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S7. Policy and Environmental Challenges in The New Era

CONTENTS

RESTORATION EFFORTS IN CORALLIGENOUS REEFS IMPACTED BY LOST FISHING GEARS: THE PLANNING PROCESS AT THE NATIONAL MARINE PARK OF ALONNISOS NORTHERN SPORADES

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ABSTRACT

Coralligenous habitats (H1170 “Reefs” in the Habitats Directive 92/43/EEC) are complex bioconstructions mainly formed by the accumulation of calcareous encrusting algae and other organisms like sponges, bryozoans, and gorgonians. These mesophotic habitats are primarily found in the Mediterranean Sea and are highly biodiverse but vulnerable to anthropogenic impacts. Most Mediterranean EU countries have implemented national strategies in line with EU directives, often including Marine Protected Areas (MPAs) and specific reef conservation regulations, while under the implementation of the Marine Strategy Framework Directive (MSFD) the maintenance or achievement of good environmental status (GES) of this conservation priority habitat is pursued. The EU Nature Restoration Law complements the MSFD by going a step further, as it actively requires restoration actions to bring degraded ecosystems back to a healthy state.

LIFE DREAM is a research program funded by the EU, whose goal is to contribute to the protection and restoration of H1170 through innovative and sustainable approaches. In this vein, in selected pilot areas across the Mediterranean, in Italy, Spain and Greece that include important reef habitats, and at locations with signs of reef degradation, 3D-printed Artificial Reef Module ARM structures, (ARMs), made of biodegradable materials and mimicing natural reef structure, will be installed to facilitate the rooting and growth of coralligenous bioformations, serving as substrates for colonization by those species.

In Greece, the pilot study area is the National Marine Park of Alonnisos Northern Sporades (N.M.P.A.N.S). Following the evaluation of coralligenous habitats at selected locations within the Park, clear signs of degradation were observed at specific sites, primarily due to the entanglement of lost fishing gears. Thus, taking also into account the seafloor topography and the steepness of the underwater terrain, suitable locations for ARS deployment have been identified, with installation scheduled to take place before the end of 2025. What is more, an underwater system equipped with continuous video monitoring and AI applications will also be installed around the structures, providing real-time evidence into the restoration process, through automated, scalable, and accurate ecological assessments. The planning process prior to the deployment of artificial structures for coralligenous habitat restoration is critically important, as it ensures that ARS are ecologically appropriate, technically sound, legally compliant, and strategically deployed to maximize ecological benefits and minimal negative impacts, and thus can determine the success of the entire initiative. Hence, thorough planning should be prioritized as a key initial step in restoration initiatives, ensuring that all subsequent actions are grounded in ecological, technical, and regulatory best practices.

Keywords: ARS-based restoration, marine biodiversity conservation

1. INTRODUCTION

Corraligenous habitats (H1170 “Reefs” in the Habitats Directive 92/43/EEC) are complex bioconstructions mainly formed by the accumulation of calcareous encrusting algae and other organisms like sponges, bryozoans, and gorgonians [1]. These mesophotic habitats are primarily found in the Mediterranean Sea and are highly biodiverse offering ecosystem services and improving the general health of the world’s seas [2]. Coral reefs and coralligenous habitats are vulnerable to anthropogenic impacts related to fishing activities, pollution and littering, introduction of alien species and climate change [3]. To preserve these sensitive ecosystems, it is crucial to adopt restoration strategies that accelerate the recovery of impacted ecosystems using sustainable methods aimed at balancing the conservation of coralligenous reefs with human needs. This ensures that coral reefs will continue to provide vital ecological, ecomomic, and cultural benefits for generations to come [4].

Recognized as priority habitats in the Mediterranean under the EU Habitats Directive, coralligenous reefs have also been included in the Natura 2000 network (Directive 92/43/EEC). In Greece, several marine Natura 2000 sites include coralligenous habitats, which are protected through national conservation measures aligned with EU directives. These habitats are managed under Special Areas of Conservation (SACs), with site-specific management plans aimed at preserving their ecological integrity and addressing local pressures such as fishing, anchoring, and pollution. In addition, the Marine Strategy Framework Directive (MSFD, 2008/56/EC) provides a broader framework for assessing and maintaining the Good Environmental Status (GES) of marine ecosystems, including coralligenous assemblages. Under the MSFD, Greece monitors the condition of these habitats, which are classified under benthic broad habitat types, to evaluate pressures, degradation, and progress toward ecological restoration and sustainable use. Then, the EU Biodiversity Strategy for 2030, and the EU Nature Restoration Law are also part of the policy framework aimed at halting and reversing biodiversity loss in Europe, the former setting strategic goals for protection and restoration, and the latter promoting concrete restoration actions based on MSFD/Habitats Directive assessments.

The restoration of degraded habitats is recognized as a priority for the coming decades. In 2015, the United Nations adopted 17 Sustainable Development Goals (SDGs) to be achieved by 2030. Among them, SDG 14 (*Life Below Water*) is specifically dedicated to the conservation and sustainable management of marine life, including the restoration of degraded marine habitats [5]. At the EU level, the Biodiversity Strategy for 2020 aimed to restore at least 15% of degraded ecosystems by 2020. According to Gann et al. [6], the concept of restoration in many global initiatives and agreements is broad, encompassing various approaches to ecosystem management and nature-based solutions, all of which contribute valuable tools to ecological recovery.

Ecosystem restoration refers to the process of halting and reversing ecosystem degradation, leading to improved ecosystem services and recovered biodiversity. It involves assisting the recovery of degraded or destroyed ecosystems by helping to regenerate their biodiversity and restore the services they provide [6]. Since the 1970s, various types of artificial reefs have been used as a solution for restoring natural coral reefs. These efforts have employed materials such as concrete modules, Armoflex, and other structures to create colonization sites for corals, with applications in regions such as Hawaii, the Philippines, the Maldives, Guam, and the Great Barrier Reef [7]. Interdisciplinary approaches that incorporate emerging technologies are essential for supporting reef functioning and maintaining biodiversity, as well as for preparing corals to withstand future environmental changes. Currently, several innovative restoration strategies are gaining attention, including reef reseeding with coral larvae, assisted evolution of coral species, acoustic enrichment of degraded reefs, and the use of 3D printing to create artificial habitats [8]. The deployment of artificial reefs is a widely used restoration tool for degraded marine ecosystems that have lost habitat heterogeneity, biomass, species richness, and overall abundance due to various anthropogenic impacts. Technologically advanced, purpose-designed artificial reefs enhance structural complexity and settlement space, and can also serve as platforms for coral nurseries; the development of sustainable, modern, and structurally complex artificial reefs can be considered an important tool for the restoration of coral ecosystems in the Anthropocene [8].

LIFE DREAM (Project 101074547 — LIFE21-NAT-IT-LIFE DREAM) is an EU-funded research project that aims to contribute to the protection and restoration of habitat H1170 (coralligenous reefs) through innovative and sustainable approaches. Within this framework, in selected pilot areas across the Mediterranean, and particularly at sites in Italy, Spain, and Greece that feature important reef habitats and show signs of degradation, 3D-printed Artificial Reef Structures (ARS) made from biodegradable materials and designed to mimic natural reef formations will be installed. This study describes the planning process undertaken to ensure that the locations selected for coralligenous restoration within the Greek pilot area are suitable for ARS deployment. It also provides insights into the design of ARS, emphasizing the importance of tailoring these structures to the specific coralligenous species targeted for restoration. Furthermore, the study outlines the national authorities involved and the timeline required to obtain legal authorization for ARS deployment, thereby shedding light on the regulatory process for implementing such restoration actions.

2. METHODOLOGY

The LIFE DREAM Project is a 5-years initiative covering four Project Areas (PAs) across the Mediterranean Sea, i.e. in Italy, Spain and Greece, all of which include important coralligenous reef habitats. These areas are 1) the Monopoli shelf and Bari Canyon (apulian margin) in the South Adriatic Sea; 2) the Dohrn Canyon (Gulf of Naples) in theTyrrhenian Sea; 3) the Seco de los Olivos Seamount in the Alboran Sea; 4) the National Marine Park of Alonnisos Northern Sporades (NMPANS) in the Aegean continental shelf (Figure 1).

The NMPANS is the first Marine Protected Area (MPA) established in Greece by Presidential Decree 519/1992 for the protection of one of the endangered Mediterranean monk seal (*Monachus monachus*) and its breeding habitats. In addition, the Park aims to maintain the favorable conservation status of other rare and endangered species of flora and fauna, along with their associated habitats. The NMPANS covers a total area of approximately 2,800 km², including the expanded boundaries defined by Law 4519/2018. The Park is located in the northwestern Aegean Sea and encompasses six large islands along with 22 smaller islets and rocky outcrops. The NMPANS is divided into two different management zones; zone A, is the core of the protected area, and strict regulations apply to activities such as fishing, anchoring, navigation, and overnight stays. The island of Piperi and the surrounding marine zone within a three-nautical-mile radius form the core of the Park, and is the area of highest protection status, where access is strictly prohibited to both fishermen and tourists. Zone B of the National Marine Park of Alonissos Northern Sporades (NMPANS) serves as the buffer zone surrounding the strictly protected Zone A. It encompasses the majority of the Park's area and includes several inhabited islands, such as Alonissos, as well as marine areas with less restrictive regulations compared to the core zone. In Zone B, human activities are allowed under specific conditions and management guidelines. The objective of Zone B is to promote sustainable use of natural resources and foster harmonious coexistence between conservation and local livelihoods, while still protecting valuable marine and coastal ecosystems, including coralligenous habitats, Posidonia meadows, and important species like the Mediterranean monk seal.

This study focuses on providing detailed information about the structures selected for the restoration of coralligenous habitats in the NMPANS, as well as the process used to identify suitable deployment locations. Site selection was informed by two surveys conducted in zone B of the study area in 2023 and 2024. Additionally, a third survey in June 2025 included the experimental deployment of two ARS at one of the selected locations within the NMPANS to ensure the smooth placement of all ARS during the full-scale restoration phase.

During the first survey, in July 2023, data collected with an underwater drone and research diving were used to identify candidate areas. Then at the second survey, in November 2024, a Remotely Operated Vehicle (ROV) was used to record detailed characteristics of the coralligenous formations and evaluate their health status. In addition, bathymetric and topographic data were collected to inform site selection. In June 2025, a third survey was conducted for the experimental deployment of two ARS to ensure a smooth process for the full-scale deployment that will take place before the end of the year.

Moreover, at the national level, legal authorization for ARMs deployment is particularly important, as individual EU Member States are responsible for implementing restoration projects in line with their own environmental, maritime, and spatial planning legislation. In this context, the study also discusses the national authorities involved in the approval process and the duration required to complete the procedure.

