

PHOSPHOGYPSUM LEADERSHIP INNOVATION PARTNERSHIP



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Particular thanks are due to Charlotte Hebebrand, outgoing IFA Director-General. The beginning of her term of office in 2013 marked the start of a new era in the history of our industry's attitude to phosphogypsum. Her engagement throughout her term of office has seen the publication of both Phosphogypsum Sustainable Management and Use, 2016, and its successor, this Report, to mark the end of her tenure. With her support and encouragement, IFA member companies have started systematically to define, to test and then to seize, the range of opportunities worldwide which phosphogypsum as a resource offers, not least in the contribution its use can make to sustainable development.

PG2 Pathfinders are gratefully acknowledged for the many and varied contributions to this Report by name and organisational affiliation, either current or at the time their contribution to PG2 was made.

EXECUTIVE SUMMARY

The favourable reception of the International Fertilizer Association's (IFA) first Phosphogypsum Report – Sustainable Management and Use, 2016 (PG1) [1] - led to the commissioning and release of this second Phosphogypsum Report – Leadership, Innovation, Partnership: Core Principles of Phosphogypsum Management and Use, (PG2) in 2020.

PG1 was constructed “from the outside, looking in”, led by an independent team of scientific and technical experts. PG2 builds on PG1 but reverses the editorial perspective. Under the same peer review procedures as for PG1, PG2 is written by the industry itself, “from the inside, looking out”. It reflects and documents a remarkable transformation which the phosphate industry is undergoing.

This transformation is manifest in the tangible, robust evidence of progress towards comprehensive use of phosphogypsum resources worldwide, as documented in the case studies in PG2 Section 2. It is also palpable in the intangible values and core principles on which the decisions to build and publish this evidence base are grounded. These core principles are Leadership, Innovation and Partnership.

So PG2 is structured in three sections aligned to these principles.

Section 1, Leadership, sets out the pathway IFA has been following since a four part industry action agenda was set out by its incoming President Esin Mete, then CEO of Toros Agri, in January 2014. This comprised: 1. Sustainable development and the United Nations Sustainable Development Goals (UNSDGs); 2. Resource use efficiency (RUE); 3. Phosphogypsum; and 4. Stakeholder engagement and social licensing. Responding to that agenda, PG1 was published in March 2016.

PG1 was launched only a few weeks after 193 Heads of State had signed the UN Sustainable Goals – Agenda 2030 – in late 2015. By early 2018, IFA members had committed to reporting progress on SDG delivery in annual corporate statements, including progress on PG valorisation and use. New senior management positions tasked with implementing SDGs, the circular economy, zero waste and resource efficiency are commonplace. Governments and regulators

at both national and local levels in parallel were engaged in developing policy and economic levers, such as regulatory amendments and subsidies for PG use, to accelerate implementation of these objectives.

In this push to sustainable development, the fertiliser sector is part of a much wider business movement. Late 2019 saw the formal launch of “stakeholder” capitalism when businesses publicly recognised that benefits to employees, suppliers, the value chain and customers, as well as society at large had their place on the corporate agenda as measures of value.

All these fast-moving policy changes have benefited the way in which industry itself, but also regulators and stakeholders, see PG.

Now the challenge is to scale up and maintain the effort. Scaling up requires leadership as well as innovation. A Table summarising results from the IFA Member PG Survey 2018-19 shows how this scale-up process is being approached across all major PG producing areas.

Section 2, Innovation, consists of case studies and national overviews. The case studies are focused on the three major high-volume opportunities for PG use: agriculture/ forestry, construction materials and roadbuilding. Two national overviews, from Brazil - from the University of São Paulo, and Mosaic - and India - Fertilizer Association of India and Paradeep Phosphate Ltd. - respectively, deal with an integrated approach to PG use, coordinating more than one of these high-volume opportunities.

A third national overview focuses on China. China's phosphate industry, by some distance the world's largest producer and consumer of PG (some 80 million tonnes per year produced of which some 40% is commercially consumed) is now facing the challenge of «comprehensive utilization» of PG - 100% use. How to achieve this ambitious goal is in active planning by the IFA-China Consultative Group, which is drawing on PG2 for some of the key aspects of the delivery strategy.

In pursuit of 100% use, Brazil is the first country to have reached equilibrium between PG production and

consumption. There are two regional PG markets within the country, one for use in agriculture the other for cement. In the Cerrado agricultural region, perhaps the single most significant agricultural zone in the world, not only is all current PG annual production being consumed but legacy PG from past years is also being mined out from both active and closed stacks for use. Mining stacks is a “win/win” outcome. It covers local PG shortfalls for meeting farmer demands and it begins the process of releasing sterilised land, long-used for “stacking” PG – in effect disposing of it as waste – back into economically productive use. Historically “disposal stacking” of PG has commonly taken place all over world. When the stacks were first started they were far away from or on the remote edges of cities. These cities, such as Uberaba Brazil, have subsequently grown to the point when PG stacks once sited far away from any human settlement are now encroached or fully encircled by dwellings and businesses.

To prevent such a problem occurring in the first place, for more than 15 years India has been investing in a solution for PG use not disposal based on a partnership between policymaker, regulator and operator. Now the benefits of this approach are starting to show, with a real prospect of 100% PG use as the outcome rather than long-term storage or disposal. This has required both established applications such as provisioning the cement industry with PG as feedstock but also innovation in the form of new products, for example sulphur-rich Zypmite, a PG soil amendment enriched with micronutrients, to be produced and sold at commercial scale. Other applications, such as roadbuilding, equally require partnerships between government and industry, such as between Paradeep Phosphate Limited and Central Road Research Laboratory. As the two companion road-building case studies from OCP, Morocco, and PhosAgro, Russian Federation, both show, companies elsewhere are following similar partnership models with their respective national stakeholders whether from a technical or regulatory perspective.

The regulatory approaches Brazil and India share is that much of the leadership to lower or eliminate barriers to market while fully protecting occupational, public and environmental health and safety, has come not from industry but from the policy maker and related regulatory authorities. Formal technical and scientific statements have been released by government agencies, referenced to evidence-based review, which justify why PG “wastes” have been reclassified – typically from “hazardous” to “non-hazardous” status - to encourage use. National regulators, supported by endorsement or encouragement from international authorities, have applied the “graded approach” to regulating specific PG applications according to local needs and priorities, for example in agriculture or as feedstock for construction materials.

Section 3, Partnership, sets out how Innovation paves the way to but also depends on Partnership. It traces the key stages of a 40-year journey from 1980 (when the then Florida Institute for Phosphate Research (FIPR) started its ground-breaking series of technical studies and publications on PG) to 2020, the point at which PG2 can claim to be opening a new chapter in the history of PG as a resource. Phosphogypsum now is classed variously as a co-product, secondary (anthropogenic) resource or reusable raw material. Building on that platform of new nomenclature, how can an ambitious vision of 100% PG use become a reality as demanded by UN Agenda 2030 in the interest of “People, Planet and Prosperity”?

In Section 3, some leading figures from that 40-year journey, Mike Lloyd and Gary Albarelli, (FIPR), Prof. Rafael Garcia Tenorio, (University of Seville), Dr. Manzoor Qadir (ICARDA and UN University), Dr. S. Nand (Fertiliser Association of India), Dr. Hari Tulsidas (IAEA and UNECE), give their views as to how we got to this point and where we are headed while confirming their respective and general willingness to continue partnership with IFA member companies to reach the goal of 100% use.

Both Manzoor Qadir and Hari Tulsidas have attended PG WG meetings since 2017 and have advised throughout the processes of compiling both PG1 and PG2. Now PG2 sees this process of synthesising the previously fragmented knowledge and evidence bases from different centres of excellence around the world reach its conclusion, from which a push towards 100% use can be launched. The close of Section 3 sets out at a high level from a UN perspective how this might be done.

The release of PG2 was originally scheduled for April 2020 during the IFA annual meeting in Delhi. The venue would have been fitting as that is where PG1 was released in March 2016. But the COVID-19 pandemic intervened and, like so much else, release has moved online. It is far too early to know what the lasting COVID-19 impact will be on the fertiliser industry in general and phosphogypsum in particular. But, as if we needed reminding, the fundamental importance of the Food-Energy-Water (FEW) resource nexus has been strongly reinforced by COVID’s threat worldwide to the security of supply of each. Likewise, COVID’s disruptions of the deeply interconnected global flows of the critical resources that meet our basic food, energy and water needs, putting much of the global economy on hold, has reminded us that we are not just in it together for ethical reasons. We have no choice but to work closely with each other to find a sustainable way forward.

1 LEADERSHIP

INTRODUCTION

The favourable reception of IFA's first Phosphogypsum Report – Sustainable Management and Use, 2016 (PG1) [1] led to the commissioning of a Second Phosphogypsum Report, Leadership, Innovation, Partnership: Core Principles of Phosphogypsum Management and Use (PG2).

PG1 was constructed “from the outside, looking in”, led by an independent team of scientific and technical experts, all of whom had been involved in the game-changing Safety Report on the Phosphate Industry published by the International Atomic Energy Agency (IAEA) in 2013 (SR78) [2]. SR78 a) classifies PG as a co-product of phosphoric acid production, not as a waste b) concludes that there is no radiological objection to use, and c) advises that a “graded approach” to comprehensive PG use, based on independent peer-review, is environmentally preferable to disposal, whether to land or sea. By “graded approach” is meant: “A structured method by which the stringency of control to be applied to a product or process is commensurate with the risk associated with a loss of control” [3] (see Fig. 5). In the context of transitioning to a global circular economy, neither mode of disposal is preferred. Instead PG should be managed as a “reusable raw material” and where economic conditions for immediate use are not conducive, these materials should be stored in suitably engineered interim storage facilities pending future use.

A detailed analysis of the radiological (Naturally Occurring Radioactive Materials (NORM)) aspects of PG production and use is contained in PG1 Sections 1 and 2, to which readers of PG2 are directed for general information on NORM, and likewise to Section 9 of IAEA SR78 which deals exclusively with PG including fully-referenced summaries of principal applications, agriculture, construction/ construction materials, and road-building.

PG2 builds on PG1 but reverses the editorial perspective, “from the inside looking out” comprised largely of peer-reviewed case studies written by IFA member companies and their partners but edited together into the fabric of the report to give an integrated industry-wide picture of progress to date. This process has also been well supported by regional associations,

notably Fertilizers Europe (FE)¹ and Fertiliser Association of India (FAI)², academic-scientific centres of excellence such as the Florida Phosphate and Industrial Research Institute (FIPRI)³, the UN University Institute for Water, Environment and Health⁴, the University of Alberta, the University of São Paulo, Department of Soil Science⁵, and the Expert Group on Resource Management (EGRM) of the United Nations Economic Commission for Europe (UNECE). Recent very fruitful consultation meetings have also been held in China under the umbrella of the IFA-China Consultative Group (IFA-CCG) in support of China's pursuit of a policy of 100% PG use. PG2 contains an outline of the IFA-CCG 2020-2025 Strategic Work Plan.

The game-changing impact of three major international policy developments that have unfolded since PG1 was written (in 2014-15) set the policy context for PG2.

These game-changing policies are:

- **The UN Sustainable Development Goals⁶**
- **The Paris Agreement on Climate Action⁷**
- **A general commitment to transitioning to a green [4], circular economy.⁸**

Anticipating these changes, all three aspects were addressed in a landmark speech made by Mrs. Esin Mete, incoming President of IFA, in January 2014. Addressing the Arab Fertilizer Association Annual Forum in Sharm-el-Sheikh, Egypt, she defined the framework for all subsequent IFA-supported activity in respect of PG. Her speech set the context for the preparation of PG1 and the subsequent publication of PG2. Key passages of the speech are published for the first time in this Report.

The impact of the policies identified above, especially the UNSDGs, can be measured in PG2 in a number of ways. First, PG can become a very powerful and plentiful phosphate industry asset to contribute to the global secondary resource inventory for sustainable development, notably for use in soils and various modes of construction. Secondly, the PG1 glossary of some 30 key terms is now expanded in both number and nature, to 58. Many of the new terms, such as circular economy, reflect the profound changes in the policy and regulatory landscape. Others, such as soil, have significantly expanded definitions reflecting a new respect for just how significant the physical, chemical and biological

health of our soils are to sustainable development as a whole. These are still far from complete in their impact not least on the phosphate industry itself. Thirdly, the list of abbreviations and acronyms has grown from 54 to 78, reflecting the same drivers for change. But perhaps the most significant measure of change is that the editorial position of PG2 is not simply one of changed perspective.

PG2 shows industry now taking an active leadership role in facing the challenges that the policy framework has thrown its way, not least in meeting the profound societal needs of the Sustainable Development Goals. Visionary leadership has been demonstrably translated into operational practice as the body of evidence contained in the case studies which comprise the bulk of this Report clearly sets out. Whereas in 2014 the objective of 100% use of PG seemed like a distant dream, now in 2020 with some major interim targets met and an industry-wide engagement with the task, getting to 100% use seems an achievable goal, in some cases even by 2030. This broad-based progress is grounded in an ethical commitment the industry now manifests to accepting that in achieving some of these SDGs only the industry has the global strength and reach to be able to mobilise resources adequate to the scale of the task.

Integral to the industry's ethical commitment are three values which Esin Mete flagged up in her speech, and which are evident across all the case studies in PG2 - Leadership, Innovation and Partnership, which have given the title to this report. It is striking that these values feature in the case studies not so much as mission statements as performance indicators of work being done or even actually finished by member companies. IFA members are now willing to measure and report on their progress with PG as co-product, as shown in the range and breadth of the case studies united into PG2. They have invested significantly in R&D and pilot projects to validate the properties and performance of the various types of PG they produce. They have also cooperated closely both with business partners from other industries – for example construction materials – and with independent centres of technical and scientific excellence to validate the findings of their pilots before scaling-up. This linkage between leadership, innovation and partnership reflects a clear recognition that stakeholder engagement is born of, and lives by, trust and confidence. Bringing PG successfully and continuously to market on a large scale worldwide will

1. Fertilizers Europe, <https://www.fertilizerseurope.com/>

2. Fertilizer Association of India, <https://www.faidelhi.org/>

3. Florida Phosphate and Industrial Research Institute, Florida Polytechnic University, <http://www.fipr.state.fl.us/>

4. UN University Institute for Water, Environment and Health, <https://inweh.unu.edu/>

5. University of São Paulo, Soil Science, <http://www.en.esalq.usp.br/departamentos/soil-science>

6. UN Sustainable Development Goals, <https://www.un.org/sustainabledevelopment/>

7. UN International Framework Convention on Climate Change, Paris Agreement, <https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement>

8. European Union, Circular Economy Action Plan, <https://ec.europa.eu/environment/circular-economy/>

depend every bit as much on market trust and confidence, as on its potential to be valorised as a product, product performance and value-add to the customer.

How these values of leadership, innovation and partnership have developed within the culture of IFA is set out in the opening sections of PG2, under the rubric of The Pathway to PG use. This process started to take formal shape in 2012, and is now driven by the IFA PG/NORM Working Group without the leadership of which neither PG1 nor PG2 would have seen the light of day.

REVIEW AND SIGN-OFF

The review and sign-off process especially for the case studies was iterative, dealing with each contribution and its contributor team one by one by a variety of methods including email and conference calls. In parallel, members of the PG WG have been engaged in the more general authorial and editorial process throughout.

In compiling and editing the case studies a “light-touch” editorial approach has been taken which respects that:

- the tone and perspectives of the contributions reflect the personalities, geographies, policy and cultural contexts and diverse socio-economic circumstances in which the various beneficial uses of PG are being developed worldwide;
- most contributors do not write in English as their first language;
- all contributors have set a high bar for themselves in terms of the technical and scientific integrity and merit of their work, as reflected in a wide range of partnerships and other forms of cooperation between industry, academia and regulatory authorities;
- this “high bar” principle has also been followed by the PG2 editorial and review team.

Case studies have followed a “co-authorship” model where the contributors have submitted drafts in a variety of stages of development. These have been reviewed and edited, some also translated, both from French to English and Russian to English, with and by the PG2 editorial and review team on an iterative basis to the point of sign-off. By this method, the case studies work both stand-alone but are also fully integrated into the Report.

What has emerged is a comprehensive and increasingly coherent picture of the industry’s changing relationship with PG. It has invested considerable energy, creativity and commitment into finding and consolidating a sustainable, long-term solution for PG use based on a stable equilibrium of environmental, economic and social benefit. In the process

a set of critical success factors has become discernible, which if applied industry-wide, significantly increase the likelihood of reaching the desired outcome of eventual 100% PG use. In that regard, compliance with SDG objectives and related policies as outlined above has become a natural outcome for the industry not a burdensome constraint.

SDG compliance has been achieved in a manner commanding increasing international recognition and respect. This comes at a good time as the industry works to revise the narrative of its global role as one of the fundamental pillars of sustainable development, resource use efficiency, the delivery of food accessibility, security and zero hunger, and as outcome, increased employment opportunity.

THE PATHWAY TO PG USE

SETTING THE AGENDA: LANDMARK EVENT, JANUARY 2014

The new public IFA approach to PG was flagged up and put centre stage in January 2014 by Esin Mete, then CEO of Toros Agri and incoming IFA President. Her landmark speech to the Annual Forum of the Arab Fertilizer Association (AFA), Sharm-el-Sheikh, Egypt, was given at the invitation of Dr. Shafik Ashkar, its Secretary-General and in the presence of Charlotte Hebebrand, the then recently appointed Director-General of IFA.

The title of Mrs. Mete’s presentation was **Looking Ahead: Building a Sustainable Future for the Fertilizer Industry.**⁹ The four themes which set out the agenda she proposed were:

- 1. Sustainable development and the emergence of what became the UN Sustainable Development Goals²**
- 2. Resource use efficiency (RUE) including nutrient efficiency at its core**
- 3. Phosphogypsum**
- 4. Stakeholder engagement and social licensing.**

All four themes are of central significance both to PG1 (2016) [1] and to this Report (PG2) (2020). They share the common requirement the speech highlighted of responding to change, reminding the industry representatives that they would do better to respond to such change voluntarily rather than waiting for it to be imposed on them.

It was also no coincidence that the region central to the global phosphate industry in terms of its holding of phosphate

9. Extensive excerpts from Esin Mete’s speech are published by kind permission of Esin Mete herself.

resources critical to the world as a whole, the Middle East North Africa (MENA) region, should be the location chosen for her speech. It is also no coincidence that the linkage between nutrient efficiency and PG should be set out by Mrs. Mete in the context of overall RUE, PG being an ideal source of sulphur-rich soil amendment.

As will be seen in later analysis of the case studies, success in transforming attitudes to valorising PG is very closely correlated with hands-on, top-down leadership based on the recognition that a sustainable solution for PG is of existential significance to the global phosphate industry.

BUILDING A SUSTAINABLE FUTURE FOR THE FERTILIZER INDUSTRY: GIVING PG A CONTEXT

To recognize the visionary significance of Esin Mete's speech, 4 major passages are reproduced in full below.

"It is both an honor and a pleasure to address you at the 20th AFA Global Fertilizer Networking Forum. I would first like to extend my gratitude to the Arab Fertilizer Association for this invitation to address this important gathering of leading fertilizer actors in the Arab world.

IFA is the only global organization of the Fertilizer Industry. This trait alone makes it a very special and unique global organization and therefore, as members of this organization, we have to make sure that IFA will carry on its activities and attain the goals put forward by its members. To achieve this, an organization having a very long history as IFA, has to be updated to cope with the changes that have been taking place in our business environment and adapt itself to these changes while still keeping its core values intact.

