile tests:** Transverse specimens (per AWS D3.6) to measure UTS, yield, elongation.
- **Bend tests:** Face and root bends to check ductility (per Class A requirements).
- **Charpy impact:** At 0°C (or standard), to assess notch toughness.

Microstructure Analysis: Use optical microscopy and SEM/EDS on cross sections. Check weld metal microstructure (ferrite/pearlite/acicular ferrite), HAZ width/hardness (Vickers HV10). Compare hardness profiles to controls; AWS limits typically <250 HV. Inspect for porosity (gas holes) and inclusions (slag). EDS to see if biomass elements (Si, K, etc.) are present.

Corrosion Testing: After cutting coupons from weld metal, perform salt spray (ASTM B117) or immersion in 3.5% NaCl for up to 1000 h. Measure weight loss and examine pit formation. Also test any flux residues for leachate toxicity (analysis of flux wash-out).

Arc Stability and Gas Measurement: Record welding voltage/current waveforms to quantify fluctuations. Capture video of arc bubble shape (smaller bubble = more stable). Measure diffusible H in deposited welds (mercury method) to compare with control. Use gas collection to analyze H_2/O_2 content of arc bubble if possible.

Porosity Analysis: Metallographic examination with image analysis to quantify porosity %. Compare to control electrodes. Gas chromatography on shielding bubble gas could identify organic volatiles.

Safety Protocols: Standard underwater welding precautions: full dive gear, dry-suit or wetsuit, safety stop, redundant breathing. Use Ground Fault Interrupter for power. Fume/ventilation for onshore

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tests. Monitor for hydrogen gas accumulation. Labs should follow typical chemical PPE for handling binders (starch/lignin dust, wax).

8. Environmental Impact Assessment

A **life-cycle** comparison will consider raw materials (fossil vs. biomass), electrode production, usage, and disposal. Biomass electrodes *use waste feedstocks*, reducing landfill or burning of agrowaste. They avoid mining of minerals (e.g. fluorspar) and reduce CO_2 emissions from electrode manufacture. However, processing biomass (pyrolysis, pulping) consumes energy – this should be minimized (e.g. solar drying, low-temperature pyrolysis). At end-of-life, unused flux powder and electrode stubs contain mainly organic ash and mild steel; they may be safer to dispose than fluorides/ heavy metals.

Biodegradability and Leachates: Organic binders (starch, lignin) are biodegradable; spent flux slag (mostly silicates and carbonates) is inert. We will analyze leachate from flux after water immersion (checking for organics, nitrates). Compared to conventional flux (which may release Na, K, trace metals), agro-flux leachate should be benign. A small drawback: if any polymers (PLAs) are used, their breakdown (lactic acid) is non-toxic. Overall, the biomass electrodes are expected to have a much lower environmental footprint.

Tables and Figures

Table 2: Proposed Electrode Formulations. (Example mixtures and expected roles)

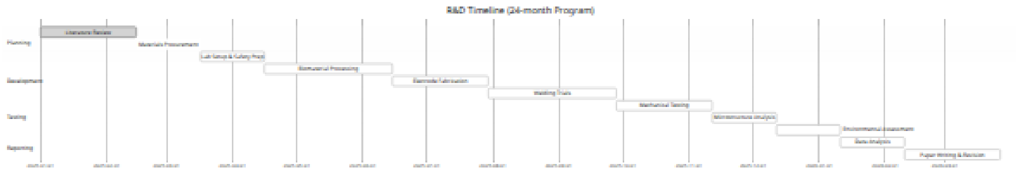
Component	**Example A**	**Example B**	**Role**
Steel core	Standard mild steel	Mild steel	Base material
Flux – Carbon source	Rice husk biochar 20%	Coconut shell biochar 30%	Arc stabilizer, reductant
Flux – Inorganics	Limestone 5%, Kaolin 5%	Feldspar 5%, RHA 5%	Slag former ($CaSiO_3$, silicates)
Flux – Other oxides	MnO_2 5%, SiO_2 5%	ZnO 5%, MgO 5%	Weld metal strengtheners/flux adjuster
Binder	Corn starch 10%	Kraft lignin 10%	Holds flux (natural resin)
Coating – base	Paraffin wax 10%	Bee/carnauba wax 10%	Waterproof outer layer
Coating – additive	Cellulose ether 2%	Rubber latex 2%	Toughening, arc bridging
Expected Effects	Stable arc, CO_2 gas, moderate H_2	Stable arc, low moisture pickup	

Table 3: Test Matrix (Lab Experiments).

Variable	Levels/Values	Measurements
Electrode type	Biomass-based (A, B, C) vs Control	Tensile, impact, bend, H content, porosity
Water depth/pressure	0 m (dry), 5 m, 20 m	Arc stability, weld defects, H_2 content
Welding current	Low, Medium, High (e.g. 100/120/140 A)	Bead width, penetration, cracks
Travel speed	Slow, Fast	Weld continuity, porosity
Flux composition	% Biochar, % Cellulose (varied)	Weld hardness, yield strength

Each combination should be repeated (3×) for statistical confidence.

flowchart TD
A[Identify Agrowaste Sources] --> B[Process Biomaterials
(pulverize, pyrolyze, extract)]
B --> C[Formulate Electrode Flux/Coatings]
C --> D[Manufacture Test Electrodes]
D --> E[Perform Underwater Welding Trials]
E --> F[Mechanical & Metallurgical Testing]
F --> G[Analyze Data: Performance Metrics]
G --> H[Iterate Formulations or Scale-up Prototyping]



9. Conclusion

Preliminary literature indicates that *agrowaste-derived* components can enhance underwater electrode performance while cutting environmental impact. High-density biomass chars and ashes serve as effective flux ingredients, and bio-binders enable arc stability. Experiments will validate these hypotheses: based on past work, we expect hardness increases and HAZ toughness improvements. Successful development could yield electrodes meeting AWS D3.6 standards while using renewable inputs. This would be a major step toward sustainable marine welding, transforming waste (rice husk, coconut shells, bagasse, etc.) into high-value industrial materials