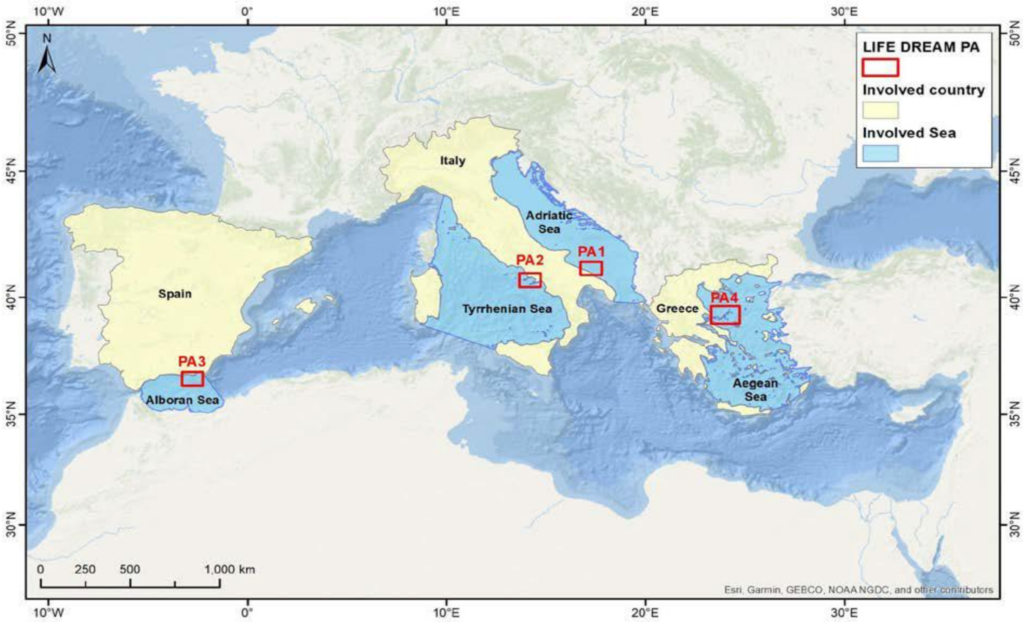

Figure 1: The Life Dream Project Areas - PAs (red square) in EU Mediterranean waters.

3. RESULTS

In the NMPANS PA, two surveys were conducted to guide the effective selection of ARM deployment sites, building on existing knowledge of areas known to host coralligenous formations in zone B.

During the first survey in the PA, conducted in July 2023, a diagnostic assessment was performed in coralligenous habitats using an underwater drone in combination along with research diving. The degradation of reef habitats was clearly evident at specific sites, primarily due to the entanglement of lost fishing gears (Figure 2). As a result, candidate locations for the deployment of Artificial Reef Structures (ARS) have been identified, taking into account the topography of the seafloor and the steepness of the underwater terrain in areas where reef habitats are in a degraded condition.

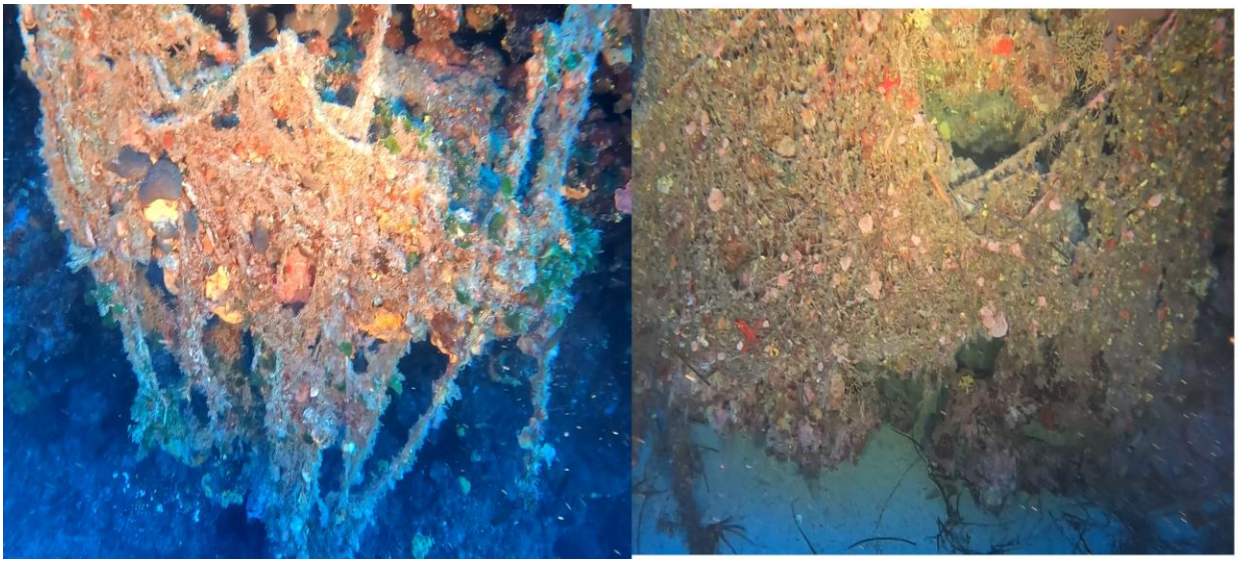

Figure 2: Fishing related marine litter entangled on coralligenous habitats at the Marine National Park of Alonnisos and Northern Sporades.

To ensure proper site selection for ARS deployment, an additional survey was conducted in November 2024 using ROV video transects. The data collected enabled a comprehensive assessment of reef health in the upper mesophotic zone, down to depths of 65 meters, with particular attention to the percentage of colonies entangled in lost fishing gear. Coralligenous and precoralligenous communities (featuring gorgonians and various sponge species) were observed in varying stages of degradation caused by the presence of abandoned gear. Based on the coralligenous species present in the NMPANS, the appropriate type of ARS for deployment was also selected (Figure 3).

Figure 3: The two types of ARS selected to be used for restoration of the upper mesophotic coralligenous species in the NMPANS.

Moreover, during the latter survey, underwater depth was also recorded using ROV images and measurements to produce detailed bathymetric maps. These maps provided accurate estimates of seafloor slope, which is a critical factor, as ARS need to be placed on relatively flat or gently sloping surfaces to ensure stability and proper functioning. An Underwater Visual Observation System (NOUS) will also be installed around the ARS, streaming real-time footage to provide continuous monitoring and real-time evidence on the restoration process.

Based on the aforementioned process, two sites were finally selected for the deployment of the ARS (Figure 4), that is planned to take place before the end of this year: (a) a rocky wall located at the north-eastern part of Alonnisos Island, descending from the surface to an approximate depth of 70 m, hosts coralligenous communities and populations of the yellow gorgonian *Eunicella cavolini*, where the impact of derelict fishing gear is evident, (b) a rocky wall located at the south-western part of Peristera Islet, descending from the surface to an approximate depth of 30 m, hosts typical sciaphillous communities, and a high diversity of invertebrate species (especially sponges).

Figure 4: The two locations where the ARS for coralligenous species restoration will be deployed in the NMPANS

Last June, the experimental deployment of two ARS was carried out to identify potential issues related to the technical feasibility of the deployment process and ensure a smooth process for the full-scale deployment of all ARS, that is scheduled to take place before the end of the year. Figure 5 shows the deployed ARMS at the NMPANS site, where the smooth terrain provides ideal conditions for their proper placement and optimal functioning. It is evident that they create a more complex environment that facilitates the settlement of coralligenous species and blend seamlessly with the surrounding habitat.

Figure 5: Photos of the ARS experimentally deployed in the NMPANS in June 2025.

Finally, regarding the process required for obtaining the legal authorization for ARMs deployment, it involved 13 authorities (Magnesia Directorate of Public Property, Municipality of Alonnisos, Ministry of Rural Development and Food, Natural Environment & Climate Change Agency, Ministry of Tourism, Ministry of Maritime Affairs & Insular Policy, Hellenic Navy General Staff, Service of Modern Monuments and Technical Works of Thessaly and Central Region of Stereas Elladas of Ministry of Culture, Region on Thessaly, Ephorate of Antiquities of Magnesia of Ministry of Culture, Ministry of Environment and Energy, Regional Development Fund of the Region of Thessaly, Ministry of Economy) and took up 10 months from the time the petition was applied till the authorization was granted in March 2025.

4. CONCLUSIONS

This study, as part of the LIFE DREAM project, focuses on the planning process of restoration activities, including careful site selection and the tailored design of ARS. It sheds light on the process followed to identify suitable sites for the restoration of coralligenous formations in the Greek PA (the NMPANS). The planning process is absolutely critical to the success of any ecological restoration effort, including marine and reef restoration using ARS, as a well-designed plan lays the foundation for achieving ecological, social, and regulatory goals.

Prior to ARS deployment, surveys providing detailed data on the health status of the target ecosystem component (e.g., coralligenous reefs) should be conducted to assess the extent of damage and identify pressures responsible for degradation. In our case, fishing-related litter was the primary cause of coralligenous habitat degradation in the NMPANS. Consequently, targeted interactions with fishers, managers, and policymakers will be essential to prevent further impacts.

Once sites with poor ecological status were identified, data on their topography and bathymetry were analyzed to select locations with low slope and minimal risk of sediment accumulation, which help prevent burial or smothering of the ARS, promoting stable conditions conducive to successful colonization.

Finally, since the design of the ARS should be tailored to the specific coralligenous species in the NMPANS targeted for restoration, two types of structures were selected based on consultations with coralligenous experts from the LIFE DREAM team. This ensures that the ARS provide suitable structural and ecological conditions for successful colonization and growth.

In addition to selecting suitable sites and deciding on the design of appropriate reef structures, a critical step in the restoration process is obtaining legal authorization for ARS deployment. This involved securing permits from 13 regulatory bodies and took approximately 10 months from the time the petition was submitted until the authorization was granted. Therefore, the bureaucratic process should be carefully factored into the overall project timeline.

Planning forms the backbone of any successful restoration effort, providing the foundation for well-informed, effective, and sustainable actions. The outcomes of the LIFE DREAM project are expected to contribute significantly to the practical implementation of the Nature Restoration Law (NRL), particularly in advancing marine habitat restoration strategies using ARS.

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MICROPLASTIC CONTAMINATION AND THE BENEFITS OF BLUEFLAG BEACH STATUS

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ABSTRACT

This study aimed to determine the effect of 'Blue Flag' status, an award that reflects a strong dedication to the sustainable management and protection of coastal resources, on the level of microplastic (MP) in beach samples. Quantitative determination of MP was carried out at two beach locations in Greece, a Blue Flag beach in Glyfada, Attica, and beaches of the remote island of Leros without Blue Flag status. Samples of surface sand sampled at a maximum depth of 3 cm were taken along the wrack line at 100 m intervals, following which MP were separated using density floatation, quantified, and optically identified based on shape and colour. In Glyfada, MP were green, yellow, blue and light blue in colour. Shapes included fragments, pellets and fibres, and the number of MP ranged from 0 to 2 items per kg dry weight sediment. In Leros, MP were mostly black, blue and white in colour. Shapes included fibres, fragments, foams, films and pellets, and number of MP ranged from 20 to 163 items per kg of dry weight sediment, at Alinda Beach, and 164 to 543 items per kg of dry weight for Gourna Beach. The results indicated that the benefits of Blue Flag status extend not only to improved microbial and chemical status of beaches but also to the mitigation of MP contamination.