The first signs of the change were initiated by my predecessor, Mr. William Doyle and will be continued with the coming presidents including myself and executive management. As the present IFA president, I strongly encourage reform to keep IFA abreast of the developments and in this respect, I have worked with my colleagues in the executive group and committees in an effort to devise a new and more transparent governance system that will facilitate engagement for member companies in every region. This new governance system will be better equipped to address the priority topics for our industry. And it is about these important topics: engagement with multilateral organizations, the post-2015 agenda, nutrient stewardship, product stewardship, and phosphogypsum that I want to talk to you about today."

1. ZERO HUNGER: SUSTAINABLE DEVELOPMENT GOAL 2

Her speech powerfully anticipates SDG2, Zero hunger, as a focal point for the industry:

"Firstly, I would like to stress that although we may all face region-specific challenges, global societal challenges present

both risks and opportunities for all of us wherever we are in the world. Together, as an industry, we need to recognize these commonalities and work in a concerted effort to best advance our unique contribution to feeding the world which is the most important challenge our world faces today. At the same time, we have to demonstrate our full recognition of our responsibility to contribute to sustainable development.

Fertilizers continue to play an essential role in supplying the nutrients to grow the crops that feed an increasing population. Furthermore, through agronomic bio-fortification, fertilizers have begun to address the micronutrient deficiencies and hence positively impact human health [SDG 3]. These important roles are not always recognized by policymakers, stakeholders and the public at large. As our industry has more generally tended to keep a low profile in the recent years, it has not been able to avoid more scrutiny, particularly on environmental issues such as greenhouse gas emissions [SDG 13], and on nutrient use efficiency [SDG 12].

The international community under the United Nations umbrella, is embarking on developing a new set of universal goals that should replace the previously established Millennium Development Goals and gear the growth strategies of developed and developing countries alike in the next 15 years. In this post-2015 and Sustainable Development Goals context, the fertilizer industry has a unique opportunity to be finally perceived on the international agenda as a strategic provider of food to feed the world and contribute to the nutrition security. However, this sudden emphasis on crop nutrients also raises the reputational risks for the industry, as this increased attention will increase the pressure on delivering on sustainability indicators. The industry will be expected to demonstrate its goals in improved nutrient performance and less detrimental environmental impacts.

I personally think that we should seize this chance to enhance our reputation by effectively adopting, implementing and then disseminating our stewardship initiatives. Among these stewardship initiatives, two in my opinion are imperative for our industry. These are namely nutrient stewardship and product stewardship."

2. RESOURCE USE EFFICIENCY AND NUTRIENT STEWARDSHIP

Next on the agenda are the key concepts of Resource Use Efficiency and Nutrient Stewardship:

"Nutrient stewardship is a powerful tool to respond to calls for stricter environmental regulations because it addresses the consumption of fertilizer and, in particular, the environmental impact of fertilizer use by farmers in the fields. Nutrient stewardship initiatives are being spearheaded around the world. North America has developed the 4R nutrient stewardship framework and the 4R research fund. Some

countries have developed their own initiatives. Australia has the FertCare program and New Zealand the Overseer. This framework conveys to farmers, policy-makers and all other stakeholders the principles of using the right fertilizer sources at the right rate, right time and right place so as to achieve economic, social and environmental goals.”

3. MINERAL FERTILIZERS AND FERTILE SOILS AS A JOINT PILLAR OF SUSTAINABLE DEVELOPMENT

The seminal changes the year 2015 would bring to sustainable development policy and practice are shrewdly anticipated:

“2015 will be a year of great importance for the agriculture sector in general and the fertilizer industry in particular. The world will converge under the United Nations umbrella to define a new pathway for development under the post-2015 development agenda. In addition, the 193 member countries of the United Nations will collectively negotiate a new set of universal goals that should guide economic growth to 2030. 2015 will also be the International Year of Soils. I reckon that it will be the first time in modern history that so much attention is placed on the role of agriculture in providing solutions to the future and in delivering a better world free of poverty, hunger and malnutrition. I believe that our industry will be prepared for this important year by focusing on the above priorities and by enjoying the collective support of member companies, sister - regional and national associations and research institutes.”

4. PHOSPHOGYPSUM

Then, and against that background, she turned her attention to phosphogypsum:

“One topic on which IFA and AFA have recently worked together on is Phosphogypsum.

Looking at the challenges and major new opportunities raised by the presence of NORM in fertilizers and agriculture is an industry priority, one that - through cooperation and effective advocacy - we can turn into a positive benefaction for our industry. Phosphogypsum encompasses many strategic issues for IFA: materials reuse and recycling, safety and sustainability, lifecycle, storage, technical opportunities and new business models, as well as stakeholder engagement and social licensing. These are areas where expertise-sharing from worldwide producers, associations and research institutes is valuable and much needed. It is clear reputationally that in the past we have as an industry risked doing more reputational damage to ourselves by not addressing the phosphogypsum issue directly than by doing so transparently. This is why phosphogypsum will be a strategic area of work for IFA's Technical Committee in 2014.

In conclusion, I would like to stress that our mission when working through our national, regional and international associations, is to raise the industry's profile and to promote

a positive and accurate image as well as the efforts we are undertaking to meet such challenges. As business leaders of the fertilizer sector, we know that challenges are a great source of inspiration and innovation to address risks and seek better fitted solutions. To this end, I invite you all to join the effort of building and promoting the fertilizer industry's reputational capital”.

The effort to which Mrs. Mete refers has been and is being made, as this Report richly demonstrates. The result is not just a gain in reputational capital but in an extensive expansion and consolidation of the aggregate knowledge base of the industry world-wide in PG applications. The product offering of the phosphate industry as a consequence now firmly includes PG as a co-product of phosphoric acid production.

LOOKING AHEAD AFRESH

Just how well constructed Esin Mete's 2014 agenda was can be measured by how well it has created a platform for looking ahead again in 2020. Now the SDGs she drew attention to are claiming more and more of industry's attention and companies are voluntarily reporting on their compliance. This Report in consequence addresses in detail the following priorities: Climate Action (SDG13), the Circular Economy, Including Reuse and Recycling of Secondary Resources, Lifecycle Analysis (LCA) and Materials Flow Analysis (MFA) (SDG 12.)

CLIMATE ACTION

How the phosphate industry best engages with climate action is still in its relatively early stages. As shown in the case studies one very exciting and promising direction to be followed for high volume uses of PG with a direct and quantifiable impact on climate action is the capacity of PG to be deployed as a substrate for planting fast-growing trees. These trees can sequester significant quantities of the Greenhouse Gas (GHG) carbon dioxide, CO₂ above ground with further CO₂ capture below ground in root mass and soil organic matter build-up. This contribution is set out in case study 1.1 based on an extensive engagement by Agrium now Nutrien. It shows that this approach is both environmentally and economically sound and sustainable. Other related opportunities of a similar nature are flagged up in PG2 for subsequent attention by IFA members.

THE CIRCULAR ECONOMY

Two related approaches to the circular economy are considered. The first is a pre-circular, “transitional” model (Fig. 1) of how the waste hierarchy acts as a bridge from the “linear” through the intermediate step of “refuse/rethink/redesign” to the circular economy and the second (Fig. 2) an “end-state” meta-schema of what circular economy means as a new, circular paradigm of continuous materials flows. Of critical significance is that materials in the circular economy remain within the boundaries of the system and do not leave as waste.

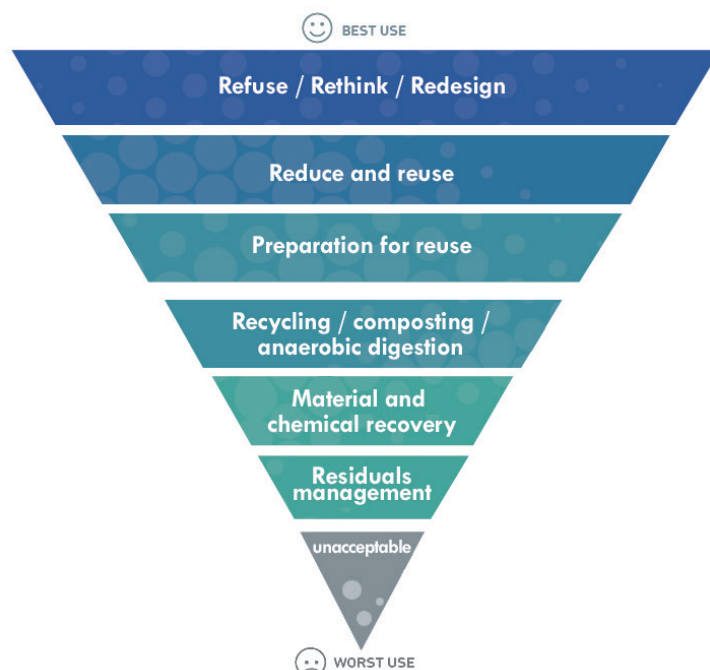


Fig. 1. Transitional: from residuals management to “refuse”, “rethink” and “redesign”

This fundamental shift in the nature of “waste” and its role within the resource management system is perhaps the most radical change demanded by the transition because it effectively takes the regulatory option to declare PG as waste *prima facie* off the table.

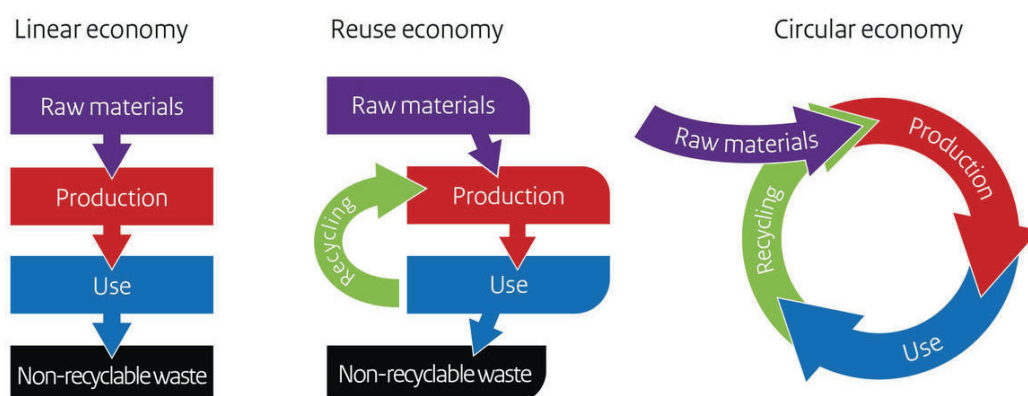


Fig. 2. Circular: meta-schema of the transition from a i. linear to a ii. reuse to a iii. circular economy

REUSE AND RECYCLING: INTERIM STORAGE AREAS AND REPROCESSING FACILITIES FOR PG

Transitioning from a linear to a circular economy affects as much our perceptions of the resources we use as the practices we engage in in using them. This leads in a formal sense to reclassifying them within a resource management regulatory code – in the case of PG from waste to co-product (or “anthropogenic resource”). Reclassification also requires other significant changes in nomenclature, such as how and where in future PG will be stored as a resource for reuse rather than disposed of in a “stack”.

An illustration of these renaming principles as applied to PG is a study commissioned by Fertilizers Europe for its PG-producing members concerning End of Life and End of Waste measures for both in-production and legacy PG, released in January 2019 [5]. By applying Full Cost Accounting procedures, as then required by the United States Environmental Protection Agency¹⁰, to PG “stacking” it concluded that the economic and environmental costs of PG “stacks” designed as disposal sites were unsustainable externalities and incompatible with circular economy objectives. These objectives are a)

10. For USEPA Full Cost Accounting model see <https://archive.epa.gov/wastes/conserve/tools/fca/web/html/what-is.html>

primary resource conservation through substitution of secondary resources and b) zero waste. PG disposal to land effectively sterilises a significant land area preventing it from providing future economic benefit and imposing an unwanted externality cost on future generations who, by definition, will not have been consulted during the decision-making that led to disposal [6].

As a starting point, in the circular economy PG is classified as a co-product of PA not a waste. Hence it is not for disposal or discharge. Quite the opposite, it remains within the system as a secondary resource or “reusable raw material”. This positioning aligns PG with the aims and objectives of the EU Circular Economy Action Plan and meets the underlying purpose of achieving End of Waste status as set out in that plan. This in turn aligns it with the fundamentals of the new EU Fertiliser Regulations [7].¹¹

An outcome of the reclassification process is to rename locations or facilities where PG is stored for the longer-term – which in view of the very high volumes produced in a small number of globally significant production facilities is an inevitable outcome for the local PG management strategy – as “interim storage areas” (ISA) or “interim storage facilities” [8] not “stacks”. Over the past 30 years PG stacks acquired the unfortunate status of waste dumps with significant negative consequences for social acceptance.

LIFE-CYCLE ASSESSMENT AND MATERIALS FLOW ANALYSIS

Life-cycle analysis and assessment (LCA), together with materials flow analysis, are essential tools for mapping how the hitherto “linear” pathway followed by PG from crystallisation in the wet process reactor, through filtration, to wet or dry stacking and disposal in stacks (for the linear model of materials flows see Fig. 3) can be converted into a reusable resource in the “circular” economy [8]. It supports the process of mapping and assessing both environmental and economic aspects associated with a product throughout its use.

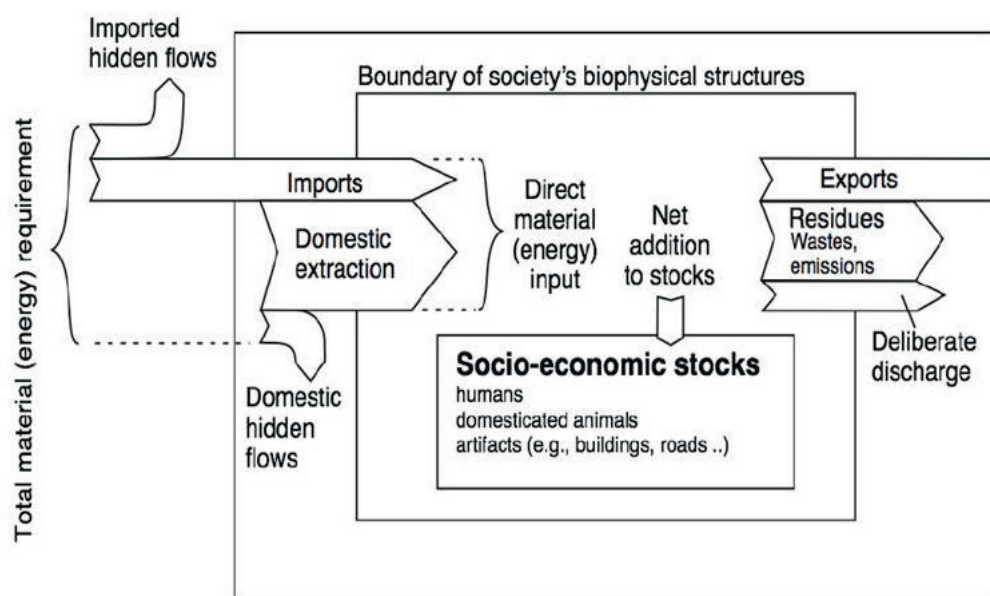


Fig. 3. Linear model of materials flows with “deliberate discharge” as waste

In a linear LCA model for PG (Fig. 3) there is likely to be at best one use and at worst no use at all. In an optimal circular economy (Fig. 2) the PG will be fully reused. Depending on what application for it is chosen, it may be reprocessed into something else, or be kept largely intact, as for example an anthrosol (see case study 1.1). As an anthrosol it a) remains intact but in productive use as a soil and b) is largely recoverable for a different use, as and when needed.

A typical LCA study may consist of one or more of four components:¹²

- 1. Scope definition and Terms of Reference:** define what parts of the product life cycle are to be included in the LCA and what purpose(s) the LCA serves.

11. See <https://www.consilium.europa.eu/en/press/press-releases/2019/05/21/eu-adopts-new-rules-on-fertilisers/>

12. See <https://www.iso.org/standard/37456.html>

2. Inventory analysis: inventory analysis assembles data from and a description of material and energy flows within the product system including its production process and technologies, source materials and inputs, outputs and emissions to the environment, energy resources and balances.

3. Impact assessment: The outcomes from the execution of the processes of production and use whether in terms of materials or economic performance or environmental and social impact, including externalities [8], is quantified and categorised by normalization and as needed by relative weighting.

4. Interpretation: LCA interpretation involves critical / independent review and peer-review, determination of data sensitivity, and findings.

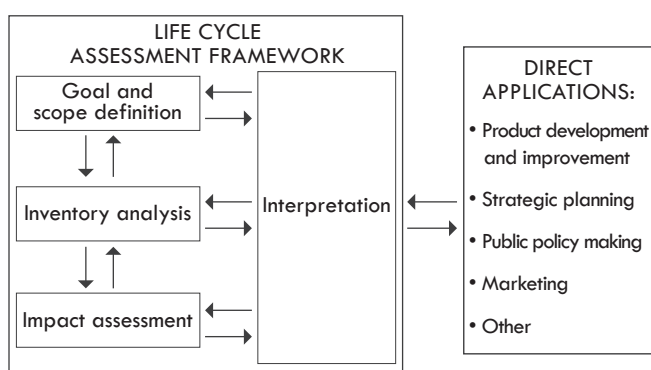


Fig. 4. Stages of a Lifecycle Analysis (LCA), EN ISO 14040

Fig. 4 above shows these aspects aligned to ISO 14040 guidelines [9].

The burdens imposed on the environment by human activities may be ascertained by accounting for the resources and energy (inputs) consumed at each stage in the life cycle of a product and the resulting pollutants and wastes (outputs) emitted. The inputs and outputs are then assessed for their adverse impacts on long-term sustainability of renewable and nonrenewable resources, human health, and biodiversity, amongst others. Once these are known, measures may be taken to mitigate the impact of the outputs (or inventories) on the environment. As an example, a full LCA done by the IAEA SR 78 team led to the regulatory finding in SR 78 that use not disposal to land or sea was a preferable environmental-economic outcome for PG [2].

RELATED OBJECTIVES FOR PG2

In addition to approving the development and publication of PG2, including a draft Table of Contents which has guided the drafting of PG2 throughout, the Phosphogypsum / NORM Working Group (PGNWG) meeting in Madrid agreed three main related objectives for PG2¹³, each of which has shaped the development of this Report. These are contributing to:

1. Enhanced communication of the new PG Narrative
2. Template for Quality Protocols for sustainable PG Management and Use as required by circular economy policy
3. Removing Barriers to Market Participation, including confidence building among stakeholders and investors.

QUALITY PROTOCOLS FOR SUSTAINABLE PG MANAGEMENT AND USE

At the April 2018 meeting PGNWG members agreed to develop and pilot a set of independent, peer-reviewed, Quality Protocols (QP) (i.e. models of good practice) for sustainable PG management and use. These QPs will be a key component of the communications and engagement strategy with both regulators and end users, as well as enabling the process of achieving End of Waste certification for PG in jurisdictions such as many EU countries where PG remains classed as a “waste” whether hazardous or non-hazardous. It was agreed this task would be undertaken with three international agencies, the United Nations Economic Commission (Geneva), the United Nations University and the IAEA (Vienna).

The goal of the engagement strategy between operators and regulators is to agree and implement a partnership strategy for classification of PG at a minimum as a “reusable raw material”. The eventual objective is 100% use both of currently produced PG and legacy holdings as found around the world in more than 50 countries. It also implements a key finding of IAEA SR78 which encourages regulators to be proactive in working with operators in this way [2].

THE QUALITY PROTOCOL AND THE SAFETY DATA SHEET

A credible PG Quality Protocol by PG use or application type will be grounded in a companion Safety Data Sheet¹⁴ (SDS) to accompany the registration and eventual application of shipped product.

QUALITY PROTOCOL STRUCTURE, TABLE OF CONTENTS AND EVIDENCE BASE

The QP consists at a minimum of four narrative sections, four appendices and a six-step drafting and maintenance process as follows:

13. See also IFA PGNWG Meeting Notes, Madrid, April 9 and 14, 2018

14. The 16-part format for the SDS according to UN standards agreed for use from 2016 may be found at <https://www.osha.gov/Publications/OSHA3514.html>

- 1. Process Description:** What is PG and how is it made?
Introduction to wet process PA and PG Production
- 2. Options for Use:** PG may be either a) reused “as is” ie little or no reprocessing or b) recycled eg by reprocessing into ammonium sulphate and calcium carbonate, sulphur rich fertiliser products such as Zypmite, or new soils (anthrosols)
- 3. Evidence of Performance and Impact:** Evidence that proposed uses conform to the stated characterisation, safety and performance data in the QP
- 4. Case studies/ Reference cases:** Worked examples specific to a company’s PG.

DRAFTING REQUIREMENTS FOR ALL QUALITY PROTOCOLS USED FOR END OF WASTE CERTIFICATION

The following components of a Quality Protocol for preparing the case for need to be included:

1. Assess if your material is currently classified as waste
2. Applicable waste management control rules
3. Relevant non-waste product rules
4. Requirements for imports and exports including permits and licences
5. Monitoring and updating the QP
6. Partnership with Environmental Regulators.

ACCEPTANCE CRITERIA

For meeting acceptance of reaching EOW status three primary conditions must be demonstrated, with supporting, independently validated evidence:

1. Is the PG application safe for use to both humans and the environment?
2. Is there an existing or likely market for use?
3. Does use contribute to objectives such as waste reduction/ zero waste, transition to the circular economy and SDG12 objectives “sustainable production and consumption”?
4. The Quality Protocol narrative and evidence-base as demonstrated in the references and peer review process must demonstrate that these three acceptance criteria have been met and will be kept under periodic review.

APPENDICES

The narrative is to be complemented by four appendices:

- Appendix A:** Definitions
- Appendix B:** Industry production standards and quality controls
- Appendix C:** Normalised classification of PG according to graded approach in respect of a) radionuclide and b) heavy metal content (Fig. 5)
- Appendix D:** Good practices in the storage, handling and use of PG.

THE GRADED APPROACH

IAEA defines the graded approach as: “A structured method by which the stringency of control to be applied to a product or process is commensurate with the risk associated with a loss of control” [3].

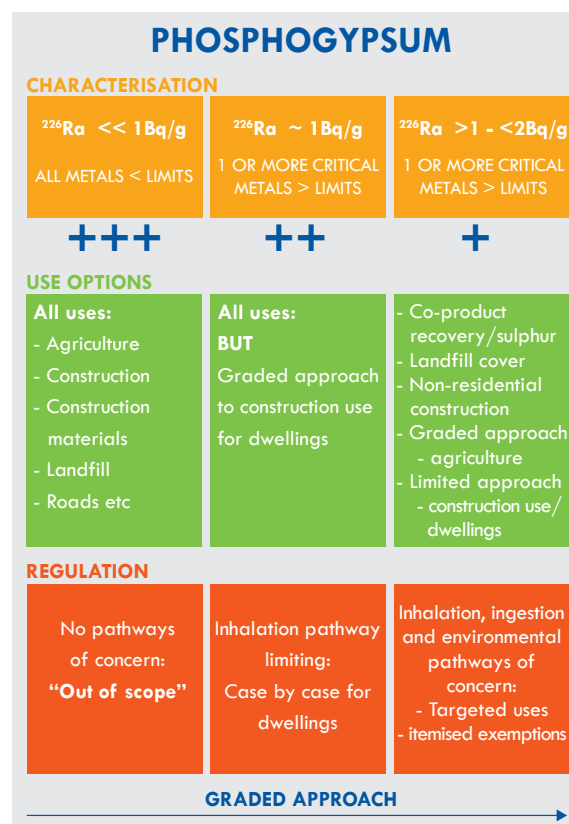


Fig. 5. The Graded Approach to categorisation of PG use type

In the case of PG as a NORM residue, application of the graded approach will, depending on the findings of protocol-based, peer-reviewed characterisation studies, result in three regulatory options (Fig. 5):

1. Out of Scope of Regulation: use is unrestricted for any given application subject to ongoing monitoring that the PG in use is consistent with characterisation as recorded in the Safety Data Sheet (SDS)
2. Authorised for general uses but with Restrictions for some applications (eg use for domestic dwellings)
3. Authorised subject to a range of application-specific restrictions, requiring either notification (lower risk categories) or licensing (higher risk applications).

THE 2018-19 MEMBER PG SURVEY

When the 2018-19 Member PG Survey was launched it was not expected that such a rich and comprehensive set of member company contributions to PG2 would be made. Hence the focus of PG2 has naturally pivoted to actual projects and initiatives implemented by member companies, each of which has indicative value for where and how to scale-up both tested high-volume uses and also new product development.

But thanks to the survey responses received, and with some supplemental information from public sources, a comprehensive inventory is forming of resource classification, regulatory context and policy trends by country with some related metrics on PG annual tonnages and % use trends by major application type (see Table 1 for current state of Summary). These application types map across to the case studies in Section 2 such that producers interested to pilot such uses can be confident they have reference examples to follow, both for execution and evaluation. This in turn will provide a rich source of reference for compiling both Safety Data Sheets and Quality Protocols for the future.

An important way to build confidence between regulators and operators is to demonstrate that Good Practices in PG

TABLE 1.
SOME PG USE, APPLICATION TYPE, POLICY AND REGULATORY TRENDS
- STATUS AS OF 2020¹⁵

	PRIMARY USES C: COMMERCIAL P: PILOT	kt PG/y	~% USE	USE R&D NPD	PG CLASSIFICATION / REGULATIONS
BELGIUM	Agriculture (C)	5	~5	✓	Permitted soil amendment – used for its water retention qualities.
	Biodiversity		~95		Recent awareness of contribution of PG as promoter of bio-diversity.
	Plaster (C)			✓	REUSABLE RAW MATERIAL (42-year commercial history) – but deliberate ambiguity. <ul style="list-style-type: none"> - AGW - 16/01/2014 - Conditions sectorielles relatives à certaines activités générant des conséquences importantes pour l'environnement - AGW - 04/07/2002 - Conditions générales d'exploitation des établissements visés par le décret du 11 mars 1999 relatif au permis d'environnement - Code de l'Environnement - Livre I: Partie réglementaire - Code de l'environnement : Livre II - Code de l'eau - Permis unique du 19/08/2015 D3200/61080/RGPED/2015/2/AU/ss-PU pour renouveler l'autorisation d'exploiter CET - AGW du 27/02/2003 fixant les conditions sectorielles d'exploitation des centres d'enfouissement technique - AGW - 13/12/2007 - Obligation de notification périodique de données environnementales - AGW - 18/03/2004 - Interdisant la mise en centre d'enfouissement technique de certains déchets. - AGW-14/06/2001 favorisant la valorisation de certains déchets

15. Sources: IFA Member Survey responses, PG 2 Case Studies, public domain

management and use have already been developed by IFA member companies, showing common attributes across all producing countries. This in turn has increased member confidence to share these practices amongst each other, indicating that the option is now available to convert some of these into standards and specifications as the natural, operational complements to the Safety Data Sheet and the Quality Protocol.

Because policy and regulatory issues concern national or regional sovereignty, content of Table 1 is arranged a) by country and b) with additional information from UN bodies, notably the regional Economic Commissions and the International Atomic Energy Agency (IAEA). Much needs to be done to harmonise these regulations which still unfortunately mean that PG when crossing borders can also change its classification status, in the process affecting its potential for use. With UN support however, there are tested ways of achieving such harmonisation if the decision is taken by IFA Member Companies to proceed that way.

With policy drivers such as zero waste and circular economy in mind, it seems likely by one means or another that the goal now expected of producers in China of 100% will be progressively adopted everywhere else.

PG USE PARTNERSHIPS	POLICY REGULATORY TREND	MARKET BARRIERS REGULATORY COMMERCIAL
<div>✓</div> <hr/> <div>✓</div>	<p>Partnership with Regulator within clear and agreed Terms of Reference. Though with ambiguity:</p> <p><i>“Non-hazardous waste when disposed of. Status of gypsum produced not officially defined at the production site. In 1995 the authorities acknowledged in a written document that calcium sulphate for the use in cement and plaster industry was not to be considered as waste. At the same time, we have an authorization for valorizing the gypsum in the cement and plaster industry, which implies a waste status.”</i></p> <p>PG Use requires permit for each use type.</p> <p>Permitting system in place for PG storage.</p> <p>Permit renewed in 2015 – runs to 2035.</p> <p>No HDPE liner required for storage.</p> <p>Bio-diversity dividend a major plus point.</p>	<p>Meeting Knauf product acceptance criteria only major issue.</p> <p>Recognising and overcoming constraints seen as stimulus to creativity and NPD.</p> <p>AGW favorisant la valorisation de certains déchets, «Plan wallon des déchets, et démarche en cours pour reconnaissance des by-products » / Walloon Plan in development by local authority on “valorisation of waste and by-products”.</p>

	PRIMARY USES C: COMMERCIAL P: PILOT	kt PG/y	~% USE	USE R&D NPD	PG CLASSIFICATION / REGULATIONS
BRAZIL	Agriculture (C)	10,000	85	✓	COMISSÃO NACIONAL DE ENERGIA NUCLEAR, Resolução No. 171 De 30 De Abril 2014, [10]
	Cement (C)		100	✓	
CANADA	Growth media (anthrosol) (P)	PA production stopped Legacy PG only		✓	REUSABLE RAW MATERIAL Health Canada Guidelines for Management of NORM ¹⁷ No restrictions on PG, subject to compliance with NORM industry diffusion and release guidelines.
	Forestry (C)			✓	
	Biodiversity				
	Cement (P)			✓	
CHINA	Agriculture	79,000	40		Non-hazardous waste. Environmental Protection Law of the People's Republic of China. Date: latest version this law comes into effect on Jan. 1st, 2015.
	Cement (C) (P)			✓	
	Construction (C)			✓	
	Fertiliser (C)			✓	
	Mine backfill			✓	
E.U.					REUSABLE RAW MATERIAL (if End of Waste ¹⁹ status can be shown)
FINLAND	Agriculture (P)				COMMON WASTE Environmental permit which is applicable for Siilinjärvi site (this includes also PG stacking regulations) - Environmental law (Ympäristönsuojelulaki 527/2014), - Waste law (Jätelaki 834/2017) - Landfill directive (Kaatopaikka asetus (331/2013))
	Forestry (P)				
	Road Building/ Embankment (P) ²¹				
	Road Building/ Embankment (P) ²²				
	Environmental (P)				

16. https://www.canada.ca/content/dam/hc-sc/migration/hc-sc/ewh-semt/alt_formats/pdf/pubs/contaminants/norm-mrn/norm-mrn-eng.pdf

17. <https://www.esaa.org/wp-content/uploads/2017/10/17-Nichol.pdf>
https://emerald.foundation.ca/aef_awards/afforestation-and-beneficial-use-of-phosphogypsum-stacks/
https://tspace.library.utoronto.ca/bitstream/1807/76065/3/Walawalkar_Mugdha_201611_MAS_thesis.pdf

18. Builds on successful PG road pilot funded by European Commission 1998-2001

	PRIMARY USES C: COMMERCIAL P: PILOT	kt PG/y	~% USE	USE R&D NPD	PG CLASSIFICATION / REGULATIONS
INDIA	Agriculture (C)	8270		✓	Atomic Energy Regulatory Board (AERB) ²³ AERB Directive 10/09 Central Pollution Control Board (CPCB) ²⁴ Phosphogypsum Guidelines (2015) [11] Product specifications - PG in plaster IS 12679 (1989): By-product gypsum for use in plaster, blocks and boards [CED 4: Building Limes and Gypsum Products]
	Cement (C)		62	✓	
	Construction			✓	
	Road building			✓	
	Soil Amendment			✓	
KAZAKHSTAN	Soil amendment (C)				NON-HAZARDOUS WASTE 1. Ecological Code of the Republic of Kazakhstan; 2. The Law of the Republic of Kazakhstan on technical regulation 3. The Law of the Republic of Kazakhstan on Consumer Protection 4. Safety requirements for fertilizers 5. ST RK 2208-2012 Phosphogypsum for agriculture. Technical conditions
MOROCCO	Agriculture - Soil amendment (P)	37,000-42,000		✓	HAZARDOUS WASTE Déchets des procédés de la chimie minérale : Déchets provenant de la fabrication, formulation, distribution et utilisation (FFDU) d'acides : acide phosphorique et acide phosphoreux
	- Fertiliser (P)				
	Roadbuilding			✓	
PHILIPPINES	Agriculture	1000			
	Cement (C)		50		
	REE & U recovery (P)			✓	

22. For AERB Directive No. 01/09 see <https://www.aerb.gov.in/english/acts-regulations/safety-directives>

23. CPCB Guidelines for PG Use <http://www.indiaenvironmentportal.org.in/content/395562/guidelines-for-management-and-handling-of-phosphogypsum-generated-from-phosphoric-acid-plants-final-draft/>

PG USE PARTNERSHIPS	POLICY REGULATORY TREND	MARKET BARRIERS REGULATORY COMMERCIAL
	India at aggregate 77% of annual PG production used (8.27mt produced, 6.96mt used) with 100% target in view. Cement is 62% of use, agriculture 7%. Balance – a range of uses. S-deficient soil seen as major opportunity for growth.	Unrestricted but requires regular monitoring and testing (soil sampling, leachate in case of run off)
		Subject to regulatory specifications Commercial – costs of transport; logistical bottlenecks
✓		Subject to regulatory specifications.
		Subject to regulatory specifications. Major opportunity for use on S-deficient soils.
	In active planning for extending application types/ use. Phosphogypsum is classified by hazard class 5 hazard class, i.e. not dangerous (conclusion of the Republican SES ST RK 2208-2012)	Established use as soil amendment severely restricted by transport costs.
		Market uptake inhibited by: <ul style="list-style-type: none"> - High costs of transport (road and rail) lack of investment - lack of commercial partners Major opportunity: <ul style="list-style-type: none"> - use in road construction
✓	PG STORAGE No specific national regulations for the storage of phosphogypsum.	First pilot tests successful. Major opportunity for use on: <ul style="list-style-type: none"> - S-deficient soils - sodic/ saline soils - physically degraded soils (erosion/ desertification)
✓	FOR HAZARDOUS WASTE: <ul style="list-style-type: none"> - Décret n° 2-07-253 du 18 juillet 2008 portant classification des déchets et fixant la liste des déchets dangereux. - Décret n° 2-09-284 du 8 décembre 2009 fixant les procédures administratives et les prescriptions techniques relatives aux décharges contrôlées. 	First pilot tests successful. Major opportunity for use on wide use of road types.
✓	New (2019) regulatory restrictions on PG import for wall board manufacture (radiological concerns)	
✓		

POLAND

RUSSIAN FEDERATION

PRIMARY USES C: COMMERCIAL P: PILOT	kt PG/y	~% USE	USE R&D NPD	PG CLASSIFICATION / REGULATIONS
		✓		NON-HAZARDOUS WASTE National legislation (available only in Polish language): - Act of 14 December 2012 on Waste. (Dz.U. 2018 poz.992 t.i)23, - Regulation of the Minister of Environment of 30 April 2013 on the Landfill of Waste (Dz.U. 2013. 523)24, - Regulation of the Minister of Economy of 16 July 2015 on the criteria of approval of waste for storage on the land fill (Dz.U.2015.1277)25, - Act of 27 April 2001 Environmental Protection Law (Dz.U.2018.799 t.i.)26, - Regulation of the Minister of Environment of 9 December 2014 on waste catalogue (Dz.U. 2014.1923)27, - Company internal regulation e.g. Integrated Permit and Landfill Manual.
Agriculture		2%	✓	NON-HAZARDOUS WASTE ²⁸
Soil amendment (C)				- Federal law of 10.01.2002 N 7-FZ «On environmental protection» - Federal law of 24.06.1998 N 89-FZ «On wastes of production and consumption» - Resolution of the Government of the Russian Federation of 03.10.2015 N 1062 «On licensing activities for the collection, transportation, processing, disposal, disposal of waste of I-IV hazard classes» - Resolution of the Government of the Russian Federation of 16.08.2013 N 712 «About the order of carrying out certification of waste of I-IV classes of danger» - Resolution of the Government of the Russian Federation of 13.09.2016 N 913 «On rates of payment for negative impact on the environment and additional coefficients» - The order of the Ministry of natural resources of Russia of 30.09.2011 N 792 «About the statement of the Order of maintaining the state inventory of waste» - The order of the Ministry of natural resources of the Russian Federation of 25.02.2010 N 49 «About the approval of Rules of inventory of objects of placement of waste» - The order of the Ministry of natural resources of Russia of 25.02.2010 N 50 «About the Order of development and the approval of standards of formation of waste and limits on their placement» - The order of the Ministry of natural resources of Russia of 04.12.2014 N 536 «About the approval of Criteria of reference of waste to I-V classes of danger on degree of negative impact on environment» - The order of the Ministry of Russia from 04.03.2016 N 66 «On the Procedure for owners of waste disposal facilities, and persons in possession or in use of which the objects of waste disposal, monitoring of condition and pollution of the environment in the territories of waste disposal facilities and the extent of their impact on the environment» - The order of the Ministry of natural resources of Russia of 01.09.2011 N 721 «About the statement of the accounting Procedure in the field of the waste management»
Roadbuilding (C)			✓	

24. <http://prawo.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20180000992>

25. <http://prawo.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20130000523>

26. <http://prawo.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20150001277>

27. <http://prawo.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20180000799>

28. <http://prawo.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20140001923>

29. Федеральный закон от 10.01.2002 N 7-ФЗ «Об охране окружающей среды»

Федеральный закон от 24.06.1998 N 89-ФЗ «Об отходах производства и потребления»

Постановление Правительства РФ от 03.10.2015 N 1062 «О лицензировании деятельности по сбору, транспортированию, обработке, утилизации, обезвреживанию, размещению отходов I - IV классов опасности»

PG USE PARTNERSHIPS	POLICY REGULATORY TREND	MARKET BARRIERS REGULATORY COMMERCIAL
	<p>Signs of regulatory climate easing.</p> <p>Permit granted 2019 for use of 5- 10kt/y for R&D into specific uses, eg soil amendment.</p> <p>Use requires permit for each use type</p>	<p>Classification as waste requires permits for each application type and inhibits market uptake.</p> <p>Transport also has restrictions.</p> <p>Working to change “waste” classification into “by-product” for 5-10 thousand t of PG/year. Recently agreed for R&D purposes.</p>
✓	<p>PG use subsidy in agriculture reinstated early 2020. 100% of farmer cost including transport (some regions) reimbursed</p> <p>Government approved as roadbuilding material</p>	<p>Established use as soil amendment severely restricted by transport costs.</p> <p>Market uptake inhibited by:</p> <ul style="list-style-type: none"> - High costs of transport (road and rail) lack of investment - lack of commercial partners <p>Major opportunity:</p> <ul style="list-style-type: none"> - use in road construction <p>Successful completion of pilot studies. Scale-up potential</p>