Keywords: beach, Blue Flag, microplastics, sustainability

1. INTRODUCTION

Plastics are essential to our daily lives [1] thanks to their many advantages, including affordability, and durability [2]. Consequently, their production has increased over the years, from 230 million tonnes in 2009 to over 350 million tonnes in 2019 [3]. The most common types of plastics are polyethylene (PE), polyvinyl chloride (PVC), polystyrene (PS), polyethylene terephthalate (PET) and polypropylene (PP) [4]. When plastics enter the environment, they degrade into smaller pieces. Those smaller than 5 mm are called microplastics (MP) [5]. MP are also categorized as primary and secondary, where primary MP are those that are produced for direct use, such as the microbeads used in skin care products [6- 8], while secondary MP are formed after the degradation of larger plastics [9]. It is well documented

[10] that MP can negatively affect human health. MP enter the human body through direct routes such as breathing, drinking water, and skin contact through hand to mouth transfer, but also indirectly through the food chain [11]. Inside the body MP can move to different tissues and organs, and have been detected in blood [12], the colon [13], testes [14], breast milk [15], semen [14] and sputum [16]. Exposure to MP has been implicated with an increased risk of acute and chronic health conditions, including infertility [17], Parkinson's disease [18], and Alzheimer's disease [19].

Carpenter et al. [20] first documented MP in the marine environment in 1972 in Saragaso Sea. Since then, MP have been found in the various aquatic environment including lakes, oceans, rivers and other freshwater including arctic ice [21],[22], the terrestrial environment and also in the atmosphere. [19]. The Mediterranean Sea in particular has been found to be heavily affected due to factors including the mismanagement of plastic waste, and activities related to tourism [23]. Studies by the organization Aegean Rebreath, in cooperation with the Hellenic Centre for Marine Research, from –20 different beaches in Greece (Attica, Anafi, Zakynthos, Corfu, Kefalonia, Santorini, Nisyros, Tinos, Syros, Paros, Chania, Naxos, Methoni, Lefkada, Pelion, Andros, Paros, Kea) indicated MP in all samples [24]. Effects on aquatic organisms include reduced food intake, developmental disorders, and behavioral changes [25].

The environmental persistence of MP threatens environmental and human health, and sustainability. under United Nations Sustainable Development Goal 14 on sustainable use of the oceans and seas. The efficient management of plastic waste in an environmentally sustainable manner may be promoted both directly, under schemes such as restriction of single use plastics [26] and indirectly through environmental initiatives such as the 'Blue Flag' program. The Blue Flag, voluntary program which aims at the sustainable use of beaches and coasts, was first adopted in France in 1985. The program aims at improving management and visitor safety at the beaches, while at the same time protecting their natural environment. It can be awarded to organized beaches and marinas managed by coastal municipalities, hotels and other agencies when strict environmental criteria are met. Among others, the criteria include the absence of industrial and urban wastewater discharge near the beach without proper treatment, adequate waste bins that are emptied regularly, and consistent removal of all litter from the beach. Under the scheme the entry of cars and motorcycles onto the beach is also strictly prohibited. Over 50 countries around the world participate in the Blue Flag Scheme, and numbers are constantly increasing [27]. The aim of this study was to determine whether the sustainable management of beaches, leading to the award of Blue Flag status, also contributed to a reduction in MP contamination.

2. METHODOLOGY

2.1. Site description

Glyfada is a town and suburb in the South Athens regional unit, situated along the Athens Riviera on the coast of the Saronic Gulf. It lies in the southern section of the Athens metropolitan area, stretching from the base of Mount Hymettus down to the Saronic Gulf. The municipality of Glyfada covers an area of 25.366 km^2. The Glyfada Marina includes both marine and coastal zones with a total length of 3 km. Beaches Glyfada, Glyfada A and Glyfada B are nominated with a Blue Flag award [28].

Leros is an island situated in the southeastern Aegean Sea, forming part of the Dodecanese complex, northwest of Kalymnos. According to the 2021 census, it has a population of 7.992 and a total area of

54 km², with a coastline measuring approximately 71 km, shaped by its characteristic horizontal segmentation [28].

2.2. Sampling and MP determination

Three (3) beaches in the area of Glyfada, Greece with Blue Flag status were selected (Figure 1). A total of 12 samples were collected from Glyfada Beach, Glyfada A and Glyfada B, Attica, Greece (Figure 1). Briefly, sampling involved demarcation of the upper part of the coastline, random selection the first sampling point approximately at the beginning of the coastline, and delineation of approximately ¼ m^2 of sand as a measure as the sample area. Surface sand with a maximum depth of 3 cm was collected using a metal scoop. Each sample was sieved (5 mm) to remove large pieces of plastic and organic matter. The weight of each sample was approximately 4.5 kg. Sampling was repeated at 0.3.km intervals.

Figure 1: Location and Sampling Points At Beach In Attica, Greece

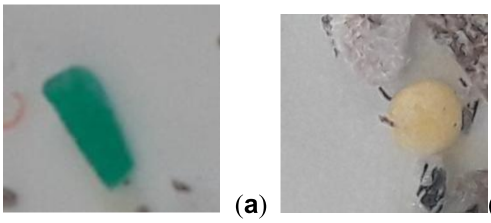
Approximately 500 g of each sample was accurately and heated (24 h at 90 °C) to remove all moisture after which dry weights were recorded. Peroxide digestion was not necessary as no significant amount of organic matter was detected. Saline solution (0.3 g mL^{-1}) was added (2:1 solution: sand) for density separation of MP [29]. After stirring (magnetic stirrer, 3 min) samples were allowed to stand for 24 h. The supernatant was collected by filtration of supernatant through a 0.208 mm sieve. This procedure was repeated at least in duplicate to ensure that all MP were collected. The supernatant was dried (24 h at 90 ° C) and weighed. MP were identified by the naked eye.

In Leros, 10 samples were collected at Alinda Beach at the East coast of the island, and 11 samples were collected at Gourna Beach on the West coast (Figure 2). Both beaches are popular with tourists in the summer season. The sampling procedure was similar to that implemented in Glyfada. with the addition of a wet peroxide H_2O_2 (30%) digestion to remove organic matter. This was performed at room temperature to avoid potential changes in the shape and structure of MP observed at higher temperatures [30], [29]. After visual inspection, further observation was performed with a stereoscope (Stemi 305, Zeiss Company, Germany) with a magnification factor of 5:1.

Figure 2: Location and Sampling Points At Leros Island, Greece

3. RESULTS

In the Glyfada beaches, MP were detected in six (6) of the 12 samples. primarily at the beginning or end of the coastline, spots frequented most regularly by winter swimmers and anglers. MP were green, yellow, blue and light blue in colour. Shapes included, fragments, pellets and fibres, and the number of MP ranged from 0 to 2 items per kg dry weight sediment.



(**a**) (**b**)

Figure 3: Microplastics Detected In Samples From Blue Flag Beaches In Glyfada, Greece. (A): Sample 1. Fragment, Green, 1.1 Mm; (B): Sample 5. Pellet, Yellow, 0.3 Mm

In Leros, MP were present in all samples. In Alinda Beach MP ranged from 20 to 163 items per kg of dry weight sediment. Blue was the most dominant colour (52.1%), followed by black (27.5%), white (14%), red (4%), green (1.1%), and brown (0.8%) ((Figure 4). The dominant type was fibre (72.2%), followed by fragments (16.7%), films (5.5%), pellets (4.9%), and foams (0.8%). In Gourna Beach, the most frequent shape was also fibre (60.3%), followed by fragments (34.5%), pellets (3.6%) and films (1.6%). One foam particle was also detected. In Gourna Beach, MP contamination was greater. MP ranged from 164 to 543 items per kg of dry weight sediment. Blue, black, white, red, brown, orange, orange, pink, gray, brown, yellow coloured MP were detected (Figure 10). The dominant colour was also blue (35,7%), followed by white (24.6%), black (22.8%), red (5.3%), green (4.1%), yellow (2.7%),

orange (1.4%), pink (1.0%,) grey (0.9%) and brown (0.9%) (Figure 5).

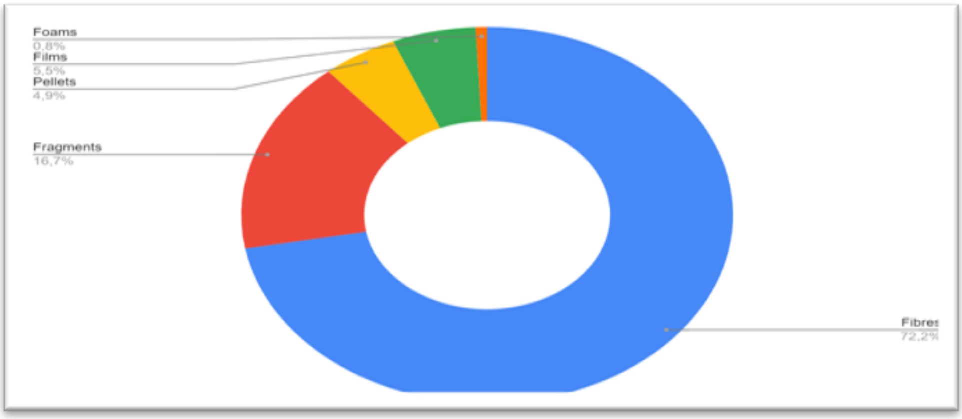


Figure 4: Shapes Of Mp In Alinda Beach, Leros, Greece

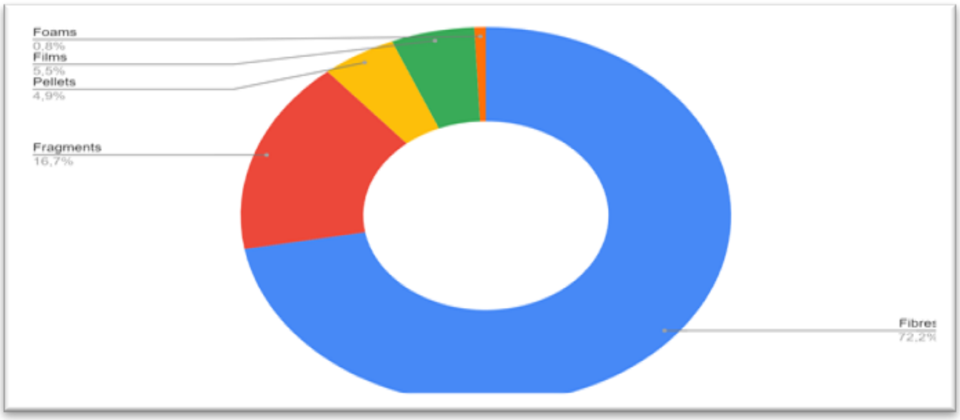


Figure 5: Shapes of Mp In Gourna Beach, Leros, Greece

Sampling at both locations took place in winter, indicating that at least in Leros island activities such as fishing or wastewater pollution may have added to MP. Although Glyfada Beaches were located to the capital of Greece frequented by many tourists and locals, MP were not as abundant as in Leros island. As in Leros, other locations in Greece, that are often remote and are without 'Blue Flag' status have indicated large scale MP pollution [24]. It appears that the criteria implemented to achieve Blue Flag status, and presumably specifically the criteria for sustainable waste management, including the monitoring of wastewater sources, facilities for litter disposal, and the overall sustainability mindset significantly reduced MP contamination. The importance of the specific scheme therefore must be emphasized, and the measures involved in sustainable beach management should be extended and applied to the management of coastal regions to reduce MP contamination and threat to environmental health.

4. CONCLUSIONS

Despite its remote location, MP were detected in all beach samples from the island of Leros, Greece.. A variety of shapes and colors were detected, indicating the different sources of MP. Fibres were the dominant shape in the beach sediments. In samples from beaches in Glyfada Attica, which were awarded with a Blue Flag, the concentration of MPs was significantly lower than those in Leros. The results reinforce what is already known, that prevention is the best practice, and the fundamental process of beach cleaning appears to offer large benefits. The Blue Flag scheme offers a holistic approach, focusing on increasing awareness of climate change and promoting strategies to reduce the global environmental footprint, and promote sustainability.

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TOWARDS RENEWABLE SYNTHETIC FUELS AND CHEMICALS AT COST PARITY WITH FOSSIL-DERIVED COUNTERPARTS

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ABSTRACT

The global transition to sustainable energy systems necessitates the development of renewable synthetic fuels and chemicals that can economically compete with their fossil-derived counterparts. Our primary objective in this work is to identify and evaluate the technological, economic, and policy pathways that can enable renewable synthetic production to reach cost parity under realistic market conditions.

Focusing on current and emerging novel renewable synthesis pathways, we identify key cost drivers—such as renewable energy (electric/thermal) demand/cost, material characteristics (e.g. catalyst efficiency), renewable carbon feedstock availability/cost, and plant scale—and analyze some recent innovations in carbon capture, water/CO_2 splitting and process integration that are closing the cost gap, leading to a circular carbon economy.

Case studies demonstrate emerging approaches achieving parity in specific applications, e.g. drop-in fuels for transportation (including aviation fuels) and basic chemicals like methanol and ammonia. Policy mechanisms, including carbon pricing, subsidies, and mandates, are also discussed for their potential role on cost competitiveness. The paper concludes by outlining a roadmap to achieve widespread cost parity by 2035, emphasizing coordinated investments in technology, infrastructure, and regulatory frameworks.

Keywords: Renewable energy carriers, Synthetic fuels and Chemicals, Circular carbon economy

SUSTAINABLE ENERGY POLICY: MYTHS & REALITY

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ABSTRACT

Environmental sustainability concerns have been high on the political and social agenda many decades now, driven mainly by the global warming concerns. These matters are extremely complex and no easy answers are available. Environmental sustainability is linked tightly to economic and social issues. The most important contributor to global warming is the energy sector. This is exactly the scope of the present paper: to review the current trends in energy production, storage, transport and distribution, and elaborate on the potential benefits but also the shortcomings and the myths concerning many of the so called ‘green’ energies.

Sustainability is, by definition, time persistent. As such, it mainly involves global phenomena and, consequently, any proposed measures must be examined in their global effects, throughout their lifecycle, considering all possible societal effects and implications. As these effects and interrelations project well into the future, they cannot be quantified but by using scenarios i.e. predictions.

The main driver for the ever-increasing demand for energy will be demography. Around 2050, one out of four persons on earth is projected to be from the sub-Saharan (sahel) Africa. Global South is projected to have the most important population rise along with the highest increase of the per capita energy consumption. On top of the obvious direct effects on the emissions and the climate change, there will also be many indirect effects (like migration pressure, social unrest and wars) with much more important potential impacts.

Unfortunately, current energy policies, both at national and EU level, have failed both in their market predictions as well as on theιρ global effects. Natural gas (NG) was to be the low-emission fuel, transition towards a future carbon-less energy. Geopolitics have made EU NG imports much more expensive and polluting, while Germany, the EU’s industrial powerhouse, has had to return to coal. Electric cars are cleaner to run but dirtier to produce and to dispose of. In many cases, the net global effect of “green” technologies is negative or close to null, effectively resulting to “pollution export” from the rich western consumers to the producers, mostly found in the developing global south. Another important consideration has to do with the suitability of our electric networks, built on stable, production centric models, to adapt to the highly distributed, fluctuating production realities imposed by the massive use of wind and solar.

From all the above, as well as from numerous similar analyses, there emerge some important considerations: Environmental sustainability is not primarily a technical or scientific issue. It is a societal problem, a problem of governance. Our current development model, based on ever-increasing production and consumption, is no longer viable. On a finite planet, society cannot expand infinitely. Either we understand it and adapt our governance models accordingly or the changes will be violent and highly disruptive.

Keywords: Sustainability, Energy, Growth, Global Warming, Green Technologies, Energy Transition

1. INTRODUCTION

The problem of combating climate change is extremely difficult and complex. It goes beyond the narrow confines of technology: it is a problem of governance and, in final analysis, deeply social and philosophical. Can humanity continue growing endlessly on a finite planet? What does "growth" mean? Instead of looking for solutions to new systems and technologies (solar, electromobility, wind turbines, etc.) shouldn't we think more seriously about new development models?

The only certainty is that such complex problems are not addressed either by the short-sighted policy of the European Union and the national governments, nor by the "religious" perceptions, proposals and practices of the "green" movements.

Among the anthropogenic factors, the most important involve the energy and agriculture sectors that cause significant emissions of carbon dioxide and methane. The subject of this work is the energy sector and, more specifically, the policies proposed to drastically reduce greenhouse gas emissions and, ultimately, ensure the path towards sustainable development.

The aim of this paper is to systematically study and highlight the contribution and the issues of the various "green" energy systems and technologies, currently proposed as solutions against the greenhouse effect and the climate change and, ultimately, contribute to the design of a realistic and effective sustainable energy policy.

2. GLOBAL WARMING AND GREENHOUSE GASES

The modern era global temperature increase is a non-disputable fact. In the last 50 years the average global temperature increase rate has been double than in the previous 100 years, [1]. What is even more worrying is the fact that this increase is more pronounced at the poles, in particular at the north pole.

On the contrary, the causes of this increase, especially whether and to what extent it is caused by human activities, are a matter of dispute in the scientific community and among the policy makers. The prevailing view is that it is due to the greenhouse effect, caused by the anthropogenic release into the atmosphere of gases such as carbon dioxide (CO_2) and methane (CH_4). However, it is worth noting that about 95% of the atmospheric greenhouse gases is plain and simple water (H_2O) in vapor form. This is only rarely mentioned in discussions on climate change, where the atmospheric humidity is considered a reinforcing factor rather than one of the causes of the greenhouse effect. The effect of water vapor is quite complex, due to the great variability of water phases and concentration in the atmosphere. The percentage of atmospheric humidity, unlike other gases, varies greatly, both locally and temporally, ranging from 0.01% (deserts with strong dry air) to over 4% (tropical climates). In any case, with an average of 2-3%, 99% of which in the troposphere, it is significantly more than any other greenhouse gas, such as CO_2 or methane, with concentrations of 0.035% and 1.7 ppm respectively.

Another important topic for study and debate has to do with the importance of anthropogenic CO_2 and CH_4 releases within the natural carbon cycle. Although very small (Figure 1), they seem to have a disruptive effect to the natural cycle balance, resulting, to a small but constant increase in the atmospheric carbon concentration and the acidity of the oceans (Figure 2), thus limiting their carbon absorption capacity. Regardless the reasons, global warming presents many severe risks, some of which have yet to be fully understood.

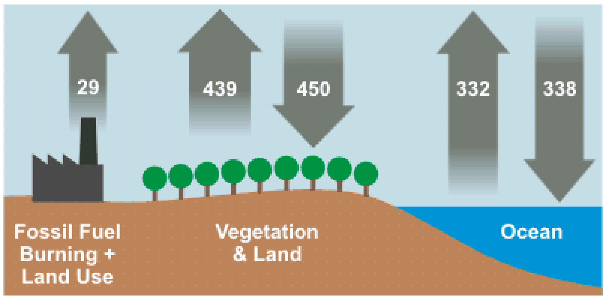

Figure 1: Simplified carbon cycle, in giga tons equivalent CO_2

Among these risks, the most important concerns the release into the atmosphere of big quantities of methane that is actually trapped, in the form of hydrates, in much of the ocean floor or under the Arctic ice and the permafrost. Hydrates are estimated to make up more than half of the total inorganic carbon in the earth's solid crust, significantly more than the sum of the world's gas, oil, and coal deposits (Figure 4). They are a potentially inexhaustible source of energy but also a major environmental risk.

Given that methane is a greenhouse gas roughly 20 times stronger than CO_2, hydrates constitute an environmental time bomb. According to many scholars, methane is the bomb while carbon dioxide is the capsule that triggers it. The Arctic temperature rise results in increased methane releases which, in turn, further increase the temperature, causing even greater releases, and so on.