Постановление Правительства РФ от 16.08.2013 N 712 «О порядке проведения паспортизации отходов I - IV классов опасности»
Постановление Правительства РФ от 13.09.2016 N 913 «О ставках платы за негативное воздействие на окружающую среду и дополнительных коэффициентах»
Приказ Минприроды России от 30.09.2011 N 792 «Об утверждении Порядка ведения государственного кадастра отходов»
Приказ Минприроды РФ от 25.02.2010 N 49 «Об утверждении Правил инвентаризации объектов размещения отходов»
Приказ Минприроды России от 25.02.2010 N 50 «О Порядке разработки и утверждения нормативов образования отходов и лимитов на их размещение»
Приказ Минприроды России от 04.12.2014 N 536 «Об утверждении Критериев отнесения отходов к I - V классам опасности по степени негативного воздействия на окружающую среду»
Приказ Минприроды России от 04.03.2016 N 66 «О Порядке проведения собственниками объектов размещения отходов, а также лицами, во владении или в пользовании которых находятся объекты размещения отходов, мониторинга состояния и загрязнения окружающей среды на территориях объектов размещения отходов и в пределах их воздействия на окружающую среду»
Приказ Минприроды России от 01.09.2011 N 721 «Об утверждении Порядка учета в области обращения с отходами»

	PRIMARY USES C: COMMERCIAL P: PILOT	kt PG/y	~% USE	USE R&D NPD	PG CLASSIFICATION / REGULATIONS
UN					ANTHROPOGENIC RESOURCE
UNITED STATES	Agriculture (C) Cement Petition to exempt (Nov 2019) Road building Petition to exempt (Nov 2019) Mine backfill	32,000			UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, National Emissions Standard for Hazardous Air Pollutants (NEHSAP) Subpart R. [13] HAZARDOUS WASTE (ON RADIOLOGICAL GROUNDS) AS DEFINED IN PHOSPHOGYPSUM RULE [17]³² Exemption under permitting conditions for agriculture in SE US if below 0.37 Bq/g activity concentration. Annual sampling and characterisation requirement
IAEA					CO-PRODUCT Basic Safety Standards (2014) [4] IAEA Safety Report 78 [7] No radiological grounds to prevent use Principle of proportionality to apply through “graded approach” [8] by use type and use context (social and environmental considerations)
UN					ANTHROPOGENIC RESOURCE

30. United Nations Economic Commission for Europe <https://www.unece.org/energy/welcome/areas-of-work/unfc-and-sustainable-resource-management/applications/unfc-and-anthropogenic-resources.html>

31. United States Environmental Protection Agency, UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, National Emissions Standard for Hazardous Air Pollutants (NEHSAP) Subpart R, National Emission Standards for Radon Emissions from Phosphogypsum Stacks (revised 1992), EPA, Washington, DC (1992)

32. United Nations Economic Commission for Europe, <https://www.unece.org/energy/welcome/areas-of-work/unfc-and-sustainable-resource-management/applications/unfc-and-anthropogenic-resources.html>

**PG USE
PARTNERSHIPS**

POLICY REGULATORY TREND

**MARKET BARRIERS
REGULATORY
COMMERCIAL**



Reclassified in UNFC as Anthropogenic resource (UNFC Guidelines, 2019) [12]³¹

Established use as soil amendment severely restricted by transport costs.

Market uptake inhibited by:

- High costs of transport (road and rail) lack of investment
- lack of commercial partners

Major opportunity:

- use in road construction

MANDATORY STACKING

Phosphogypsum Rule subject to Petition for limited exemptions for use in a) cement and b) road building.

Mandatory use requirements may be of benefit as market and NPD stimulus

Mine backfill in N Carolina (Aurora) permitted, Can be seen as Interim PG storage facility – PG available for future use.

Storage must ensure public and environmental health and safety.

Use environmentally preferable to disposal whether to land or sea.

Engagement with potential contribution of high-volume PG use for:

- CO₂ sequestration/climate action
- Combating desertification/ deforestation

Reclassified as anthropogenic resource within FEW resource nexus [13]³³

Engagement with potential contribution of high-volume PG use for:

- CO₂ sequestration/climate action (SDG 13)
- Combating desertification/deforestation (SDG 12)



INNOVATION

1. CASE STUDIES: AGRICULTURE

As recorded in PG 1 [1] the primary areas for PG reuse worldwide are for agriculture, construction / construction materials and roads. Several IFA member companies have given detailed consideration to the development of PG reuse in one or more of these areas and have documented their approach in the following case studies. While the editorial process has harmonised approaches across the contributions, regional needs and local working cultural practices have been respected as presented in the original unedited contributions. There is evidence throughout the case studies of the major investment being made in developing good practices, whether in company policy formation or the science-based implementation of the case studies. No attempt has yet been made to normalise the many good practices in evidence into a single, uniform standard for formal accreditation in due course. Such a process can now be initiated but it will be for IFA members to determine when they wish to undertake that next step.

Phosphogypsum has been intensively studied for use in agriculture since the 1980s, notably in the United States funded and part-led by the Florida Industrial and Phosphate Research Institute (FIPRI) and in Brazil, supported by a coalition of interest between government agencies including federal and state-level regulators, academia and industry. An excellent summary of US work on agricultural applications was provided by Alcordo and Rechcigl in 1993 [14].

S is now recognised as a key macro-nutrient along with N, P and K as increasing areas of the world's soils suffer from S-deficiency. PG is a good source of S and Ca for crops, a conditioner for sodic and clay soils, an ameliorant for subsoil aluminium toxicity but also provides significant gains in water use efficiency in irrigated systems. Research has been conducted worldwide on successful PG application more than 50 major crops in a wide variety of climates and on a wide variety of soils. Since 2018 PG is being increasingly used as a feedstock for innovation in affordable S-rich fertilizers, such as Zypmite (see case study 4.3.4 below).

The first evidence-based study of PG uses in agriculture from a radiological and wider environmental perspective was conducted in south-west Spain 2000-2005 under the leadership of Prof. Rafael García Tenorio and his team from the universities of Seville and Huelva [15]. PG was first used in the 1950s as an anthrosol to reclaim large areas of land from the salt marshes from the delta of the Guadalquivir for crop production. It has since become one of the most productive agricultural areas in Europe. Details of the Tenorio team's work may be found in IAEA SR 78 Section 10.5.1. [2] which also provides a more general summary of research conducted under scientific conditions of PG applications in agriculture. PG1 Section 3 also presents a wide range of agricultural applications.

The following case studies and high-level overviews of PG use in agriculture and forestry from Brazil, Canada, India, Kazakhstan, Morocco and Russia offer detailed perspectives regarding the use of PG for agriculture in those countries. As indicated above a "light touch" approach has been taken to copy-editing, respecting the tone and style of the original submissions.

1.1 AFFORESTATION AND THE PG ANTHROSOL: CANADA

AUTHOR

Connie Nichol began working at Agrium in 1995 and is a long-standing member of the IFA PG WG. Connie is passionate about phosphogypsum education and regularly gives presentations to employees, community groups, and university classes. In 2010, she created an informative and entertaining video, *The Story of Phosphogypsum* which has been significantly updated in 2020. The video can be viewed at <https://vimeo.com/392091921/5ec1339ac7>. Connie has a BSc in Agriculture and a PhD in Soil Chemistry from the University of Alberta. She taught as a sessional instructor at the University of Alberta between 2007 and 2014, developing a fourth-year land reclamation course on waste management and utilization.

1.1.1 BACKGROUND

Nutrien (formerly Agrium) has two PG storage facilities in Canada, of which one is located in Fort Saskatchewan, Alberta where phosphate fertilizer was produced by a predecessor company between 1965 and 1991. Approximately 5 million tonnes of PG were produced during that period. The PG storage area is approximately 32 ha and approximately half of this area is currently reclaimed. Agrium acquired these PG resources as part of another

business deal in 1996.

Nutrien's second, much larger, Canadian PG storage area is located near Redwater, Alberta. Phosphate fertilizer was produced in this location for 50 years, resulting in a legacy output of ~ 50 mt PG covering an area of ~275 hectares. Phosphate fertilizer production was shut down in April 2019 and therefore, all of this PG storage area must be reclaimed in the near future.

Agrium spent some time examining PG reuse opportunities in the '80s and '90s and developed Material Safety Data Sheets (MSDS) sheets for the use of their PG by-product (see Appendix 2). PG was used variously as a soil amendment for sodic soils, an additive in composting manure and for oil sands tailing remediation, but only in small-scale trials and demonstrations. Historically, PG use in Canada was neither encouraged nor prohibited, and is not subject to any regulations other than Health Canada Guidelines which outline the release limits for diffuse NORM materials.

Phosphogypsum was never promoted as a product at Agrium and the focus of the company in the early 2000s changed from PG reuse to PG "reclamation" *in situ* ie at the storage site itself. Agrium still provides PG to local farmers for use in dairy barn bedding or for soil amendment upon request but is not actively developing reuse markets.

1.1.2 REGULATORY CONTEXT

There are no government regulatory requirements or standard methods for reclaiming PG stacks in Alberta or in Canada. The default reclamation scenario in Alberta is to essentially treat the stacks as landfills and cover them with 1 m of soil material at closure. Agrium argued that this depth of soil was unnecessary for reclamation success or environmental protection. Research in Florida, sponsored by the Florida Industrial and Phosphate Research Institute (FIPR), has shown that excellent vegetation cover can be established directly on phosphogypsum if the pH is raised above 4.0 and if nitrogen, potassium and magnesium nutrients are supplied³³. Studies on the Redwater PG stack in 2001 confirmed this finding and shown that only very small amounts of soil amendment are required to encourage healthy and vigorous vegetation growth on gypsum that is leached of acidic process water.

The provincial regulator agreed to let Agrium conduct research to determine the optimum reclamation strategy and instructed Agrium to identify the key factors that need to be investigated prior to finalizing a reclamation plan. These factors included designing an End of Life (EOL) cover which would perform several environmental protection functions

33. Establishing Vegetation Cover on Phosphogypsum in Florida, December 1995. FIPR Publication No. #89-01-086.

including:

- providing a suitable substrate for vegetation growth
- minimizing infiltration and downward migration of - potential contaminants from the phosphogypsum stack
- attenuating radon gas and gamma radiation emanation from the phosphogypsum stack
- minimizing wind and water erosion from the phosphogypsum stack
- minimizing exposure pathways between potential receptors and the phosphogypsum material
- providing a self-sustaining EOL design.

1.1.3 COLLABORATION WITH UNIVERSITY OF ALBERTA

In 2005, Agrium began a collaborative reclamation research program with the University of Alberta, Department of Land Reclamation. Over the years, they have worked with different soil science, reclamation and forestry professors, depending on what area of research they require expertise in. Although Agrium had done previous reclamation research themselves on the Redwater PG stack, it was not perceived by the regulator to be robust and unbiased, hence the need for collaborative projects with independent external organizations.

In the last thirteen years, seven students have earned their MSc degrees working on different aspects of this project³⁴. Initially research projects examined the depth of soil needed to cover the PG stacks and what grasses to seed. But over time it became apparent that it was beneficial to mix soil into the gypsum rather than using a barrier approach to reclamation. Once soil was mixed into the gypsum and the rooting depth of vegetation was no longer an important consideration, growing trees could be considered and this created the possibility of reducing long term maintenance costs and sequestering carbon dioxide to combat climate change.

Nutrien has provided technical and financial support to the university students as well as serving on their advisory committees. It costs approximately \$50,000 a year to support a graduate student and run the research program. This covers the student stipend, analytical and equipment costs, vehicle allowance and university overhead. The students have enjoyed the opportunity to work on an industrial plant site while helping create innovative solutions to a real-world problem.

In 2014, the Canadian Forest Service joined the collaboration to provide expertise on applying short rotation woody crop systems to industrial sites. Nutrien is currently supporting an eighth University of Alberta M.Sc. student who is working on assessing the hydrological balance of a forested PG stack. This student will measure infiltration, run-off, evapotranspiration and examine rooting habits of the trees and model different inputs to determine the long-term water balance.

The results of the research projects are widely shared through presentations at forestry, industry and reclamation meetings and workshops as well as publication in newsletters, journals and theses. Presentations regarding the collaborative PG reclamation research have been given at meetings of the International Fertilizer Association (IFA), Soil Science of America, Canadian Land Reclamation Association, Remtech and Soil Science Workshops. Publication has occurred in refereed journals such as the Journal of Environmental Quality and the Canadian Journal of Soil Science, Logging and Sawmill Journal as well as community and industry reports and local newspapers. The forested gypsum stacks have also been frequently toured by individuals, community groups and the Canadian Land Reclamation Association (CLRA) as part of their 2015 summer tour.

1.1.3.1 LESSONS LEARNED FROM WORKING WITH INDEPENDENT SCIENTIFIC PARTNERS

Collaborating with universities or other external organizations is a really good idea to answer any sort of research question or to test an innovative approach for PG reuse or reclamation. It benefits both the fertilizer company and the university. The fertilizer company obtains unbiased statistically verifiable results from a dedicated researcher and access to different areas of expertise and equipment for a relatively small amount of money. The university and graduate student gain experience working on an industrial plant site solving a real-world problem. They enjoy this immensely and it gives the student valuable skills towards finding a job once they graduate.

As much as possible, get to know people in different disciplines by getting out in the community and going to workshops, lectures and conferences. This is where new ideas and ways of looking at things can come from as

34. Here are links to recent presentations and MSc theses:
<https://www.esaa.org/wp-content/uploads/2017/10/17-Nichol.pdf>
https://emerald.foundation.ca/aeef_awards/afforestation-and-beneficial-use-of-phosphogypsum-stacks/
<https://era.library.ualberta.ca/items/b57259a7-1f24-45bf-b022-8d21048cad88>
<https://era.library.ualberta.ca/items/92037285-9602-48a1-9d92-3302f485e807>
<https://era.library.ualberta.ca/items/3537fbc4-d862-43f5-b222-4c07480543ad>
<https://era.library.ualberta.ca/items/f92c2a19-8068-43dc-bc9f-6c3c8792805b>
<https://era.library.ualberta.ca/items/f60ecfb4-cff8-45a8-86ea-62f074bf0109>

well as opening up possibilities for future collaborations. It takes time to conduct research, and you cannot look too far ahead. Results from one experiment will guide the next project and results are often surprising. Be willing to think ‘out of the box’ and try new ideas.

1.1.4 BENEFICIAL USE OF PG RESOURCES *IN SITU*

PG resources in North America are classified as wastes, or waste by-product, with disposal to land as the End of Life plan. Reclamation of disposal facilities (stacks) involves contouring the piles, covering with soil and seeding to a grass mixture.

Nutrien began conducting research into alternative methods of reclamation in 2005 and with help from the University of Alberta and the Canadian Forest Service discovered that rather than the usual method of covering the gypsum stacks with a layer of soil to create a barrier, reclamation procedures could be improved by mixing soil into the phosphogypsum (PG) to create a high-performance “Anthrosol”.

PG/soil mixes have been shown to result in greater vegetation health and biomass over plants grown in soil alone. Concentrated tree plantations can then be established in the PG/soil seedbed. The project can be viewed as both an innovative approach to reclamation and a beneficial use of PG *in situ*. It also provides valuable data for the concept of creating ‘designer soil’ (anthrosol), especially in countries where agricultural resources are scarce or where there is significant pressure on, or conflict over land-use, for example close to highly populated urban areas.

Establishing a forest on top of PG storage facilities has many positive impacts on the environment including the fostering or reintroduction of biodiversity. The afforestation approach results directly in carbon, while producing biomass for energy production. Trees are also capable of phytoremediation of any excess nutrients and water within their rooting zone, thereby improving long-term groundwater quality. Field observations indicate that there is little or no water infiltration into the gypsum pile under the concentrated tree plantations in the semi-arid climate of the Canadian prairies. Tree plantations have already been established on 20 hectares of phosphogypsum (PG) at the Nutrien facility in Fort Saskatchewan, Alberta, Canada (Fig. 6, Fig. 7).



Fig. 6. Hybrid Poplar cuttings, 25 cm length
(Image courtesy Nutrien)



Fig. 7. Planting the cuttings on top of the PG stack
(Image courtesy Nutrien)

The trees grow extremely vigorously – see willow growth after nearly two growing seasons 2015 to September 2017 (Fig. 8); and between 2016 and September 2017 the hybrid poplar cultivar Tristis grew from an average height of 85 cm to 280 cm, a gain of almost 2 m height in a single year (Fig. 9). Many trees are over 5 m in height after three years of growth (Fig. 10).



Fig. 8. Willows Sept 2017 - almost two growing seasons
(Image courtesy Nutrien)



Fig. 10. Hybrid Poplar - ~three growing seasons
(Image courtesy Nutrien)



Fig. 9. Poplar - almost two growing seasons
(Image courtesy Nutrien)



Fig. 11. Canopy closure – willows after 3 years
(Image courtesy Nutrien)

Crown closure has been observed after less than three years (Fig. 11). This inhibits vegetation growth beneath the trees, with the site essentially left in a free-to-grow state without any need for maintenance. Trees are observed to be growing much faster on the gypsum stacks than the same trees growing on regular soil. This is likely because the PG has excellent water holding capacity and some residual plant nutrients.

The tree plantations established at Nutrien are predicted to sequester 30 t CO₂ equivalents/ha/y. Thus, in 20 y, the gypsum stack area reclaimed to date will sequester 12,000 t of CO₂ equivalents. This same area is also predicted to produce 10 oven dry t/ha/y of above-ground woody biomass. It is therefore, estimated that 4,000 green t will be produced in this area over the next 20 y. These numbers will continue to increase as Nutrien continues to reclaim and establish concentrated woody plantations on its PG stacks.

1.1.4.1 THE BUSINESS CASE

The economic benefits of afforestation can be substantial. Carbon credits are worth \$30/t in Alberta. 20 ha forested gypsum stack can potentially generate \$360,000 (Canadian) in C credits in 20 y. The cost of establishing a short rotation woody crop is approximately \$3,800/ha, therefore afforestation pays for itself in a few years. If desired, woody biomass could also be sold. Woody biomass is worth approximately \$50/t in Alberta. In terms of meeting the self-sustaining EOL outcome, once the trees close canopy, maintenance is essentially eliminated, so the reduction in maintenance and mowing costs compared to a grassed PG stack can be significant.

1.1.5 BIODIVERSITY INCREASE

Incorporating trees into the reclamation plan will also improve the long-term sustainability and ecosystem diversity of the gypsum stacks. Increased wildlife such as deer (Fig. 12), rabbits, foxes, small rodents and many birds have been observed in the forested areas.



Fig. 12. Wildlife habitat created in less than two growing seasons on PG anthrosol. Deer are regular visitors. (Image courtesy Nutrien)

1.1.6 ESTABLISHMENT AND MAINTENANCE OF AFFORESTATION PLANTATIONS

Nutrien follows the protocols developed by the Canadian Wood Fiber Center, Natural Resources Canada to develop high yield afforestation plantations that maximize biomass and carbon accumulation over the short to medium term. Typically, these types of plantation are established on moderate- to high-quality land across Canada but have proven to be very successful on the PG Anthrosol, comprising 80-90% PG and 10-20% soil.

In the prairie provinces of Canada, the primary tree species to be considered for high yield and carbon sequestration afforestation is hybrid poplar (*Populus* spp). Hybrid poplar plantations of 1100 – 1600 stems/ha produce yields of 13.6 – 20 m³ or 7.3 – 10.8 ODT (oven dried tonnes) ha/y of above ground woody biomass. The preliminary assessments of below and above ground carbon budgets estimate potential carbon increase of 500-650 t CO₂ eq/ha over a 20-year rotation, or 25 – 32.5 t CO₂ eq/ha/y. Hybrid willows (*Salix* spp) are also suitable for high yield and bioenergy development. Plantations of 15,625 stems/ha were designed to produce yields of 6 – 12 ODT (oven dried tonnes) ha/y of above ground woody biomass. Preliminary assessments of below and above ground carbon budgets estimate potential carbon increases of 14 – 28 t CO₂ eq/ha/y over 6-7 3y rotations.