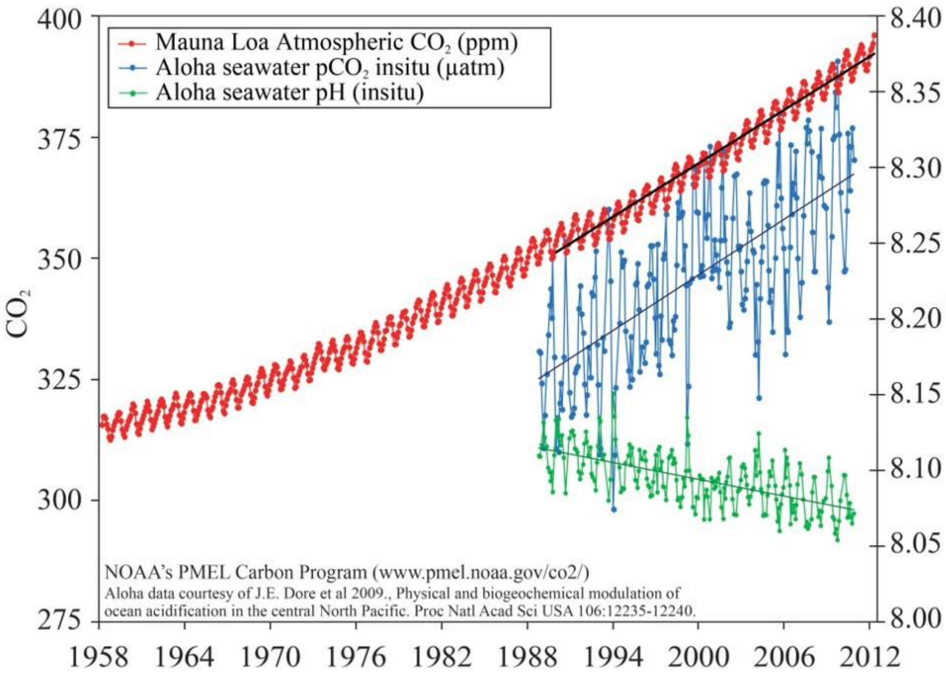

Figure 2: Increasing trends in atmospheric CO_2 concentration (ppm - red) and partial pressure in the ocean (µatm - blue), as well as in ocean acidity (decreasing pH - green)

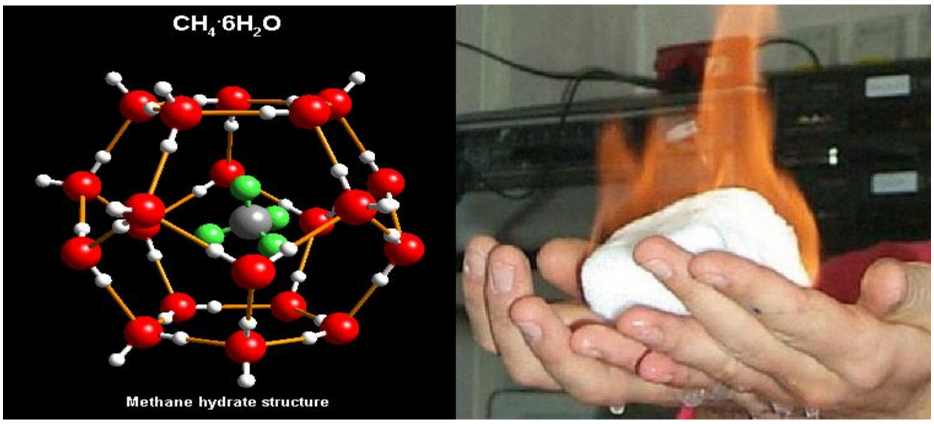

Figure 3: At high pressures and/or low temperatures, methane in contact with water, gets trapped in the ice crystal and forms solid methane hydrate crystals, with physical properties roughly like those of ice. At lower pressures and/or higher temperatures, methane hydrates are transformed into methane gas and water.

Unfortunately, as shown in Figure 5, both temperatures and methane concentration in the Arctic are steadily increasing. This is also due, largely, to the particulate matter of unburned carbon, man-made (derivatives of industrial processes, internal combustion engines, etc.) or natural (the large forest fires, volcanic eruptions, etc.), which are transported by the air currents and deposited on the arctic ice, reducing the surface reflection coefficient (albedo) and, consequently, significantly increasing the absorption of incident solar radiation.

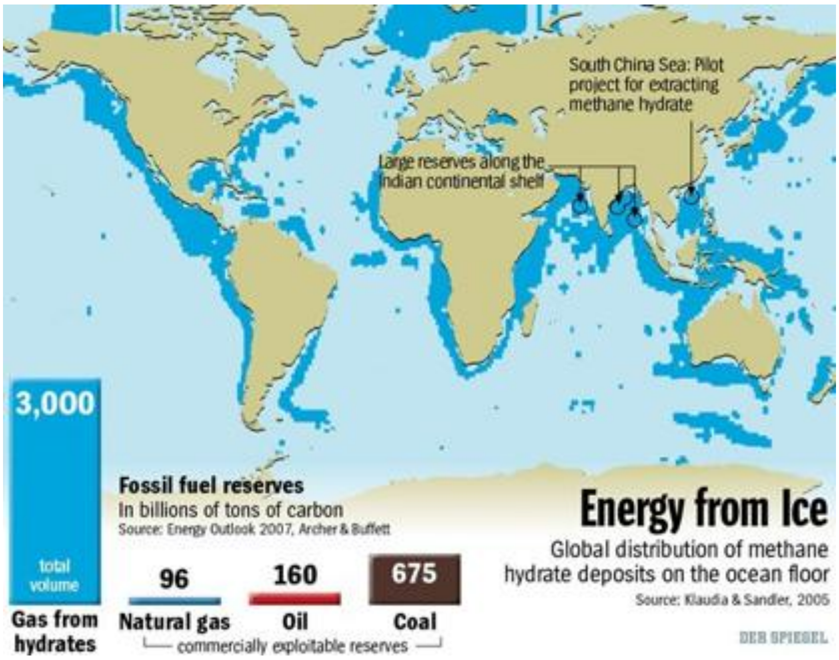

Figure 4: Hydrate deposits distribution along the globe's ocean floors

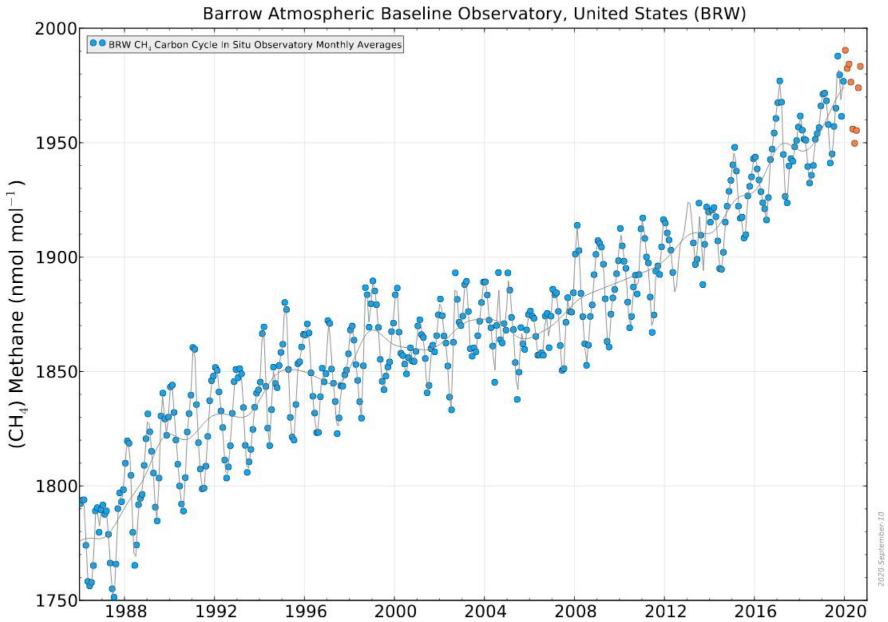

Figure 5: Evolution of the atmospheric methane concentration in the Arctic over the last 50 years, monthly averages, source NOAA via Wikipedia

Humanity must take drastic measures to limit the greenhouse effect and protect the planet's poles. This is now well understood both by the public, the governments and the international organizations. What is much more difficult and less well understood is how to achieve this goal. What is extremely sad and dangerous is that <u>there are many misconceptions on some so-called "green" energy policies, often presented as magic solutions, which distract rather than contribute towards the climate change goals</u>. The problem is very complex and has no "magic" solutions. It requires a very cautious step-by-step approach, technology being only a small part of it.

3. DEMAND FOR ENERGY

According to most indicators, the global demand for energy will increase significantly, throughout the coming decades, no matter the measures adopted in Europe and North America. In fact, the prime factor affecting the demand for energy is demography. The world population will continue to grow, mainly in India, Africa, South America and South-East Asia. The sub-Saharan Africa (Sahel) will be the region with the greatest population growth worldwide: a demographic time bomb. In 2050 it is predicted that roughly 1/4 of the world's population will be born in Africa, [1].

Africa is the continent with the lowest per capita energy consumption, hence with the highest expected per capita growth. As shown in Figure 6, the largest rate of increase in the per capita energy consumption over the last 60 years has occurred in the developing areas like China and India. In fact, during the period 1980 – 2022, the specific energy consumption in China had tripled, jumping from roughly 10% to 33% of the US specific consumption over the same period. The same trend, with a time lag, appears now in India, of which both population and the per capita energy consumption are steadily increasing.

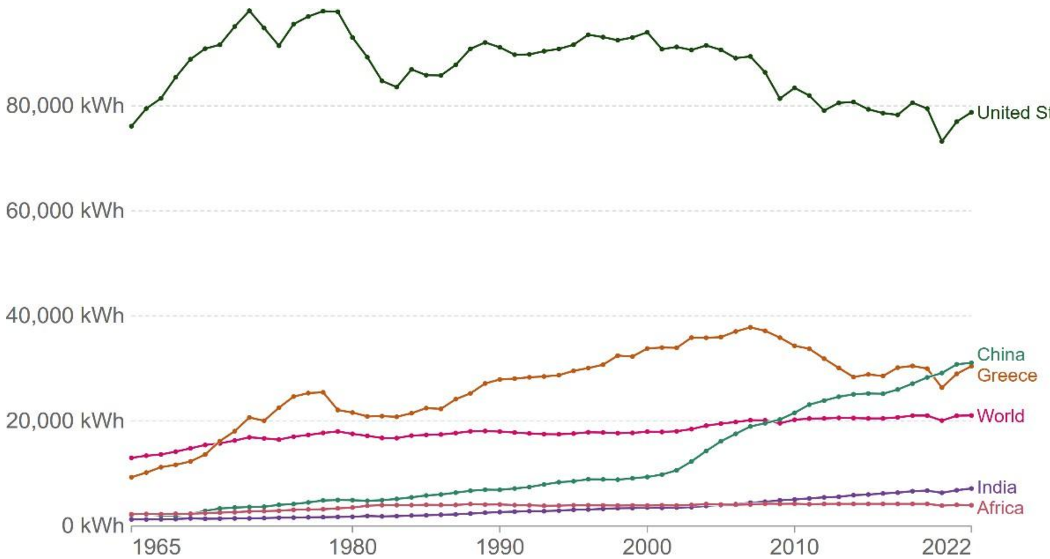

Figure 6: Evolution of primary energy consumption per capita in selected areas, source US Energy Information Administration (EIA)

With the current socio-economic development model, there is no reason why the remaining developing countries of the so-called Global South (Africa, South and Central America, Southeast Asia) should not follow the same path as China or India.

In conclusion, the energy demand for the remaining decades of our century will increase significantly, mainly because of the developing “global south”. Africa, in particular, is expected to experience an explosive demographic growth combined with an inevitable substantial increase in the very low per capita energy demand (less than 5% of the US or 20% of the global average per capita consumption). If this demand is met primarily by low-quality forms of energy, it will inevitably cause an even more significant increase in the global greenhouse emissions. In other words, it is the growth model of developing economies that will determine, to a large extent, the global energy demand and, ultimately, the consequent environmental footprint. It will have a much greater specific weight than the energy policies in the developed economies of Europe, US or Cina.

Thus, the international community should invest and steer the developing countries towards a sustainable development instead of considering them as a source of raw materials, cheap labor and a global garbage dump.

4. ENVIRONMENTAL FOOTPRINT ASSESSMENT

Estimating the costs and the environmental footprint of a certain system or technology is difficult and hides many pitfalls, [3]. A first issue has to do with the definition of the purpose of the assessment and, in particular, its temporal and spatial horizon: a study aiming at short-term measures for a specific region, is very different from one on the climate change or the greenhouse emissions that are long-term and of planetary scale. In the latter case, a correct assessment must include:

- Analysis of the full life cycle, from the necessary raw materials extraction, production, transportation, installation and maintenance to the end-of-life and the waste management.

- Comprehensive analysis and assessment of all possible environmental impacts, not only on the atmosphere but also on water, soil, health, etc.
- Assessment of all possible societal impacts, including politics, culture, migration etc.
- Interaction with other systems and technologies.
- Assessment of broader, indirect impacts such as on the evolution of technology and science.
- Analysis and assessment of the risks for the impact of possible accidents.

Sustainability is, by definition, time persistent. It mainly involves global phenomena and, consequently, any proposed measures must be examined in their global effects, throughout their lifecycle, considering all possible societal effects and implications. As these effects and interrelations project well into the future, they cannot be quantified but by using scenarios (i.e. predictions) regarding the evolution not only of environmental parameters but also factors such as the market, the technology, geopolitics, etc. Inevitably, any impact analysis is as good as the assumptions and the scenarios on which it is based. The problem is that all these factors and phenomena are too complex and, despite our best efforts, are far from being reliably modelled. In a certain sense, they are chaotic, thus, by definition, unpredictable. This fact is supported by the dramatic failure of the majority of our predictions and evolutionary models. In such situations, in the presence a high degree of uncertainty, the safest way is to proceed with cautious small steps rather than with ambitious radical policies. Even more so when the complexity of the analysis and the inevitable subjective assumptions, provide ample room for predetermined results, depending on the authors' interests, dependencies or beliefs.

5. FOSSIL FUELS

Fossil energy has been a fundamental driver of the technological, social, economic, and development progress that has followed the industrial revolution. Fossil fuels (coal, oil, gas) play a dominant role in global energy systems. Despite all the efforts and the "green" policies towards alternative forms of energy, it is highly probable that they their dominant role will continue throughout the next decades. In fact, fossil fuel consumption has risen 14 times over in the 20th century and by 50% just during the first 24 years of the current century (Figure 7). In 2024, each of the three fossil fuels has been, in terms of TWh of produced energy, more important than the sum of all the renewables and the nuclear together.

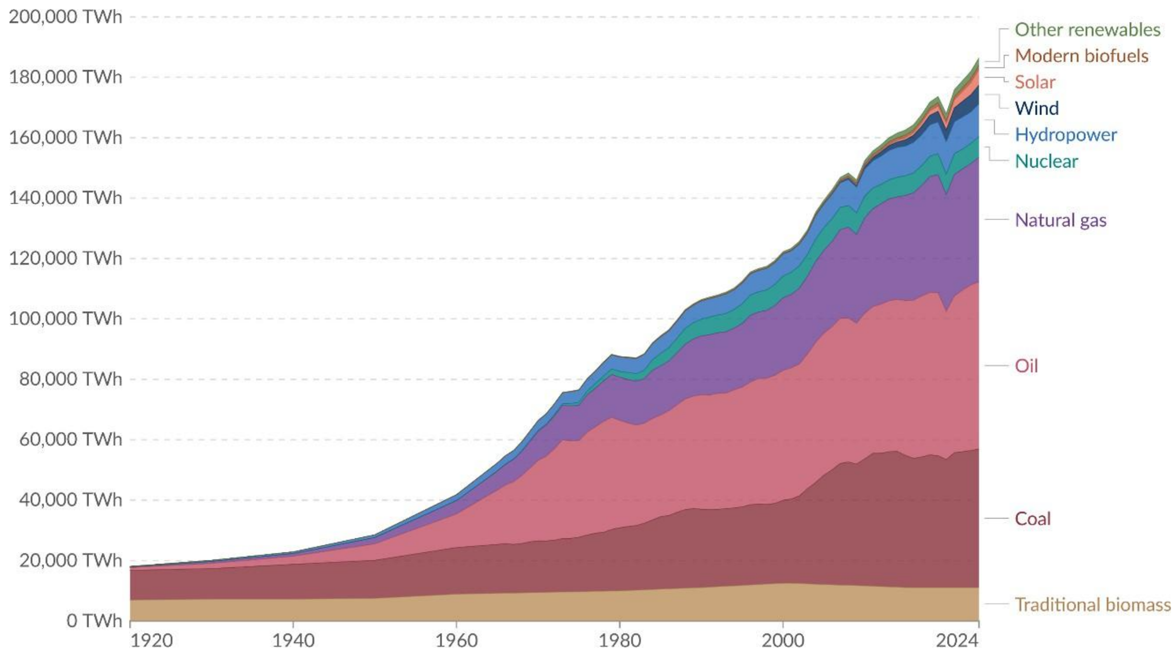

Figure 7: Global primary energy consumption evolution by source; Energy Institute (2025)

The energy sector is blamed for as much as 73%, transportation alone accounting for 16.2% of the 2019 greenhouse gas (GHG) emissions as well as other health hazards, such as the organic carbon and the NO_x, most of these taking place at the developed parts of the globe. There, under the pressure of public opinion, policy makers and industry have taken effective step-by-step measures to improve engine efficiency and lower emissions through exhaust filters, with spectacular results, unimaginable just 50 years ago. The same is true in the power generation and the aviation sectors, where modern combined cycle turbines and turbofan engines have reached record efficiencies, [2].

On the contrary, very little has been done in the production phases, which are mostly taking place in regions of the “global south”, away from the rich western consumers. One of the biggest issues of hydrocarbon production has to do with the venting and the flaring of the associated gas that accompanies oil production. Flaring results in the release of substantial volumes of GHG emissions, including methane, black soot and nitrous oxide. Venting causes even worse environmental damage than flaring. It is estimated that, in 2018, over 145 billion m^3 of NG have been flared worldwide, roughly equivalent to 3.5% of the global NG production or the 17% of the US consumption. It could generate enough electricity power the whole African continent.

Lately, EU has adopted a series of policies and measures aiming at the substitution of liquid hydrocarbons by natural gas (NG), the cleanest burning hydrocarbon. NG was to be the low-emissions fuel, in transit towards a future carbon-less energy. A nothing comes for free, while NG is well suited for applications served through pipeline-based distribution networks (power plants, industries, district heating etc.) it is much less suited for transport, mainly because of its low energy density and the severe problems associated with its use in liquefied form (LNG): high cost, reduced efficiency and high environmental footprint, [5]. Unfortunately, these policies have failed spectacularly. Geopolitics have made EU to shift from pipeline NG to significantly more expensive and polluting LNG imports. Germany, the EU’s industrial powerhouse, having dropped nuclear energy, has had to return to coal and become one of the major GHG emitters worldwide. LNG, that was supposed to fuel a good part of the maritime vessels sailing through the EU waters has failed even to start.

6. ‘GREEN’ ENERGY MYTHS

6.1. Photovoltaics and wind systems

The construction of a photovoltaic panel requires a significant amount of electricity representing 5+ years of panel operation under ideal conditions. This means that while the panel will contribute to a better environment and save some carbon emissions at the consumption site it will add emissions at the production site. In practice, this is equivalent to exporting emissions from the place of consumption to the place of production. Therefore, the use of photovoltaics clearly contributes to the improvement of the environment of a specific place but not necessarily to the global issues such as the greenhouse emissions.

Life cycle analysis of wind systems is somewhat more complicated, their environmental impact being distributed across many phases (site preparation, component production, transportation and assembly, maintenance and decommissioning) and, thus, being dependent from many variables. What is certain is that windfarms are not as “green” as presented, [3].

An important issue, shared among both photovoltaic and wind systems, has to do with their intermittent unpredictable availability and the consequent necessity for energy storage. Solutions range from thermal backup powerplants to batteries and pumped hydraulic storage, all of them contributing significantly to the systems’ cost and overall environmental footprint. Another important issue concerns the adaptability of the electric networks, which were built on stable production centric models and have to adapt to the highly distributed, fluctuating production realities of the massive use of wind and solar.

6.2. Electric vehicles

Electric cars have a significantly reduced environmental footprint during their use but their production has a much greater environmental impact than that of conventional cars, mainly due to the lithium batteries. In other words, electromobility promises a cleaner environment in the consumption areas (usually the rich countries of North America and Europe) at the expense of the lithium mining and processing regions (China, Latin America, Africa). Moreover, the sheer weight of the batteries results to much heavier vehicles consuming more energy, with heavier and more expensive structural components etc.

The EU policy of complete electrification of the road traffic within few decades, besides being completely unrealistic (short supply of batteries, unsuitable electric networks etc.) has backfired in two ways: (a) as electric cars are impractical and, despite the subsidies, very expensive, EU consumers tend to stick with their old cars, specially the diesel, resulting to an increasingly aging car fleet, and (b) all the old, substandard vehicles are exported to the "global south", resulting to an overall increased global mobility footprint, [1].

6.3. Biofuels

Biofuels are fuels derived from biomass, i.e. the biodegradable part of certain plant products or waste. Unlike fossil fuels, whose deposits are not renewed, biomass can be replenished very quickly, even several times in a year. Biomass is one of the most polluting fuels, much more so than diesel or natural gas. However, its overall CO_2 balance appears significantly reduced because its carbon content has been derived from capturing atmospheric CO_2 through photosynthesis in quantities equal, theoretically, to that emitted during combustion. The most common biofuels are bioethanol, biodiesel, biogas, pellets and briquettes. The first two are used in internal combustion engines, usually mixed with fossil gasoline or diesel. Like any other source of primary energy, in order for biofuels to be sustainable, it is necessary to:

1. Provide a net energy profit;
2. Have a clean combustion and, in general, a low environmental footprint;
3. Be able to be produced in large quantities and be economically competitive.

In addition to the above, biofuels must also meet an additional very important criterion:

4. No harmful land-use changes, such as deforestation or food crop replacement.

Unfortunately, in most cases, none of the above criteria is met. The underlying cause is the very low efficiency of photosynthesis in converting incident solar radiation into energy. Calculating the full biofuel cycle, from field preparation, sowing, watering, harvesting, transport and conversion into biofuel, it is found that:

1. The net energy gain is very small, sometimes even negative (e.g. in the case of maize biofuels);
2. Their environmental footprint is often greater than many fossil fuels, even in terms of CO_2, where biofuels are supposed to have zero balance;
3. In most cases, they are financially viable only because of subsidies.
4. The land needed to replace a significant proportion of fossil fuels by crop biofuels would be prohibitively large, displacing food crops and/or leading to extensive deforestation with devastating economic and environmental consequences.