Natural Resources Canada has also designed a mixed wood afforestation plantation using hybrid poplar and white spruce that is designed to maximize biomass accumulation, carbon sequestration and fibre production over both the medium (20 years) and long term (70 years) through the development of both hardwood and softwood crops. Preliminary assessments of below and above ground carbon budgets estimate potential carbon increases of 644-820 t CO₂ eq/ha/y over the 20- and 70-year rotations for the respective hardwood and softwood crops.

1.1.6.1 SEEDBED PREPARATION

Approximately 15 cm of topsoil was placed on an inactive weathered gypsum stack and mixed into the gypsum to a depth of approximately 25 - 30 cm to create a suitable rooting environment for poplar trees (Fig. 7). The equipment needed for mixing will depend on how compacted the gypsum is, but deep tillage and good seedbed preparation is essential for afforestation success. We have had success using a heavy-duty disc to mix soil into the PG to the appropriate depth. For heavily compacted gypsum we have first used a ripping blade of a D6 Caterpillar to break up the gypsum, followed by heavy-duty discing to create a suitable seedbed.

Note that the gypsum stacks reclaimed and forested in this trial have been inactive for almost two decades and are

washed free of acidic process water. The pH of the gypsum at the surface was approximately 5. For newer gypsum stacks, process water must first be removed, and the pH of the gypsum adjusted to at least 5 with lime or other alkaline amendments before adding soil and cultivating.

1.1.6.2 TREE PLANTING AND MANAGEMENT

The goal for any plantation design is to ensure an even distribution of stems over the entire area so that each tree can take advantage of the site's resources equally. The design must also take operational factors into consideration.

PLANTATION DESIGN: HYBRID POPLAR, ASPEN

DENSITY: 1,100-1,600 stems/ha

SPACING: 3m x 3m (1,100 stems) or 2.5m x 2.5m (1,600 stems)

PLANTING: Manual

ROTATION: 15-20 years

YIELDS: 13.6-20.0 m³/ha/y or 7.3-10.8 ODT/ha/y

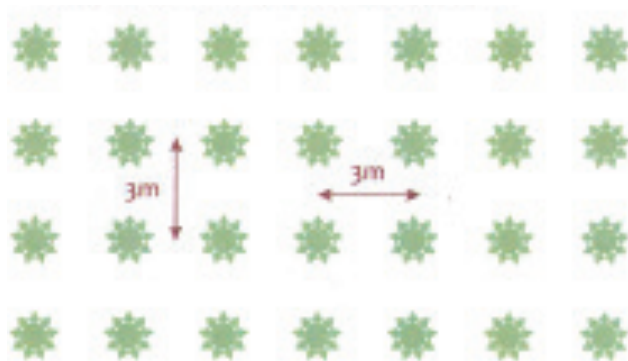


Fig. 13. Hybrid Poplar plantation design

PLANTATION DESIGN: HYBRID WILLOW

DENSITY: 15,625 stems/ha

SPACING: 3-row/bed design: 60cm x 60cm between trees, 60cm between rows, 2.0m between rows

PLANTING: Mechanical

ROTATION: 6-7, 3-year rotations

YIELDS: 6.0-12.0 ODT/ha/y

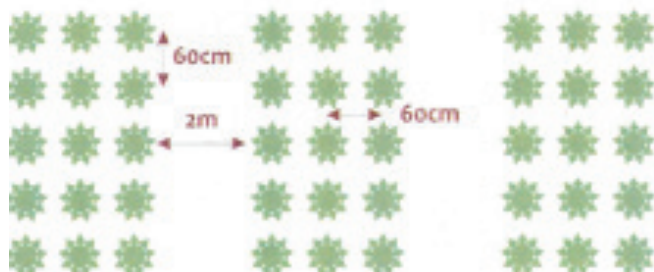


Fig. 14. Hybrid Willow plantation design
(Image courtesy Nutrien)



Fig. 15. Planting hybrid poplar cuttings in rows
(Image courtesy Nutrien)



Fig. 16. Willow cuttings leafing out, August 2015
(Image courtesy Nutrien)

Nutrien followed the recommendations of the Canadian Wood Fibre Centre and use a planting design of 3.0 m x 3.0 m, 1600 stems/ha (Hybrid Poplar/ Aspen, (Fig.13, Fig.15)) or 3-row bed design 60 cm x 60 cm between trees, 2 m between rows, 1100 stems/ha Hybrid willow willow, (Fig.14, Fig.16)). The uniform spacing between rows and between trees within rows allows for multi-directional management operations.

PLANTATION DESIGN:

MIXED WOOD - HYBRID POPLAR, WHITE SPRUCE

DENSITY: 1,600 stems/ha hybrid poplar + 1,200 stems/ha white spruce

SPACING: 1.88m x 1.88m

PLANTING: Manual

ROTATION: hybrid poplar @16-20 y; white sprouts @70 y

YIELDS: hybrid poplar → 13.6-20.0 m³/ha/y or 7.3-10.8 ODT/ha/y

white spruce → 4.0-5.0 m³/ha/y or 1.9-2.3 ODT/ha/y

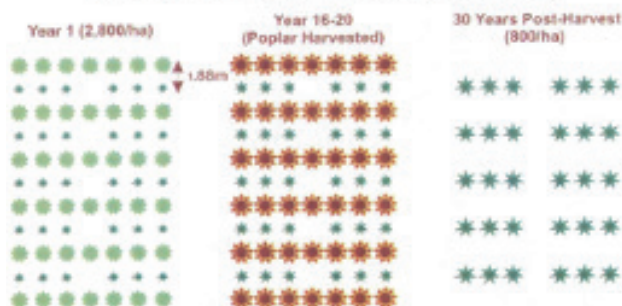


Fig. 17. Mixed Wood Plantation and 70 year life-cycle
(Image courtesy Nutrien)

A “mixed wood” plantation design is shown in Fig. 17. This also sets out two complementary planting life-cycles whereby the faster growing poplar variety is commercially harvested for green energy after 16-20 years while the white spruce is harvested at ~70 years for a range of uses including timber for construction and pulp for the paper industry.



Fig. 18. Hybrid poplar planted 2015, growth by 2019
(Image courtesy Nutrien)



Fig. 19. Willow planted 2015, growth by 2019
(Image courtesy Nutrien)

For comparison three season growth in hybrid poplars is shown in Fig. 18, next to willow growth over the same period in identical climatic conditions in Fig. 19. A simulation of growth in hybrid poplars after 10 years is shown in Fig. 20.



Fig. 20. Simulation: Hybrid Poplars at ~10 years
(Image courtesy Nutrien)

1.1.7 GROWING OTHER CROPS

The phosphogypsum/soil anthrosol can grow many types of high value crops, the sole constraint on what we can grow successfully at Nutrien Fort Saskatchewan being crops that the deer do not eat before we can harvest them.

1.1.7.1 OTHER CROPS GROWN ON PG ANTHROSOL



Fig. 21. Patty Pan squash (Images courtesy Nutrien)

The following crops have been on the reclaimed PG storage site in the last two years: raspberries, rhubarb, watermelon, potatoes, tomatoes, tomatillos, pumpkins, squash (Fig. 21), ornamental gourds and various kinds of flowers. Analytical results indicate that the quality of the vegetables is the same or better than plants grown on regular soil.

The PG storage facility vegetable garden/pumpkin patch continues to expand and is a great opportunity to dispel myths during tours, presentations and team building functions.



Fig. 22. Assorted vegetables and a potato from the PG Garden
(Image courtesy Nutrien)

Employees are thrilled to see the progress whether on the gypsum storage site reclamation itself, its subsequent afforestation or application to the vegetable garden. These brings smiles to many faces. Although Nutrien is in the business of 'feeding the world', the process of fertilizer manufacture goes well beyond merely working the soil and growing things in or on it. The vegetables grown on the PG site (Fig. 22) are distributed to employees throughout the growing season. Pumpkins and ornamental gourds are used to decorate the administration buildings and control rooms and to raise funds for the United Way charity through donations, pumpkin carving contests and the inaugural pumpkin smash/guess the weight contest.

1.2 PHOSPHOGYPSUM - A GYPSUM-CONTAINING SOIL AMELIORANT: RUSSIA

AUTHORS

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1.2.1 OVERVIEW

Phosphogypsum is not only a valuable ameliorant for salt-affected soils that improves soil structure and its physical properties, it is also a multi-nutrient sulphur-rich fertilizer. A long-term research program has evaluated the agronomical and economic efficiency of phosphogypsum application, resulting in the development of protocols and related regulations for its application in agriculture. The most significant outcome from this research program has been the re-adoption of phosphogypsum into the Government fertilizer subsidy program as a gypsum-rich soil amendment, based on an independent, fully referenced Protocol for Use [16].

Keywords: phosphogypsum, soil fertility, high-alkaline soil, nitrogen, phosphorus, potassium, fertilizers, soil structure, gypsum-rich ameliorants

1.2.2 EUROCHEM IN CONTEXT

EuroChem is one of the world's leading mineral fertilizer producers. It is driven by the world's increasing need for food, delivering a full range of crop nutrients for food production. The Company combines mining and processing facilities, producing mineral fertilizers, industrial products, and animal feed supplements while equipped with its own logistics and distribution network in Russia, Europe, Asia and America.

With potash mining underway, EuroChem is one of only three global fertilizer companies with capacity in all three primary nutrients: nitrogen (N), phosphate (P) and potash (K).

In 2018, EuroChem accounted for 2.5% of annual global mineral fertilizer production in terms of nutrient capacity. Sales volumes for the year were: 7,813 kt for nitrogen fertilizers, 5,685 kt – phosphorus and complex fertilizers, 632 kt – potash fertilizers, 5,977 kt – mining products and 1,871 kt – industrial products.

EuroChem is currently developing new-generation products such as water-soluble and related innovative fertilizers.

EuroChem is very R&D focused, currently working with 18 research partners and 12 universities to conduct more than 250 field trials in 25 countries. The intention is to test new soil amendment formulations, among them some phosphogypsum-

based, that will deliver optimal results in specific soils, whatever the crop, location or climate.

As context for its PG research programme, EuroChem not only produces and supplies mineral fertilizers, but also develops mineral nutrition systems adapted to specific regional agro-climatic conditions and crop requirements. EuroChem is committed not only to obtaining high crop yields, but also to preserving soil fertility and good physical condition.

Primary production is located in the European part of Russia, but there are divisions in Kazakhstan, China and Europe (Belgium and Lithuania). In Russia, phosphate fertilizers are produced in Kingisepp (Leningrad region) and Belorechensk (Krasnodar region). EuroChem operates additional complex mineral fertiliser plants: at Nevinnomyssk, Stavropol region, «NAC Nitrogen» at Novomoskovsk, Tula Region and the Usolsky potash plant in the Perm region.

1.2.3 PHOSPHOGYPSUM: POTENTIAL FOR USE IN AGRICULTURE

The use of phosphogypsum (PG) in agriculture can provide a range of benefits such as a) improving soil fertility and physical condition b) enhancing plant productivity and crop yield, c) optimising rational use of natural resources and d) contributing by reuse and recycling to waste management and reduction [17] [18] [19] [20]. Currently in Russia phosphogypsum is stored in stacks near enterprises as a by-product and enjoys only limited use in agriculture.

In Soviet times by contrast, the practice of using gypsum-containing ameliorants was widespread. In 1964, for example, a special resolution "About activities in liming acid and gypsuming alkaline soils and development of production of limestone flour and raw ground plaster" (dd 10.09.1964 No.776) was accepted, according to which 50%-85% of the costs for PG use as soil amendment were to be subsidized from the state budget. This measure led to its widespread use throughout the country and in the late Soviet period, the volume of application of gypsum-containing ameliorants reached some 1.5 mt/y (Fig. 23). At present PG use as amendment in Russia is no more than a few thousand tonnes per year (Fig. 24) [21].

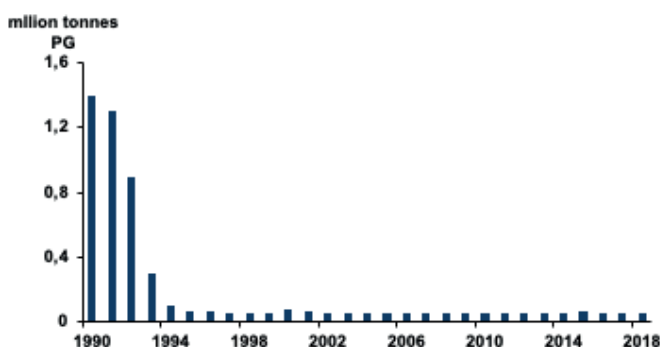


Fig. 23. The dynamics of reduction of phosphogypsum fertilizer use in Russia

Currently Russia produces ~14 mt of phosphogypsum per year, of which 1 mt is accounted for by EuroChem-BMU. Consumption of neutralized phosphogypsum produced at EuroChem-BMU remains insignificant, despite a significant relative sales growth (Fig. 24) [22].

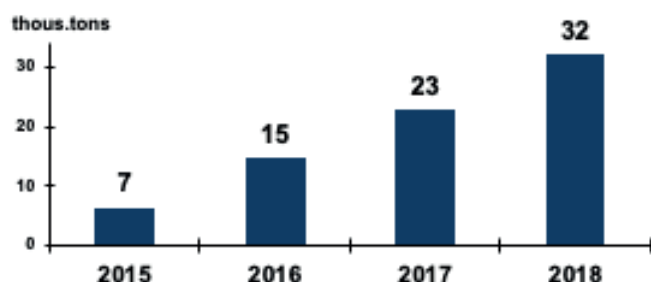


Fig. 24. Volumes of phosphogypsum sales

As a result EuroChem-BMU has accumulated legacy PG reserves of more than 30 mt. This situation is typical for the whole territory of the Russian Federation and has deep roots in the economic and social transformations of the 1990s.

EuroChem Phosphogypsum (PG) has great potential for use in agriculture. Typically, PG is characterized by a low pH (high acidity). But at its mineral fertilizer production facility «EuroChem-BMU», Krasnodar Region, neutralized PG is produced by reacting it with a weak alkaline medium. The PG itself is a co-product of the phosphoric acid resulting

from acidulating domestic phosphate apatites which are naturally low in both heavy metals and naturally occurring radioactive materials (NORM). It is environmentally benign and as a material does not cake [20] [23].

The neutralized PG contains some 92% calcium sulphate (CaSO_4) and is well suited for use as an amendment for saline soils to improve their physical, chemical and water retaining properties [24]. As produced EuroChem PG is not only an effective ameliorant, but it also acts as a source of plant nutrients. 1 t PG contains 25-30 kg of phosphorus (P_2O_5), 200 kg of sulphur (SO_4^{2-}), 370 kg of calcium (CaO) as well as a range of trace elements* (Si – 210 kg/t, Mg – 2.5 kg/t, Mn – 1 kg/t, Cu – 0.8 kg/t, Zn – 0.3 kg/t). The total area of salt-affected land in Russia is in the range 35-40 mha equating to some 20% of the farmland area. Of this affected arable land is ~10 mha, indicating that the need for remediation of these soils remains very high. Estimated demand for phosphogypsum for this task is ~ 1.5-3 mt/y [25] [26].

1.2.4 FIELD TRIALS

Since 2013, EuroChem-BMU jointly with leading agricultural research institutions of Russia has conducted a number of field experiments first to research and then confirm the effectiveness of PG as soil amendment in agricultural production (Fig. 25).

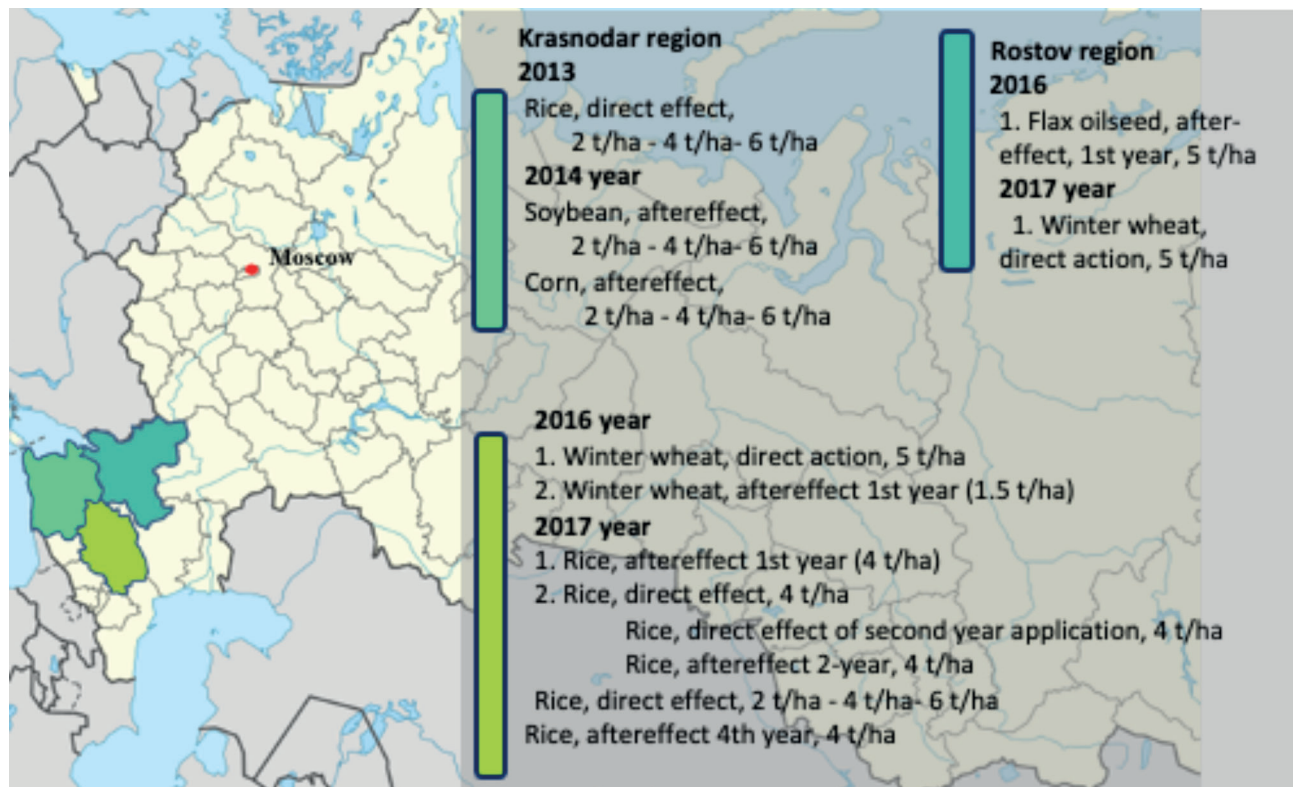


Fig. 25. Phosphogypsum field trial map Krasnodar and Rostov regions

PG use was tested in Krasnodar, Rostov, and Stavropol regions, (Fig. 25) regions in which problems with soil salinity, soil structure deterioration because of irrigation and high soil pH are widespread significantly limiting crop yield. Field trials tested different variables and parameters, such as a) relative dosages of PG, b) relative impact and benefit of both spring and autumn application, c) the impact over 4 years of PG application for following crop-in-crop rotation, d) effect on yield, e) soil properties, and f) soil pH.



Fig. 26. PG spreading by bulk material distributor BOMAG BS12000 (Image courtesy EuroChem)

PG was applied with standard equipment adapted for agricultural use. First, PG was spread over the soil surface using either an organic fertilizer spreader or using a bulk material distributor (construction equipment) (Fig. 26) and then was harrowed in (Fig. 27). Further field work was carried out according to standard farming procedures.



Fig. 27. The process of disc-harrowing in (Image courtesy EuroChem)

The findings indicate three notably effective modes of PG use:

1. As Gypsum-rich soil ameliorant for sodic soil. Calcium (Ca^{2+}) contained in phosphogypsum displaces sodium (Na^{+}) from the soil absorbing complex, which is washed out of the soil in the form of sulfate salts (cation exchange mechanism) [27] [28] [29]].

2. Ameliorant to improve the physical condition of irrigated land. PG improves soil structure, increases its water-holding capacity, promotes the formation of soil aggregates and improves water permeability of soil [26].

3. As provider of essential S and P nutrients to degraded soils. PG has a sulphur content of 21-22% and a P content of some 4-6%. These nutrients are essential for cereal and oil-seed crops due to their positive impacts on quality characteristics and yield [30].

1.2.5 AMELIORANT TO ENHANCE PHYSICAL CONDITION OF IRRIGATED LAND

Krasnodar is the main agricultural region in Russia where more than 80% of the country's rice is grown.

Rice production has very particular requirements, notably periodic flooding of the paddy fields. One of the biggest problems associated with paddy-fields is the deterioration of soil structure causing crust formation and soil compaction. In 2015, EuroChem staged a demonstration field trial to evaluate effective dosages and application periods for neutralized PG in rice-growing systems. PG was applied as both P source and soil ameliorant. The dominant soil type was Chernozem (humus-rich grassland soils) leached (pH – 7.4, humus content – 2.5%).

The most effective option was autumn treatment at the rate of 4 t/ha (Fig. 28), which increased productivity by 0.5 t/ha (or 6%). The outcome was a higher level of effectiveness than in traditional fertilization system using conventional ammonium-phosphate fertilizer (typically MAP 12-52). PG application as indicated also increased the yield of subsequent crops, as for example alfalfa which showed yield increases after treatment of 47% in spring and 76% in autumn.

The results of the experiment showed that the replacement of traditional fertilizers for rice mineral nutrition (dose rate 150 kg/ha of ammonium phosphate (12-52) before sowing) by 40 kg/ha of urea and 4 t/ha of phosphogypsum applied in the spring, maintains the level of nitrogen available forms, phosphorus and potassium in the soil and plants, as with the application full nutrients dosage $\text{N}_{18+56+46}\text{P}_{78}\text{K}_{60}$. The application of phosphogypsum in autumn before ploughing is more effective than in the spring before sowing, and can increase the yield by 5 kg/ha (or 6%) (Fig. 28). In this case, we have even higher efficiency than in the traditional fertilizer system with the usual P-containing fertilizer (usually MAP 12-52).

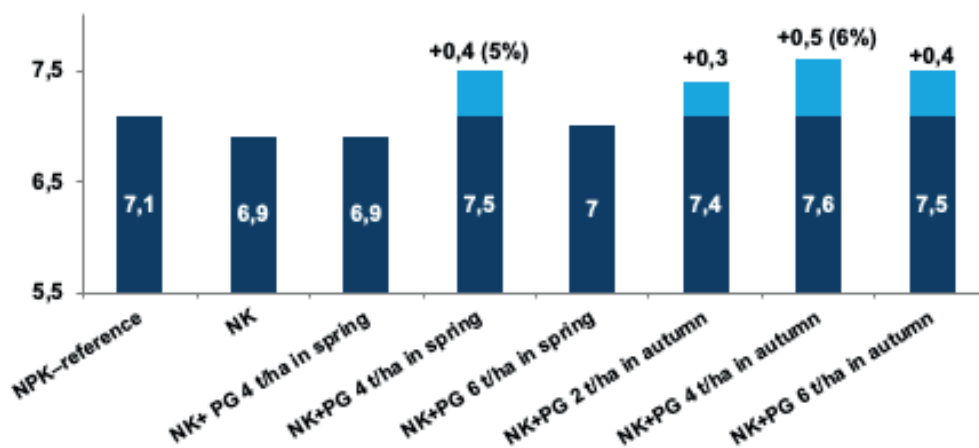


Fig. 28. Efficiency evaluation of rates and periods of phosphogypsum application in rice cultivation, t/ha

Productivity increase occurs as a result of enhancing survival of plants, increasing the number of kernels per panicle and improved grain weight gain per plant. In addition, the positive effect of neutralized PG lasts for 2 years following application. A year after application (2nd year impact) the yield of green mass of alfalfa 1 year was higher than the control (impact of mineral fertilizers) by 18-49% (2.0–5.3 t/ha). PG had a positive impact on yield of alfalfa of 47%.

TABLE 2. Humus and nutrients soil content, standard scale

NUTRIENT SOIL CONTENT GRADE (STANDARD SCALES)	HUMUS % (TYRIN METHOD)	P ₂ O ₅ (CHIRICOV METHOD)	K ₂ O (CHIRICOV METHOD)
EXTREMELY LOW	<2	<50	<40
LOW	2 - 4	50 - 100	40 - 80
AVERAGE	4.1 - 6	101 - 150	80.1 - 120
HIGH	6.1 - 8	151 - 200	120.1 - 180
HIGH	8.1 - 10	201 - 250	180.1 - 250
EXTREMELY HIGH	>10	>250	>250

In 2017, a similar experiment was staged to research the effect of neutralized PG on rice productivity in the Republic of Adygea. The soil of the experimental site was rice meadow-marsh characterized as pH – 6.3, humus* content – 2.9%, potassium exchange content – 198 mg/kg (very high), mobile phosphorus content – 38.6 mg/kg (low). The standard scale is shown in the table above (Table 2).

Plot size was 1000 m² (25m × 40m) (Fig. 29). The trial was carried out in 3 replications: i) Phosphogypsum was applied before sowing in the autumn with dosage 4 t/ha; ii) Predecessor – rice; iii) Sowing – scattered, irrigation regime – shortened flooding. As in the previous experiment, PG application at a rate of 4 t/ha increased the yield by 0.9 t/ha (Table 3) with an additional profit of +8000 Rubles/ha (18%) compared to the control without fertilizers.



Fig. 29. Trial field placement (Image courtesy EuroChem)

TABLE 3. Rice yield after phosphogypsum application

TREATMENT	YIELD, t/ha	ADDITIONAL YIELD	
		t/ha	%
CONTROL (WITHOUT FERTILIZERS)	5.0	-	-
Phosphogypsum application, 4 t/ha	5.9	0.9	17.1

To assess the effectiveness of neutralized PG on winter wheat a field trial was carried out in 2016. The predominant type of soil was ordinary carbonate Chernozem with heavy loam granulometric composition. In general, the soil of the experimental plots according to fertility, particle size distribution and soil physical and mechanical properties was favorable for the cultivation of winter wheat (Table 4).

TABLE 4. Experimental plot agrochemical characterization

TREATMENT	pH	CONTENT, MG/KG SOIL*		
		P ₂ O ₅	K ₂ O	S-SO ₄
Before phosphogypsum application	-	18.6	430	2.0
After phosphogypsum application	8.3	35.1	421	24.1

Pre-sowing treatment with neutralized PG in combination with mineral fertilizers for previous crops in crop rotation - soybeans and maize contributed to an increase in the concentration of water-soluble forms of nitrogen, phosphorus and potassium in the soil and had a positive effect on the growth and development of subsequent crops - winter wheat. The highest additional yield due to the longer-term impact of PG application relative to the NPK control was registered for the variant with the application rate of 5 t/ha, amounting to 4.3 dt/ha (9%) (Table 5).

TABLE 5. The influence of the phosphogypsum aftereffect on the winter wheat yield

TREATMENT	YIELD, t/ha					± TO CONTROL	
	I	II	III	IV	average	t/ha	.%
Control (no fertilizers)	4.58	4.70	5.03	4.65	4.74	-	-
Phosphogypsum application, 5 t/ha	5.30	5.00	4.98	5.40	5.17	0.43	109

1.2.6 NUTRIENTS SOURCE, PH CORRECTION

In 2016, an experiment was held to examine the effects of neutralized PG on the productivity of oil-bearing flax in the growing conditions of Rostov Region (Table 6). The dominant soil type is typical Chernozem in this case with values of pH – 8.3 and humus content – 3.4%. Under PG treatment at the application rate of 5 t/ha more uniform flax seedlings with darker leaf colour were noted in comparison with the control variant (Fig. 30). The additional yield averaged +4 t/ha with an additional profit of +3 thousand rubles (or 24%) as compared with the control plot with no added PG. Oil yield was 0.54 t/ha, which is higher than the treatment without fertilizers by a factor of 0.13 t/ha. The oil content of seeds was 32%, which is higher by 1.4% than the control treatment. A further benefit of treatments containing PG was seen in modification to soil pH, PG reducing the alkalinity from a mean value of 8.3 to 7.7.

TABLE 6. Agrophysical and agrochemical parameters in the upper soil horizon (0-30 cm)

TREATMENT	pH	HUMUS, %	CONTENT, MG/KG SOIL*				SOIL DENSITY, g/cm ³ t/ha
			N-NO ₃	P ₂ O ₅	K ₂ O	S-SO ₄	
BEFORE GERMINATION							
Control (no fertilizers)	8.3	3.40	8.1	22.7	385	4.2	1.28
Phosphogypsum application, 5 t/ha	8.1	3.42	9.3	31.1	403	10.1	1.17
AFTER HARVESTING							
Control (no fertilizers)	8.3	3.37	4.0	19.2	361	4.0	1.41
Phosphogypsum application, 5 t/ha	7.7	3.38	4.2	24.4	340	9.4	1.28



Fig. 30. Oil-bearing flax (Image courtesy EuroChem)

1.2.6.1 SOIL PH CORRECTION

An experiment was conducted in Stavropol region on a spring barley field to research the effect of neutralized PG on pH as a key soil fertility indicator and to assess the direct effect of PG as an ameliorant of alkaline-affected soils (Fig. 31). Planting areas were selected with a) flat terrain, b) similar soil types, c) homogeneous fertility rates, d) similar predecessor and current agrochemical indicators (Table 7). The results of the analysis show that on average the content of mobile phosphorus* (17.5 mg/kg) and humus (4.5-4.8%) in land use corresponded to the average content, with potassium exchange* at 554-581 mg/kg (high).

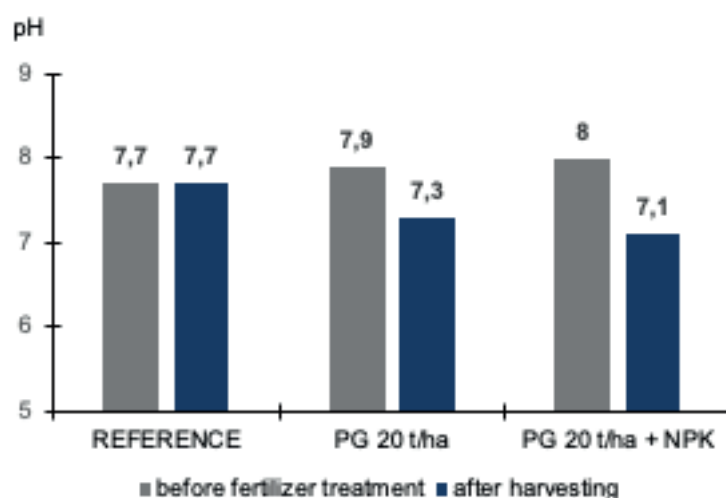


Fig. 31. Application of neutralized phosphogypsum for amelioration of alkaline soils in Stavropol Region, 2017

The dominant soil type was typical Chernozem. PG application reduced soil acidity from 0.5 to 1.2 units per growing season. For soils with no PG application, pH reduction was insignificant by factors ranging from 0.09 to 0.13. The best aggregate indicators of the crop structure were typical for the variant with PG application at a dose rate of 20 t/ha. As a result of increasing nutrient availability in options with added PG, productive bushiness, grain weight and barley yield all increased.

TABLE 7. Soil agrochemical characterisation

PLOT N°	P ₂ O ₅ mg/kg	K ₂ O mg/kg	pH KCl	pH	HUMUS %	S mg/kg
1	18	581	6.6	7.84	4.8	4.2
2	17	554	6.9	8.02	4.5	5.0

Therefore, EuroChem-BMU confirmed that phosphogypsum can be used as an effective ameliorant based on its own protocol-driven field experiments referenced to controls based on conventional nutrient regimes and growing conditions.

PG use as soil amendment is recommended for application to previously untreated soils during ploughing in areas with favorable growing conditions (temperature, rainfall) that are best suited for the cultivation of high-margin crops. According to data modelled by Pryanishnikov All Russian Research Institute of Agriculture and Soil Science, phosphogypsum use in 4 major agricultural regions of the Russian Federation (in Krasnodar and Stavropol Regions, in Rostov and Vologda Regions) can provide an increase in overall grain yield 5 million tonnes, equivalent to 50 billion rubles of additional profit.

1.2.7 COST-BENEFIT ANALYSIS

From an economic (cost-benefit) perspective, PG application represents a large financial investment, of which handling and transportation costs to the site of application comprises the largest share. Financial support from the state for PG delivery to site can extend the benefits of amelioration to much larger areas of saline soils.

To address the economic challenges faced by PG application the following steps were taken:

1. To increase the use of phosphogypsum and other ameliorants, EuroChem-BMU made targeted proposals to responsible governmental agencies. The Ministry of Agriculture of the Russian Federation supported the initiatives of EuroChem-BMU in including PG amelioration of saline soils in the “National program of export of agricultural products” to improve soil fertility. Under instruction from the Russian Federation (RF) Ministry of Agriculture, EuroChem-BMU prepared specific commercial proposals for southern regions of Russia.

2. EuroChem in cooperation with the leading soil research institution developed a government-approved standard for gypsum-rich soil ameliorants based on the results of systematic, protocol driven expert-reviewed field trials.

3. Subsequent to this initiative, (ie government standard development and validation of PG soil amendment benefits made by EuroChem and the Russian Association of Fertilizer Producers) and within the framework of national government support for its domestic food security policy, the RF Ministry of Agriculture announced requirements for mandatory soil amendment for degraded soils. The related decision was taken to subsidize 30% of agricultural enterprise costs in respect of soil liming, with the simultaneous application of key nutrients P and S in PG form. This subsidy started

in 2019. It covered up to 50% of the expense of PG application as required by the official PG application protocol, and as authorised according to the stipulations of the budget allocated to the farm amelioration program (including expenses for transportation, application and product purchase). In some selected regions this subsidy was as high 100%.

The success of the 2019 programme led to a decision from early 2020 in the Stavropol region to initiate a new programme. This will cover up to 100% of the cost as required by the official PG application protocol including cost of acquisition of the PG by farmers and up to 50% of related transportation costs. This program is supported by the regional Ministry of Agriculture and EuroChem company.

As of the date of publication of IFA PG2, agricultural producers in Russia have concluded that soil amendments are essential to increase the production efficiency of national soils. In its turn, the government jointly with fertilizer producers, is committed to supporting efforts to encourage the widespread use of ameliorants, including phosphogypsum.

1.2.8 PROTOCOL-DRIVEN APPLICATION

While the term “Protocol” is not used in the title, the scientific underpinning for the pilot was devised in a manner fully consistent with the EU concept of a Quality Protocol, and functioned as a reference document for the field trial under the title Scientific and Practical Recommendations for the Application of Neutralized Phosphogypsum as Chemical Ameliorant and Sulphur-rich Fertilizer [14]. The document has the status of an official Protocol, as outlined immediately below. The document is too long to reproduce in full for PG2 but was kindly provided in English translation together with the Case Study.

To illustrate the similarity with the EU QP format, and for comparison purposes two aspects are cited here, the opening paragraphs and the Table of Contents.

1.2.8.1 PROTOCOL STATUS

“The scientific and methodological recommendations contained in this document on the use of neutralized phosphogypsum have been developed in order to encourage and promote the use of this valuable product as a mineral fertilizer for all soil types for the purposes of i) improving soil structure and its physical-chemical properties, ii) enhanced provision of calcium, silicon and sulphur nutrients to plants, iii) appropriate application of gypsum soil amendment to solonetz soils. Neutralized phosphogypsum is not only a by-product of wet-process phosphoric acid manufacture, it is a material whose properties can be significantly enhanced by neutralisation for application as mineral fertilizer. The transformation of useful by-products into high-quality fertilizers is a major way of improving their agronomic

value, while also saving energy and reducing overall CO₂ emission across the lifecycle. This not only increases its wider environmental friendliness, but also illustrates the requisite environment protection qualities of by-products which can be considered suitable for increasing soil fertility.

The recommendations set out scientific, evidence-based methods for application of neutralized phosphogypsum in agriculture as supported by published evidence concerning the performance of currently available experimental material. This includes the applied phosphogypsum's chemical composition and granulometric texture, its main characteristics as enhancing the soil's properties, increasing the yield and quality of plant products, and as suited to the most effective technological methods of field application. The methods for calculating phosphogypsum dosage and special aspects of its application for various crop rotations are also indicated in this document.

The recommendations contained herein are intended for the agrochemical service employees, planning authorities, service agencies of the agro-industrial complex, land users with different various forms of ownership relationship with their land, and production personnel from engineering institutions. The authors of the document believe that this publication will also be useful for researchers, since not all the positive aspects and application techniques of neutralized phosphogypsum have yet been discovered and publicly disclosed.

Scientific and practical recommendations were reviewed and approved by the Scientific Council of the D. N. Pryanishnikov Institute of Agrochemistry, Protocol No. 11 dated 12.20.2011."

1.2.9 TABLE OF CONTENTS - PG PROTOCOL

The Table of Contents of the official PG protocol is comprehensive and robust, giving an excellent reference example of what the scope and approach of such a protocol should be irrespective of which jurisdiction is the responsible regulatory authority. Its credibility is secured by the partnership which produced it comprising producers, independent scientists and experienced end users and customers, testimonials from whom also complete the dossier, showing close engagement between all stakeholders.

Introduction

1. Agronomic Efficiency of Phosphogypsum
2. Genetic Diversity of Solonetz Soils and Their Classification
3. Chemical Method of Reclamation
 - 3.1. Methods of Calculating Ameliorants Dosage
4. Special Aspects of Solonetz Soils Reclamation under Irrigation Conditions
5. Technology of Chemical Method of Reclamation

6. Environmental Constraints of Chemical Reclamation of Solonetz Soils with Neutralized Phosphogypsum
7. Phosphogypsum Application as Sulphuric Fertilizer
8. Importance of Phosphogypsum as Silicon-Containing Fertilizer
9. Combination of Phosphogypsum with Other Fertilizers
10. Forecast of Possible Effective Use of Neutralized Phosphogypsum at Highway Side Lanes and Intra-City Areas
11. Quality Requirements for Neutralized Phosphogypsum
 - 11.1. Main Characteristics of Technical Indicators
 - 11.2. Safety and Environmental Requirements
 - 11.3. Acceptance Rules
12. References
13. Appendix

As is shown above, while the Protocol is primarily for use as soil amendment the recognition that the same PG has potential applications in road construction is recorded, see Case Study Section 3.

1.2.10 TESTIMONIALS



Fig. 32. Askhat Khazritovich Sheudzhen

We are actively exploring the possibility of using neutralized phosphogypsum as a multicomponent fertilizer. Phosphogypsum can be used as a complex fertilizer because it consists of dozens of essential and even indispensable nutrients for plants. We have developed and approved the full-application technology - timing, dosages, application methods - but also shown the real need for the phosphogypsum application in agriculture.