The only biofuel applications with an overall positive footprint are those that combine energy production with other environmental applications, such as recycling or waste treatment. Examples of such applications are the production and use of biogas from biological treatment plants and landfills or the agricultural biomass residues used for the energy needs of greenhouses, [7].

6.4. Hydrogen

Lately, there has been a lot of talk about a future "hydrogen economy", based on hydrogen (H_2) in "green" or, alternatively, in "blue" form. "Green" is the name given to hydrogen produced from water using exclusively clean electricity (e.g. solar, wind or hydraulic) or from nuclear power. When produced from fossil hydrocarbons accompanied by full carbon capture it is called "blue" or "grey", when without full carbon capture.

The product of hydrogen combustion is none other than pure water. Unfortunately, although it is the most widespread element in nature, it is very rarely found in pure form (H_2). For this reason, hydrogen is not considered a primary energy source but a mean for energy storage and transport. To date, hydrogen is produced almost exclusively from natural gas, i.e. in "grey" form, being overall less efficient and dirtier than the hydrocarbons from which it is produced. "Blue" hydrogen does not have clear environmental advantages either, compared to the use of natural gas. In fact, the total amount of CO_2 emitted during the carbon capturing process is often more than the CO_2 emitted during the natural gas combustion.

Hydrogen can also be used for direct electricity generation in fuel cells, with efficiency comparable to that of thermal engines. However, the cost of hydrogen cell-based systems is prohibitively high. Despite its claimed advantages and the significant investments and research efforts, the practical impact of hydrogen technologies is, to date, negligible. The reason lies in the formidable challenges, mainly related to the H_2 transport, storage and distribution.

It must be also noted that hydrogen is not as clean as many believe. Potential leaks into the atmosphere have very negative environmental impacts, much worse than either CO_2 or methane.

7. CONCLUSIONS – WAY FORWARD

Environmental sustainability is not primarily a technical or scientific issue. It is a societal problem, a problem of governance. Our current development model, based on ever-increasing production and consumption, is no longer viable. On a finite planet, society cannot expand infinitely. Either we understand it and adapt our governance models accordingly or the changes will be violent and highly disruptive.

Unfortunately, current energy policies, both at national and EU level, have failed. Natural gas was to be the low-emissions fuel, in transit towards a future carbon-less energy. Geopolitics have made EU NG imports more expensive and polluting. Electric cars are cleaner to run but dirtier to produce and to dispose of. In many cases, the net global effect of "green" technologies is negative or close to null, effectively resulting to "pollution export" from the rich western consumers to the producers, mostly found in the developing global south.

The complexity of the problems faced and the inevitable subjective assumptions, provide ample room for steering the analysis depending on financial interests, political dependencies or beliefs. The hasty introduction and reckless use of many of the so-called "green" technologies has only exacerbated the global greenhouse effect. In such an uncertain environment, instead of promoting elusive radical solutions, policy makers and industry must proceed cautiously and in small steps. Moreover, these steps must aim primarily at the developing "global south". Examples of such policies / solutions include:

- Small, simple, low-cost solar and/or wind systems, produced at industrial scale for use at household or community level, primarily in developing regions but also in "western" households / communities to partly fill their energy needs and reduce their dependency from the grid.
- Hybrid rather than electric cars, using small cheap batteries assisting the thermal motor for further improving vehicle efficiency and lowering emissions.
- Make larger use of efficient hybrid (photovoltaic & thermal) panels for households.
- Promote the community use of alternative energy storage methods such as pumped, inertia, pressure etc., taking into account community resilience aspects.
- Promote local biofuels from recycling and waste treatment instead from cultivated crops.

Such policies / measures, applied at community or household level could have the non-negligible side effect of a social education towards new values necessary for a new sustainable development model.

On top of such consumption-aimed policies, drastic measures should be adopted to clean the production phases. A first very important measure is that of drastically reducing, even eliminating, the routine flaring from hydrocarbon extraction and processing.

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ASSESSING BIOECONOMY POLICY IMPLEMENTATION PERFORMANCE IN THE CASE OF GERMANY

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ABSTRACT

The bioeconomy is an emerging political concept that deals with a variety of sectors such as bioenergy, bioengineering, and biotechnology towards a low-carbon economy. In this context, bioeconomy policies have been published in more than 50 countries and scholars have increasingly focused on bioeconomy policy analysis. For example, they have studied bioeconomy policy visions, the sustainability orientation of bioeconomy policies, and the role of resilience in bioeconomy policy design. However, the implementation of bioeconomy policies has not attracted scholarly interest so far. This is an important research gap because the bioeconomy transition depends on the (un)successful implementation of bioeconomy policy instruments. Against this background, this paper studies specific factors – namely policy coordination and the work culture of implementers – that influence bioeconomy policy implementation in Germany. In particular, it focuses on how participation of stakeholders, power, politics, collaboration, and trust affect the success of implementation. The analysis is based on data derived from desk research and semi-structured interviews. It shows that there are signs of negative policy coordination accompanied by a rigid and dysfunctional work culture of the implementers, thereby holding existing instruments such as the inter-ministerial working group back. This study aims to contribute to a better understanding of the implementation performance in bioeconomy policy and public policy more broadly and to provide insights into the role of implementers in the success of the bioeconomy transition.

Keywords: bioeconomy, policy implementation, coordination, work culture, Germany

SUSTAINABLE DRUG FUTURES: MAPPING 3D PRINTING INNOVATIONS FOR SAFER THERAPIES

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ABSTRACT

Three-dimensional (3D) printing is reshaping pharmaceutical development by enabling sustainable, personalized, and resource-efficient drug manufacturing. In this context, the 3D-SustainDrugs project develops sustainable, 3D-printed, patient-tailored drug delivery systems for non-steroidal anti-inflammatory medicines, integrating green manufacturing principles with advanced pharmaceutical design. This study presents a scientometric analysis of the scientific literature on 3D-printed pharmaceutical formulations, with emphasis on non-steroidal anti-inflammatory drugs. Using VOSviewer software, metadata from recent publications are analysed to identify research trends and thematic clusters. As a result, five domains emerged, namely; (a) dosage forms and drug release mechanisms, (b) formulation development and hot-melt extrusion, (c) drug delivery applications, (d) material properties and additive manufacturing methods, and (e) fused deposition modeling for advanced biomedical uses. These clusters highlight the multidisciplinary nature of 3D printing in drug design, bridging pharmaceutical sciences, materials engineering, and sustainability research. By mapping the evolving research landscape, this work positions 3D-SustainDrugs at the intersection of pharmaceutical innovation and environmental responsibility, offering evidence-based directions for the green transition of medicine production.

Keywords: Sustainable pharmaceuticals, Personalized medicine, Green manufacturing

1. INTRODUCTION

Pharmaceutical manufacturing is undergoing a profound transformation driven by the dual imperatives of digitalization and sustainability. The need to reduce environmental impacts while delivering effective, patient-centred therapies has positioned three-dimensional (3D) printing as a disruptive technology within the pharmaceutical sector. Unlike traditional batch production, 3D printing enables on-demand manufacturing, personalized dosing, and optimized use of raw materials, aligning with the principles of the circular economy and Industry 5.0 [1-2].

Non-steroidal anti-inflammatory medicines represent one of the most widely used therapeutic classes worldwide [3], yet they present persistent challenges of solubility, gastrointestinal tolerability, and patient safety [4-6]. The 3D-SustainDrugs project addresses these challenges by developing sustainable, 3D-printed, patient-tailored drug delivery systems for anti-inflammatory treatments, integrating green manufacturing principles with advanced pharmaceutical design.

To support this effort, it is critical to map the existing research landscape, identifying dominant themes, methodological approaches, and knowledge gaps. This paper presents the results of a bibliometric analysis of 3D printing in pharmaceutical sciences, with emphasis on applications to anti-inflammatory drugs. By systematically analysing co-occurring terms in recent literature, we highlight the clusters of research activity most relevant to sustainable, patient-centred pharmaceutical development.

2. BACKGROUND

3D printing in pharmaceuticals has expanded rapidly over the last decade, with fused deposition modeling (FDM) and hot-melt extrusion (HME) emerging as key enabling technologies [7-10].

In practice, HME serves as the upstream, solvent-free platform to disperse the active pharmaceutical ingredient within a polymeric carrier, often producing drug-loaded filaments with enhanced amorphous content and printability, while FDM uses those filaments to build dosage forms layer-by-layer. This tandem workflow enables fine control over;

(i) micro-geometry (e.g., infill density, shell thickness, layer height, internal channels), which directly tunes surface area and diffusion paths,

(ii) material composition (polymer grade, plasticizer, and API load), which governs solid-state stability and dissolution, and

(iii) process parameters (nozzle/bed temperature, speed), which affect both performance and energy use.

Collectively, these levers allow precise tailoring of release kinetics—ranging from immediate to modified and pulsatile profiles—simply by adjusting print design or filament formulation, as shown in geometry-dependent release studies and flexible-dose “printlets.” In parallel, new carriers (e.g., PVA, EVA) and HME process know-how have broadened the printable space for poorly water-soluble actives, supporting amorphous solid dispersions that improve solubility and bioavailability.

From a sustainability standpoint, the solvent-free nature of HME, the on-demand/near-patient production enabled by FDM, and the reduction of overproduction and transport all contribute to lower waste and potential carbon savings aligned with Industry 5.0 and circular-economy goals.

Recent studies demonstrate the potential of amorphous solid dispersions and polymeric carriers to overcome solubility limitations of poorly water-soluble drugs, including anti-inflammatory medicines [11-16]. Mechanistically, hot-melt– or printing-enabled dispersions convert the active to an amorphous state and use miscible carriers (e.g., PVA, EVA, PVP, HPMC-AS, methacrylate copolymers) and plasticizers to;

(i) raise the glass-transition barrier to recrystallization,

(ii) strengthen drug–polymer interactions (H-bonding/ionic), and

(iii) maintain supersaturation during dissolution, yielding higher apparent solubility and faster absorption.

Evidence spans class exemplars: indomethacin dispersions and microfiber scaffolds showing high drug loading and controlled release; ibuprofen extrudates achieving stable amorphization; and naproxen dispersions with hydrophilic carriers improving in-vivo analgesic readouts. In parallel, 3D printing exploits geometry–property coupling (infill, shell, internal channels) to fine-tune surface area and diffusion pathways, enabling immediate, modified, or pulsatile profiles without changing the API, only the filament recipe or the build design.

From a sustainability standpoint, selecting benign, recyclable, or biodegradable carriers (e.g., PVA/EVA families) and using solvent-free hot-melt extrusion reduces unit operations, solvent handling, and waste; on-demand, localized printing further cuts overproduction and transport, lowering the process footprint in line with circular-economy goals.