Askhat Khazritovich Sheudzhen

Doctor of Biological Sciences, Head of the Department of Precision Technology, Rice Research Institution, corresponding member of Russian Academy of Science (RAS)



Fig. 33. Akanova Natalia Ivanovna

Long-term experiments conducted to the specifications of the all-Russian Scientific Research Institute of Agrochemistry showed significant efficiency of phosphogypsum not only as an ameliorant for saline soils, but also as a fertilizer with soil-improving properties. There is no need to revalidate the importance to crop yield of phosphorus application as contained in phosphogypsum, but in phosphogypsum there is another essential element for plant nutrition - sulphur! Farmers all over the world in the last decade are paying more attention to the necessity of S application, notably from affordable sources. Together with EuroChem, The Institute has developed comprehensive regulations for phosphogypsum use in both remediation of salt-affected soils and as a wider source of nutrients. Now detailed information on the method of application and efficiency is available to any farmer.

Akanova Natalia Ivanovna, Doctor of Biological Sciences Professor, D. N. Pryanishnikov Institute of Agrochemistry

We grow from 5 to 7 agricultural crops in our fields. Active use of irrigation systems leads to the appearance of spots in the fields with high salt content – or in cumulative process of soil salinization. Irrigation also leads to over-compaction of the upper soil horizon, reducing soils' fertility. To remove or rebalance excess salt concentrations and improve soil structure we apply 2-6 tonnes of phosphogypsum per hectare. The development of this phosphogypsum application system was based on soil analysis results, crop yields, and visual examination of the fields. We apply phosphogypsum on average once or twice in the crop rotation. Special attention is paid to rice fields, where phosphogypsum is sorely needed.

With the application of phosphogypsum, phosphorus nutrition is improved, the lack of calcium in our soils is remedied, and the soil forms a more structured humus horizon. Following our standard application procedure, we plan to apply phosphogypsum in the autumn of 2019, in a total amount of the ~10 000 tonnes.

Rothko Anatoliy Viktorovich, Director, Manych-Agro Company, Rostov region.

- Phosphogypsum is needed to remedy failures in soil structure, and to stabilize the soil's water-air interchange. This it will

improve plant nutrient uptake. That's the most important thing for our soils. Yes, phosphogypsum will slightly increase yields, but its main role is to improve the physical condition of the soil. This way the soil will sustain less damage from either mechanical operation or rainfall and conditions for plant growth will be better.

- Phosphogypsum - is highly effective for land affected by soil salinity. In the Krasnodar region as a whole, we have about 10% of saline land, but in the Bagaevsky district this reaches even 30%, the farm in question consisting of 7 thousand hectares. If I irrigate in those conditions the situation only gets worse. In my conditions, the use of phosphogypsum becomes essential; but first the product should be tested, which is what we plan to do in the nearest future.

Independent expert opinion (agricultural producers).

A survey of independent expert opinion was conducted within the framework of 6 Focus groups each of 30 members for assessment of consumer demand for phosphogypsum.

1.3 INTEGRATED USE OF PHOSPHOGYPSUM TO DEVELOP RESILIENT AGROECOSYSTEMS IN CENTRAL ASIA: KAZAKHSTAN

AUTHOR

Dr. Manzoor Qadir, Deputy Director, United Nations University Institute for Water, Environment and Health (UNU-INWEH)

1.3.1 CONTEXT AND CHALLENGE

Increasing freshwater scarcity and deteriorating water quality are key bottlenecks to achieving sustainable increases in agricultural production in Central Asia in particular and more widely contributing to delivery of key sustainable development goals (SDGs), particularly SDG 2 warranting food security and SDG 6 ensuring water and sanitation for all. Central Asia is more sensitive to climate change as extreme high-temperature events are expected to become more intense, more frequent, and longer-lasting compared with the average global warming scenarios [31]. With the average crop water requirement expected to increase, the anticipated water gaps between precipitation and crop water requirement are set to expand and intensify.

Land degradation is a further major challenge in the region. It negatively impacts agricultural productivity and economic development along with future implications for SDG 13 on combating climate change and SDG 15 on reversing land degradation. Eradicating extreme poverty and meeting the SDGs without adequately addressing underperforming land and water resources is highly unlikely in Central Asia. This would mean that the region at large would be lagging in addressing the key elements of the 2030 Sustainable

Development Agenda including SDG 13 (Climate Action) defined also in the Paris Agreement, which aims to strengthen the global response to the threat of climate change. The same applies to other United Nations initiatives and conventions, notably the Convention to Combat Desertification³⁵ (UNCCD) to combat catastrophic erosion and soil loss, and the Convention on Biological Diversity³⁶ (CBD) based on Aichi biodiversity targets.

The cost of “inaction” on underperforming degraded lands is estimated to be a loss in revenues of from 15% (best case) to 69% (worst case) depending on variables such as the crop grown, intensity of land degradation, and level of water quality deterioration, among others [32]. These estimates do not account for additional costs such as loss of employment, increased human and animal health problems, reduced property values, and associated environmental costs. Based on the comprehensive economic analysis, the annual cost of land degradation in the Central Asian region is estimated to be about US\$ 6 billion [33]. The costs of action against land degradation are lower than the costs of inaction in the region by 5 times considering a 30-year horizon; i.e. each dollar spent on addressing land degradation is likely to yield ~5 dollars of value-add returns. These estimates suggest a compelling economic justification favoring action to reverse land degradation as compared with inaction, allowing land degradation to continue and intensify.

Land degradation caused by elevated levels of salts is a major reason for low productivity and environmental implications in Central Asia. Intensive irrigation and excessive leaching of agricultural lands are common practices in the region [34]. In some sub-regions, such as southern Kazakhstan, irrigation water contains high levels of magnesium than calcium [35], causing land degradation. Known as magnesium-affected soils and characterized by low infiltration rates and hydraulic conductivities, such soils also occur in other Central Asian countries. More than 30% of the irrigated land in southern Kazakhstan already has soils with 25-45% exchangeable magnesium percentage (EMP), and in some cases as high as 60% EMP [36]. The consequence has been a gradual decline in cotton yields on these underperforming irrigated lands; around 1.5 t/ha and declining further in a region that still relies heavily on cotton.

1.3.2 RESPONSE OPTIONS

Considering the availability of natural and human resources in Central Asia, there is the potential for reversing environmental degradation in all countries in the region. Ameliorating magnesium-affected soils requires the application of a source of calcium to replace excess magnesium from these

soils' cation exchange sites. The amount of calcium to be applied is based on the extent of exchangeable magnesium to be replaced. The displaced magnesium is then leached from the root zone through excess irrigation.

The common source of calcium for the amelioration of magnesium-affected soils is gypsum. Phosphogypsum (PG) (calcium sulphate) is an alternative, affordable source of both calcium and sulphur, which also contains trace quantities of phosphorus. PG thus provides additional value to farmers supplying a range of nutrients, notably P and S, essential for plant growth and crop yield.

Several pilot studies, using a farmer-participatory approach, have been undertaken on reversing magnesium-led soil degradation with locally produced PG. A 4-year study on high-magnesium soils in southern Kazakhstan [37] was carried out with the participation of local farming community to:

1. determine the effects of different rates of phosphogypsum application on chemical changes in magnesium-affected soils
2. observe the response of cotton to the application of phosphogypsum
3. perform economics of using phosphogypsum as a soil amendment.

Three treatment variants were applied: (1) no phosphogypsum application, (2) phosphogypsum application at 4.5 t/ha, and (3) phosphogypsum application at 8.0 t/ha. The water used for irrigation also contained high levels of magnesium (magnesium-to-calcium ratio > 1.3).

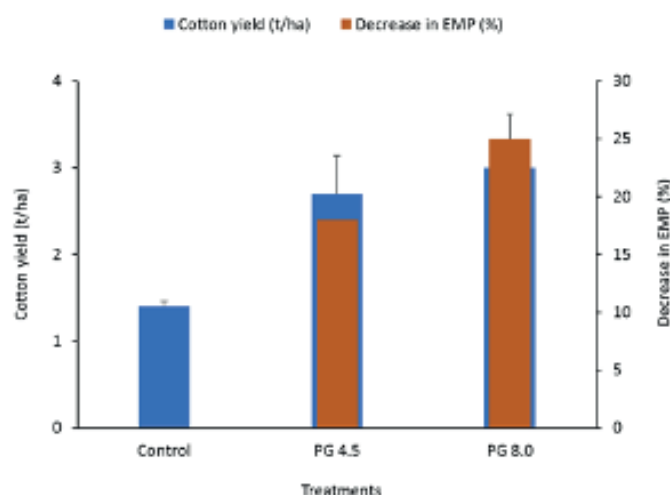


Fig. 34. Cotton yield and exchangeable magnesium percentage (EMP) as affected by phosphogypsum (PG) application to a magnesium-affected soil in southern Kazakhstan [36]

The analysis of soil samples collected after the harvest of

35. Convention to Combat Desertification, <https://www.unccd.int/convention/about-convention>

36. Convention on Biological Diversity, <https://www.un.org/en/events/biodiversityday/convention.shtml>

cotton each year revealed the beneficial effects of applying PG through an increase in calcium concentration in the root zone. The increased levels of calcium forced the chemical equilibria in favour of calcium by prompting replacement with calcium of excess exchangeable magnesium from the soil. The beneficial effects of calcium were evident in recorded yields of cotton in the first year and there was a significant decrease in EMP of the root zone when compared with the EMP levels before the application of PG to the soil. There was 18% decrease in EMP in the plots with PG application at 4.5 t/ha and 25% decrease in EMP where PG was applied at 8 t/ha (Fig. 34).

PG application led to a decrease in soil EMP, an increase in nutrient (phosphorus and sulphur) availability, and an improvement in soil structural stability. When these factors combined, the beneficial effects of soil application of PG were clear from the crop yields: the first cotton crop yielded 2.7 t/ha in the treatment with PG application at 4.5 t/ha. The crop yield further increased to 3.0 t/ha when PG was applied at a higher rate of 8.0 t/ha (Fig. 34). There was a marked difference between the cotton yield in the PG applied plots (2.7-3.0 t/ha) and control plots (1.4 t/ha); i.e. cotton yield was doubled with the soil application of PG [36].

The cotton yield from the control plots remained somewhat unchanged ($1.3\text{-}1.4\text{ t ha}^{-1}$) in subsequent years, while cotton yields in the PG treatments started to decrease from peak yields obtained in the first year. This was proportional to substantial decrease in EMP in the root zone in the first year followed by a gradual increase in EMP as PG was applied only once at the start of the study. With time, it started depleting and most of it was used in successive years.

Over 4-year period, the first crop yielded cotton at 2.7 t/ha and then decreased to 2.2 t/ha in the case of fourth cotton crop (4-year average cotton yield 2.4 t/ha) in the treatment with PG applied at 4.5 t/ha. In the treatment with PG applied at 8.0 t/ha, cotton yield decreased from an initial 3.0 t/ha to 2.2 t/ha (4-year average cotton yield 2.6 t/ha). As a major portion of the applied PG was utilized in soil amelioration within a 4-year period,) [36] application of a supplemental dose of PG to magnesium-affected soils after every 4 years was recommended. This time interval may vary depending on the yield pattern and soil condition. The financial feasibility analysis using multi-year data revealed that economic benefits from the PG treatments were almost double than those from the areas where no amendment was applied.

A further study undertaken in Kazakhstan to investigate the suitable combinations of applying phosphogypsum to a magnesium-affected soil at different rates and times. The soil amendment was applied at 3.3 and 8.0 t/ha in winter before snowfall (January) or in spring after snowmelt. The PG treatments outperformed the treatment where the amendment was not applied. The effect was distinct in three ways: (1) a decrease in EMP in the root zone, (2) an increase in water movement and moisture content in the upper soil layer, and (3) an increase in cotton yield per unit area and per unit of applied water [35]. Based on the overall effects, application of PG in winter before the snowfall performed better than its application in spring. The 2-year average crop water productivity was 0.32 kg/m^3 in the plots where no PG was applied while it increased to as high as 0.52 kg/m^3 in the PG treatment where the amendment was applied at 8.0 t/ha in winter before snowfall (Fig. 35).

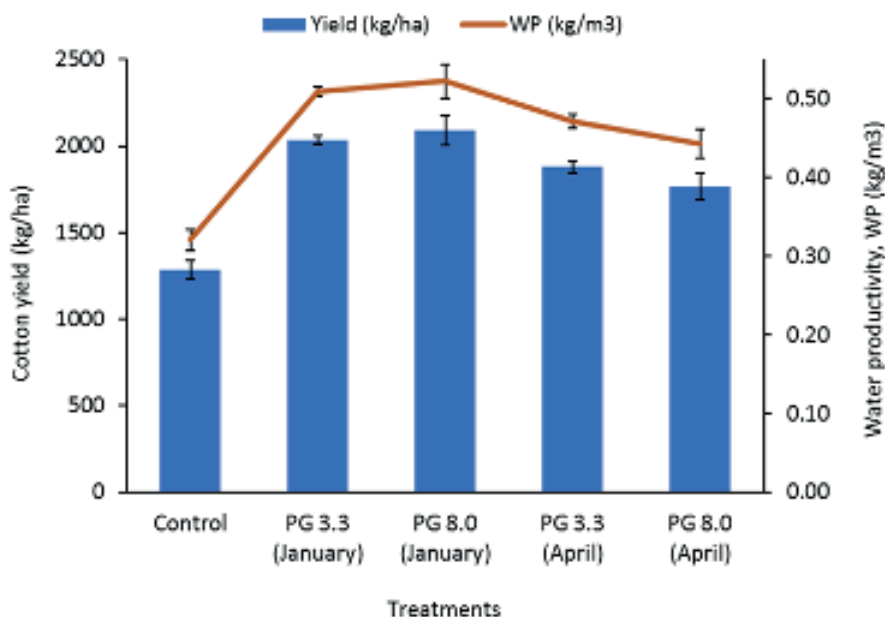


Fig. 35. Crop yield and water productivity as affected by phosphogypsum (PG) application (3.3 and 8.0 t/ha) applied in winter before snowfall (January) and in spring after snowmelt to a magnesium-affected soil in Kazakhstan [35]

1.3.3 ECONOMICS OF RESPONSE OPTIONS

A range of costs result from the occurrence of land degradation stemming from high levels of magnesium in soils, such as: (1) damage to the environmental health and ecosystem services; (2) declines in market value of the farm property; (3) reduction in farm-level employment which may result in possible trans-migration; (4) social costs translated through decrease in farm operations and business opportunities; and (5) potential impact on local culture and decline or loss of cultural heritage.

Some studies have been undertaken on the economics of (1) 'inaction' translated through the loss of potential benefits due to high-magnesium soils, and (2) 'action' based on the measures undertaken to prevent or reverse magnesium-led water quality deterioration and land degradation in irrigated areas. For example, a study [36] evaluated the economics of 'action' versus 'inaction' for high-magnesium waters and soils by using the following treatments: 'inaction' in case of control without PG application and 'action' by applying PG at 4.5 and 8.0 t/ha. The economics of 'action' versus 'inaction' was based on net income, which was \$241/ha in the case of 'inaction' and ranged from \$522 to \$554/ha from 'action', suggesting that the cotton farmers were compromising on less than half of the net income compared with those applying PG to magnesium-affected soils.

The multi-year studies involving local farming communities demonstrated that the farmers can improve their livelihoods by applying PG to degraded lands resulting from high levels of magnesium in soils and irrigation waters rather than compromising on low crop yields [36]. In the study area, pricing of cotton is dictated by the private companies that deal with cotton purchase and regional marketing. As most farms belong to subsistence farmers, they have little means to afford the full cost of farm operations even for one crop season. They enter into agreements with the private companies to take loans for the purchase of farm inputs and operational expenses. In return, they settle the price of cotton with these companies at the beginning of the season. This agreed price is always lower than the actual price of cotton in the open market. The companies receive the cotton crop and give back the farmers the amount based on the difference between the revenue from cotton and the amount of loan given to the farmers. The whole equation works well in favour of the companies as the farmers are left with small amount of money in the end, which forces them to take loan for the next crop and remain in the 'subsistence' trap under 'no action' situation.

The 'action' based on PG application to magnesium-affected soils helps the farmers to (1) improve soil condition by reversing land degradation; (2) increase crop productivity significantly (Fig. 36); (3) receive high net profits, almost

double than the 'no action' areas; (4) get out of the contracts with the companies; and (5) make independent decisions on purchasing farm inputs and operational expenses and sale of harvested crop in the open market. Large reserves of PG are available within 300 km of the area characterized by magnesium-affected soils, a haul distance judged according to World Bank cost-benefit models to justifiable economically when measured against the financial gains to the farmer listed above.



Fig. 36. A farmer in his field where he used phosphogypsum on a magnesium-affected soil and harvested a bumper cotton crop (Arys Turkistan, southern Kazakhstan) (Image courtesy United Nations University)

1.3.4 FUTURE PERSPECTIVES

The environmental degradation in Central Asian countries necessitates the application of pertinent ecosystem resource management strategies to improve productivity of water and soil resources. Without compromise to the ecosystem health as a whole, particular environmental benefits can be seen, such as mitigating climate change impacts through enhanced soil carbon sequestration and enhanced food security. Research and practice in the region have demonstrated the beneficial uses of calcium-supplying amendments, such as PG, to trigger restoration of degraded lands in irrigated, rangeland, and rainfed systems for enhancing agricultural productivity, ensuring food security, mitigating climate change impacts through carbon sequestration, and supporting livelihoods resilience.

Central Asia region has one of the richest natural resource endowments, which are present in environmentally fragile areas. Planned, effective, efficient, and productive use of PG in the region can bring a range of benefits to the environment, ecosystems, and natural resources while strengthening livelihoods resilience of the people along with socio-economic benefits.

1.3.4.1 SALT-AFFECTED SOIL REHABILITATION

Rehabilitation of salt-affected degraded lands by phosphogypsum application as a soil amendment results in measurable gains in agricultural productivity, carbon capture, land value, economic and livelihoods gains (Fig. 37). Studies have shown doubling agricultural productivity on salt-affected degraded lands [35] [38] and reducing poverty significantly to those levels where farmers can make independent decisions on purchasing farm inputs and operational expenses and sale of harvested crop in the open market [36].

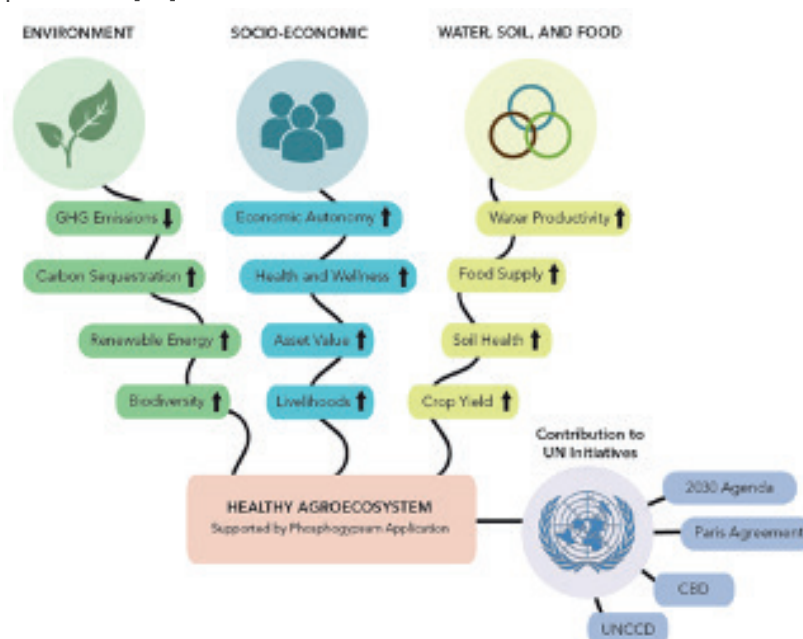


Fig. 37. Healthy agroecosystems resulting from phosphogypsum applications can bring a range of benefits while contributing to the global sustainability process

Creation of anthrosols from phosphogypsum as the primary source material leads to high-yielding afforestation plantations to sequester carbon, potential use for green energy or wood chips, and ecosystem diversity [39].