Yet, despite growing momentum, the environmental footprint of 3D printing processes remains insufficiently explored [17-19]. Questions regarding energy consumption, emissions, and recyclability of materials highlight the need for sustainability-oriented roadmaps—precisely the niche that 3D-SustainDrugs project aims to address.

3. METHODOLOGY

The dataset analysed derives from the bibliographic corpus focusing on 3D printing in pharmaceuticals. Metadata (titles, abstracts, keywords) were collected from peer-reviewed publications. Inclusion criteria emphasized studies on formulation development, printing techniques, and drug delivery applications relevant to anti-inflammatory drugs.

VOSviewer (v1.6.20) was used to perform a co-occurrence analysis on the bibliographic corpus, parsing the title, abstract, and author keywords fields to capture both topical breadth and methodological signals. A minimum term occurrence threshold of eight was applied to filter sparse terms and improve the stability of inferred relationships. Terms passing the filter were consolidated with a light thesaurus/stop-word pass (e.g., singular/plural normalization and removal of function words) before network construction.

Networks were generated with fractional counting/normalization to reduce dominance effects from highly prolific terms and better reflect shared specificity across items. The clustering resolution was tuned to separate coherent themes while preserving interpretability (i.e., avoiding over-fragmentation); clusters were labelled ex post using their highest-weight and context-defining terms (e.g., “hot melt extrusion”, “filament”, “drug release”, “fdm”, etc.)..

The number of terms, cluster sizes, total link strength, and exemplar terms are reported in detail in the relevant project deliverable D1.3. Visualizations (network map and density view) complement the statistical analysis.

4. RESULTS

The dataset reveals a rapidly expanding research field, with significant growth in publications after 2015. Articles are concentrated in journals bridging pharmaceutics, materials science, and biomedical engineering.

The analysis yielded a network of 163 terms grouped into five major clusters (Figure 1), as follows:

- Cluster 1: Dosage forms and release mechanisms: terms such as *tablet*, *drug release*, *filament*, *PVA*.
- Cluster 2: Formulation and hot-melt extrusion: *formulation*, *polymer*, *extrusion*, *amorphous solid dispersion*.
- Cluster 3: Applications and production processes: *drug delivery*, *fabrication*, *process*, *production*.
- Cluster 4: Additive manufacturing and materials: *additive manufacturing*, *mechanical property*, *technology*.
- Cluster 5: Fused deposition modelling and scaffolds: *FDM*, *scaffold*, *deposition modelling*.

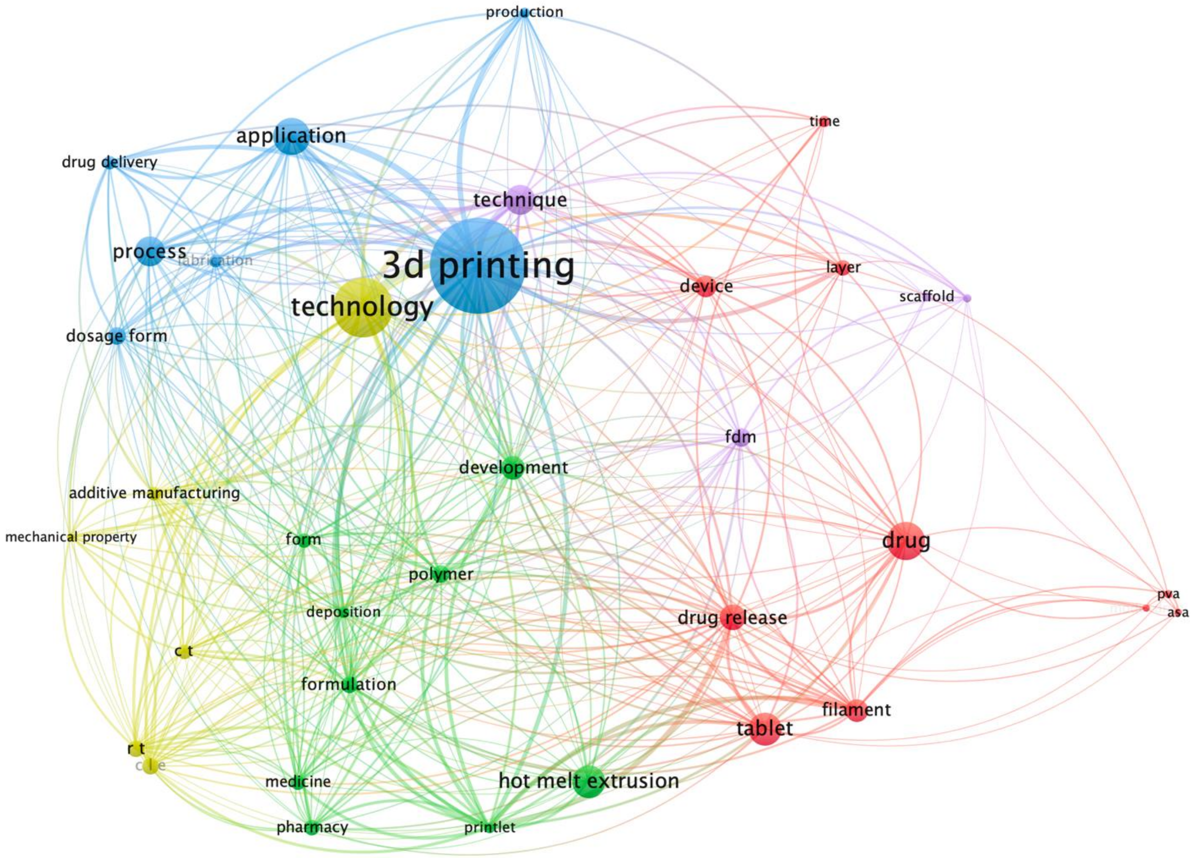

Figure 1: Co-occurrence network of terms in pharmaceutical 3D printing research

Table 2. Cluster summary (cluster ID, size, representative terms)

Cluster	Size	Terms
Cluster #1	10 terms	asa, device, drug, drug release, filament, layer, model drug, pva, tablet, time
Cluster #2	9 terms	deposition, development, form, formulation, hot melt extrusion, medicine, pharmacy, polymer, printlet
Cluster #3	9 terms	3d printing, application, dosage form, drug delivery, fabrication, process, production
Cluster #4	6 terms	additive manufacturing, c l e, c t, mechanical property, r t, technology
Cluster #5	4 terms	deposition modeling, fdm, scaffold, technique

Within the co-occurrence map, anti-inflammatory drug terms concentrate in Clusters #1 and #2, which are dominated by formulation/printing levers such as filament, tablet, drug release, PVA (Cluster #1) and hot-melt extrusion, polymer, formulation, printlet (Cluster #2). This adjacency links the therapeutic focus directly to amorphous solid dispersions, polymeric carriers, and geometry-tuned release—the core toolset for addressing low solubility and variable exposure. Concretely, the Cluster #1 terms reflect dosage-form micro-geometry (e.g., infill, layers, shells) that modulates surface area and diffusion paths, while Cluster #2 terms capture the HME–FDM tandem that embeds poorly water-soluble actives into miscible carriers and prints patient-tailored forms.

Representative literature in the corpus echoes this emphasis for canonical anti-inflammatory agents, e.g., indomethacin systems stabilized and structured via polymer matrices, and ibuprofen/naproxen dispersions achieving improved dissolution and performance with hydrophilic carriers. Taken together, these cluster patterns indicate a field-level pivot toward bioavailability enhancement via sustainable formulation strategies: solvent-free hot-melt extrusion to reduce processing steps and solvents, filament-based FDM for on-demand, localized manufacturing, and carrier/geometry choices that can deliver efficacy with a lower process footprint—priorities that align with the sustainability aims articulated for the 3D-SustainDrugs framework.

5. DISCUSSION

The five-cluster structure of the bibliometric network illustrates the interdisciplinary nature of pharmaceutical 3D printing. At one end, formulation science and hot-melt extrusion provide the foundation for printable materials; at the other, dosage form design and delivery applications reflect clinical and patient-centric goals. Material science and additive manufacturing technologies bridge these domains, while FDM and scaffold engineering represent enabling techniques.

For anti-inflammatory drugs, bibliometric evidence underscores the centrality of amorphous solid dispersions and polymer carriers in addressing solubility issues [11-12, 13-15]. Customizable 3D-printed “printlets” can tailor drug release and mitigate adverse effects, advancing both therapeutic safety and sustainability [20-21].

From a sustainability perspective, the results point to three priorities:

1. Energy and emissions monitoring in printing workflows to align with green manufacturing [17-19].
2. Sustainable materials such as biodegradable polymers to reduce lifecycle impacts [2].
3. On-demand, localized production to minimize waste and transportation emissions.

These insights directly support the 3D-SustainDrugs objectives, positioning the project to integrate bibliometric intelligence into experimental design, material selection, and sustainability assessment.

6. CONCLUSION

This study applied bibliometric analysis to map the knowledge structure of 3D printing in pharmaceuticals, with a focus on applications for anti-inflammatory drugs. Five thematic clusters capture the field’s dynamics, linking formulation science, additive manufacturing, and sustainable drug delivery.

By situating these trends within the scope of the 3D-SustainDrugs project, the analysis highlights opportunities to advance eco-efficient, patient-tailored therapies. The project’s next steps (developing hot-melt extruded filaments, optimizing FDM parameters, and embedding green assessment tools) are informed by these bibliometric insights, contributing to the broader transition toward sustainable pharmaceuticals.

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UNCERTAINTY, COMMUNITY AND ARTISTIC PRACTICE: PARTICIPATORY ART AS RESILIENCE AND SUPPORT FOR CULTURAL IDENTITY OF COMMUNITIES

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ABSTRACT

Strategy Summary: Participatory art is presented as a creative practice that does not seek to exclude uncertainty but embraces uncertainty but embraces it as a prerequisite for knowledge production and relationship building. This presentation is based on theoretical frameworks (Helguera, Bishop, Brice and Arconada) and the case study of the long-term participatory project Amolí, implemented in a rural, post-industrial, multicultural community in Aspropyrgos, Greece. Highlighting the embedded, interactive and interdisciplinary nature of participatory art or socially engaged art, the paper explores how participatory methodologies can serve as transformative tools for enhancing social resilience (Sturle Hauge Simonsen) in complex environments. Through artistic co-creation and community empowerment, participatory art is proposed not only as a form of expression but also as a strategy for collective learning, redefinition of place, cultural identity and emergence of new forms of sense of belonging.

Scalability and adaptation of the “Amoli” program: While the core principles of the program remain constant - integrating the dynamics of community, place, technology and sustainability - its implementation can vary depending on local needs and resources. This flexibility is crucial to the scalability of the model, allowing it to be replicated and modified in a variety of settings, from rural to urban. Future efforts could explore the factors that influence the scalability of such models, including community readiness, cultural heritage, surrounding space, technological access, and the availability of local artistic assets.

Keyword: Participatory art, community resilience, cultural identity, integrating knowledge

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