Saline water irrigation while using phosphogypsum to mitigate salinity effects in crop production and agroforestry systems offers saving water for other uses, carbon sequestration in soil, renewable energy, farm produce, and crop diversification options [40].

There are common gains from these phosphogypsum-led interventions, such as environmental gains through carbon sequestration; increase in land value and livelihoods resilience; improved aesthetics; and livelihoods resilience. These interventions sit at the heart of the global sustainability processes as they contribute to the UN initiatives such as 2030 Sustainable Development Agenda, Paris Agreement on Climate Change, Convention to Combat Desertification and Convention on Biological Diversity.

A commercially beneficial use of phosphogypsum to develop resilient agroecosystems in Central Asia based on well-defined business models while considering sensitivity to stakeholders' requirements is the way forward to provide multiple benefits and prosperity stemming from phosphogypsum-assisted

management of underperforming land and water resources in the region.

1.4 VALORISATION OF PHOSPHOGYPSUM AS FERTILISER - RESULTS OF AGRONOMIC FIELD TRIALS: MOROCCO

AUTHORS

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Mohammed VI Polytechnic University (UM6P)³⁷ is a hub of education, research, innovation and entrepreneurship, aspiring to become a solid bridge of knowledge between Morocco, the Africa region and the wider world. From its campus located near Marrakech in the "Mohammed VI Green City" district of Benguerir, UM6P applies a "learning by doing" approach to promoting leadership and academic excellence in focused research areas while in the process developing sound partnerships with a network of world-class universities. By contributing in these ways to the training of a new generation of Moroccan and African researchers, entrepreneurs and leaders, UM6P is committed to positioning Morocco as a country at the forefront of technology and human sciences.

37. For Mohammed VI Polytechnic University see <https://www.um6p.ma/en>

1.4.1 INTRODUCTION

Plants require sulphur (S) for synthesising amino acids to produce proteins. Plant uptake of sulphur varies considerably depending on plant variety and agricultural practices. Crop need for sulphur ranges from 13kg/ha to more than 60kg/ha while Ca uptake may vary between 20kg/ha and 196kg/ha.³⁸ S content in cereals varies between 0.08% and 0.173% dry weight [41] and of Ca between 0.5 and 5% dry weight.³⁹ Only moderate S deficiency can affect both yield and quality of the plant even when not exhibiting symptoms of S and various studies [42], TSI⁴⁰ 2018 [43], [44] have demonstrated that S has not only enhanced the nutritional value of cereal crops but also increased their yield. Enhanced yields are also likely to be better achieved when N and S are applied simultaneously [45] [46] [47]. The fertiliser application rate may be considerable because of poor S resource use efficiency by cereals, which averages only around 18% [48].

S deficiency is increasingly prevalent in many different regions of the world. More than 70% of soils analysed in India have a sulphur level in the range “low to average” while S applications to S deficient soils have resulted in significant yield increases for many crops.⁴¹ A further decline in S availability in field crops is to be expected, because of increasing agriculture intensification, limited use of fertilisers containing sulphur, reduced S emissions to the atmosphere by factories in some regions, and reduction of soil organic matter (SOM) levels (principal S source) caused by “mining agriculture” (i.e. soil depletion due to SOM decay and limited fertilizer application).

Phosphogypsum may be used as a fertiliser, particularly as a source of S, of Ca and of acidity (low pH) but the quantities consumed this way are small when compared to PG used as a soil amendment. This Case Study evaluates the impact of (1) PG application as nutrient source to a non-saline soil and for two different types of crop, rapeseed and legumes, in a favourable rain-fed area and (2) the environmental impact of such use on crop and soil.

1.4.2 MATERIALS AND METHOD

1.4.2.1 TRIAL SITE SELECTION AND TREATMENT REGIMES

Phosphogypsum application trials were conducted at fields at nine sites in different locations in the Settat region of Morocco (Fig. 38). The soils of this region were chosen according to their differences in texture,

depth and pH.

Treatments consisted of applications of varying doses of PG to rapeseed and/or food legumes.

Each trial consisted of three (3) plots of 900m² (300m² each) in which plot 1 was 0kg/ha PG (control), plot 2 treated with PG rate of 1,500kg/ha and plot 3 received 3,000kg PG/ha. PG was incorporated to the soil by a shallow tillage (around 15 cm depth).



Fig. 38. Settat region

Field trials were conducted as follows:

Rapeseed

- i. Ouled Saïd - Settat region (latitude: 32°58'50.21"N, longitude: 7°48'21.34"W). The soil-type (deep) is Vertisol (locally called TIRS).
- ii. Aïn Ali Moumen - Settat region (latitude: 32°55'50.78"N, longitude: 7°36'23.73"W). The soil-type is Calcixeroll - a clayey soil shallow soil with lime hard pan ~20-35 cm deep.
- iii. Jamaat Riah - Settat region (latitude: 33°9'11.23"N, longitude: 7°26'21.41"W), which is the INRA agricultural research station (Institut National de la Recherche Agronomique). The studied soil-type is sandy loam with lightly acidic to neutral pH.
- iv. El Gara - Settat region (latitude: 33°17'24.80"N, longitude: 7°19'7.68"W). The soil type is a Vertisol, very clayey and very deep.

38. See <https://www.cropnutrition.com/efu-secondary-nutrients>

39. See <https://www.extension.uidaho.edu/publishing/pdf/CIS/CIS1124.pdf>

40. See <https://www.sulphurinstitute.org/about-sulphur/sulphur-the-fourth-major-plant-nutrient>

41. See <https://www.researchgate.net/publication/298788613>

Legumes (food crops)

- El Gara - Settati region (latitude: 33°17'24.80"N, longitude: 7°19'7.68"W). Tested crop is winter chickpeas. The soil type is the same as in iv above.
- Ain Sbit - Rommani - Rabat region (latitude: 33°33'9.28"N, longitude: 6°32'21.64"W). Tested crops are spring chickpeas and lentils. This site has higher rainfall than the other tested sites.

Phosphate was applied as DAP to all trial plots (types, 1, 2 and 3) before sowing. No S source was applied other than of PG.

1.4.2.2 SOIL AND PLANT SAMPLING AND ANALYSIS

Plant samples were taken at two different stages for rapeseed: at full flowering/ seed setting stage and at harvest (maturity) while samples for both chickpeas and lentils were taken at harvest. Three (3) composite plant samples were taken from each of the trial plots at every site.

All samples were air dried after harvest. The rapeseed plant samples at flowering were then weighed and separated into stems + leaves and seedpods. The chickpea and lentil samples were threshed and cleaned manually to determine both grain and straw yields. The rapeseed yield at harvest (maturity) were evaluated in terms of dry matter

1.4.2.3 SUMMARY OF FINDINGS

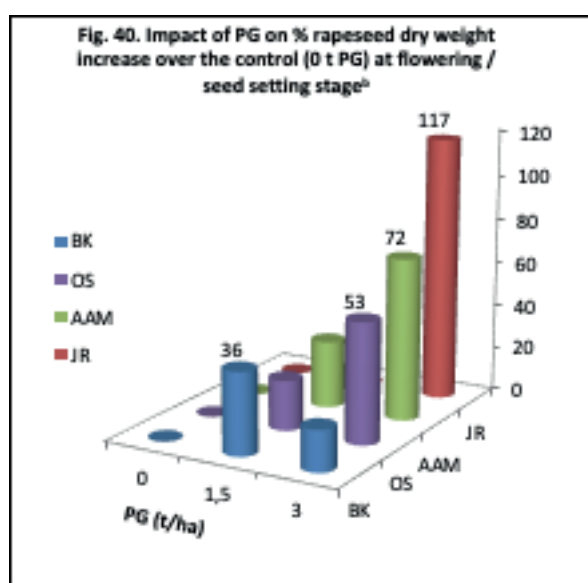
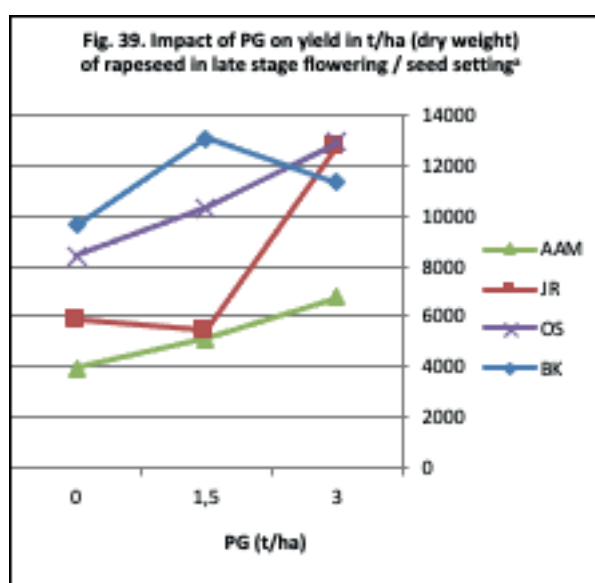
The soils of the trial plots at Ouled Saïd and El Gara are very clayey, lightly calcareous, with a slightly alkaline pH, while soil at the Jemaat Riah experimental station has a balanced to sandy texture and a slightly acid pH. Soils of Ouled Saïd and El Gara have similar medium K levels but different levels of plant available P and trace elements. P levels in soil at Ouled Saïd were markedly low but average at El Gara and Jemaat Riah. The impact of PG application to rapeseed was measured by sampling at two different stages of growth, (1) late flowering/ seed setting and (2) maturity (harvest) (Fig. 39, Fig. 40, Fig. 41, Fig. 42).

and grain. Dry matter and grains of all components of the tested crops were analysed separately for their nutrient, heavy metals and radioactivity contents. The analysis concerned N, P, K, S, Mg, Ca, Na, Cl, Zn, Mn, Fe, Cu and B together with certain heavy metals, As, Cd, Hg and Pb. (Table 8) The same procedures for analysis and sample preparation were applied to the rapeseed for both sampling date and for lentils and chickpeas at harvest.

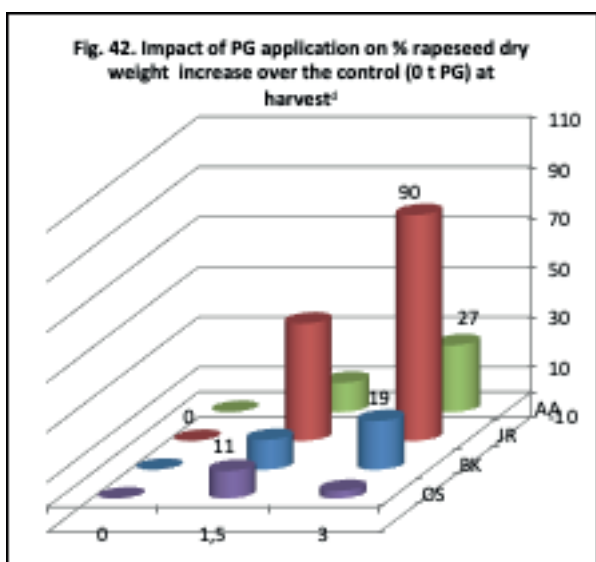
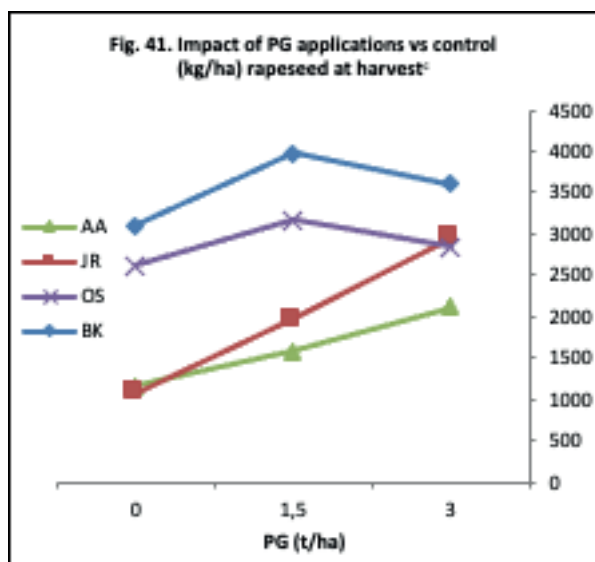
Soil samples were taken from rapeseed trial plots (control plot and PG treated plots) at Ouled Saïd, El Gara and Jemaat Riah in the upper soil horizon (0-20cm). They were oven dried, ground and sieved to pass 2mm.

Soil physical and chemical analysis concerned:

- Granulometry (five (5) fractions: clay, two (2) fractions of silt and two (2) fraction of clay), pH, soil organic matter (SOM), CaCO_3 , active Ca, electrical conductivity (extract 1/5)
 - Plant available P_2O_5 ; exchangeable cations (K_2O , Na_2O , CaO and MgO), Fe, Mn, Zn, Cu, Cl, nitrates and ammonium (NO_3 and NH_4)
 - Heavy metals: As, Cd, Hg and Pb
- Radioelements: ^{238}U chain (^{234}Th , ^{226}Ra , ^{214}Pb , ^{214}Bi); ^{232}Th chain (^{228}Ac , ^{208}Tl , ^{212}Pb , ^{212}Bi), ^{235}U and ^{40}K chain.



^{a, b} Legend of pilot site locations (Figs. 39, 40) . BK: El Gara; OS: Ouled Saïd; AAM: Ain Ali Moumen; JR: Jemaat Riah



^{c, d} Legend of pilot site locations. BK: EL Gara, OS: Ouled Saïd, AAM: Aïn Ali Moumen, JR: Jemaat Riah

TABLE 8. Content of As, Pb, Cd and Hg in both grain and plant matter (dry weight) samples taken at late stage flowering/seed-setting

SITE	PG (t/ha)	LATE STAGE FLOWERING/SEED-SETTING				GRAIN AT HARVEST				STRAW AT HARVEST			
		As	Pb	Cd	Hg	As	Pb	Cd	Hg	As	Pb	Cd	Hg
AA.Moumen (AAM)	0	0.56	0.24	0.11	0.3	0.54	0.04	1.99	0.06	0.85	0.1	0.07	0.39
AA.Moumen (AAM)	1.5	0.69	0.08	0.12	0.61	0.21	0.33	0.47	0.03	0.56	0.08	0.09	1.0
AA.Moumen (AAM)	3	0.58	0.03	0.11	0.4	0.48	0.02	1.69	0.05	0.16	0.27	0.1	0.59
El Gara (BK)	0	0.47	0.29	0.09	0.65	0.59	0.01	2.01	0.03	0.66	0.9	0.06	0.76
El Gara (BK)	1.5	0.38	0.23	0.1	0.75	0.59	0.13	2.28	0.03	0.65	1.02	0.07	0.39
El Gara (BK)	3	0.36	0.08	0.09	0.53	0.6	0.01	1.92	0.03	0.47	0.22	0.08	0.49
Jemaat Riyah (JR)	0	0.2	0.36	0.08	0.58	0.28	0.4	0.85	0.03	0.01	0.52	0.08	0.31
Jemaat Riyah (JR)	1.5	0.81	0.09	0.07	0.62	0.49	0.06	1.54	0.03	0.48	0.46	0.08	0.54
Jemaat Riyah (JR)	3	0.4	0.03	0.01	0.56	0.44	0.2	1.14	0.02	0.56	0.53	0.05	0.56
Ouled Saïd (OS)	0	0.4	0.3	0.1	0.46	0.52	0.17	1.91	0.05	0.17	2.71	0.09	1.26
Ouled Saïd (OS)	1.5	0.36	0.14	0.15	0.41	0.49	0.17	1.49	0.03	0.27	0.29	0.1	0.92
Ouled Saïd (OS)	3	0.44	0.16	0.1	0.4	0.79	0.17	2.43	0.04	1.3	1.65	0.09	0.66

TABLE 9. Radioactivity in soil and plant (Dry Matter, grain and straw) in Bq/kg

	Treatment	²²⁶ Ra	²³⁴ Th	²¹⁴ Pb	²¹⁴ Bi	²²⁸ Ac	²⁰⁸ Tl	²¹² Pb	²¹² Bi	²³⁵ U
Soil	Control	25.9	20	13.5	9.1	33.3	11.7	32.9	32.9	0.9
	1.5° t/ha	29.8	18.2	14.3	15	33.8	10.8	32.7	32.7	0.8
	3° t/ha	25.9	18.3	13.1	14.6	34.7	10.7	31.1	31.1	0.8
Plant (DM, grain & straw)	All	<LD:3.7	<LD:7.9	<LD:2.09	<LD:2.2	<LD:2.7	<LD:2.4	<LD:1.9	<LD:1.9	<LD:5.2

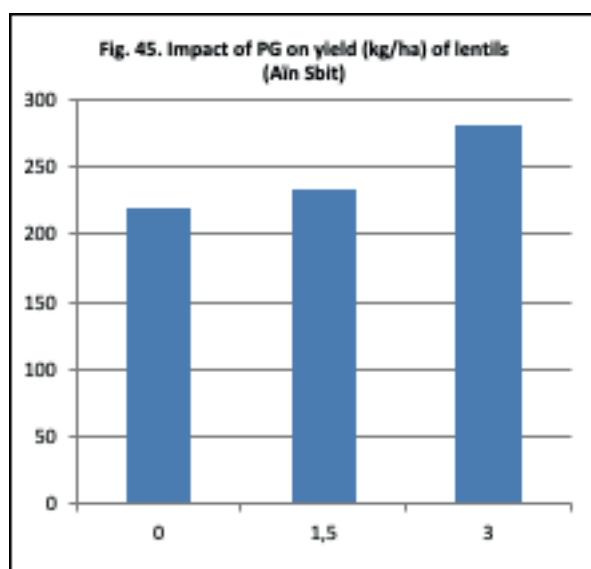
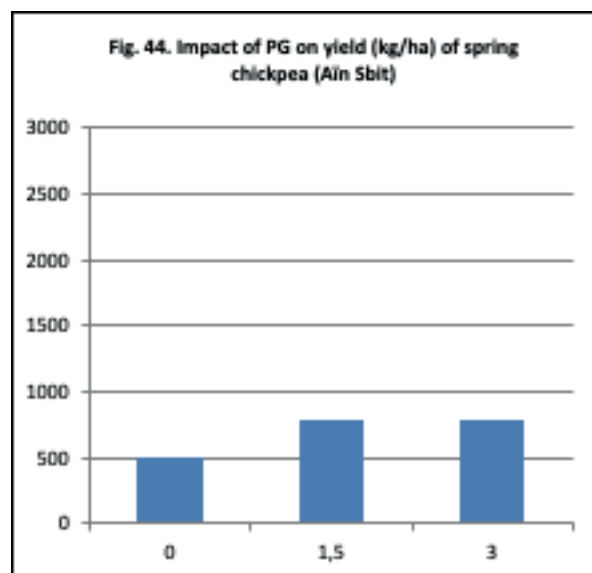
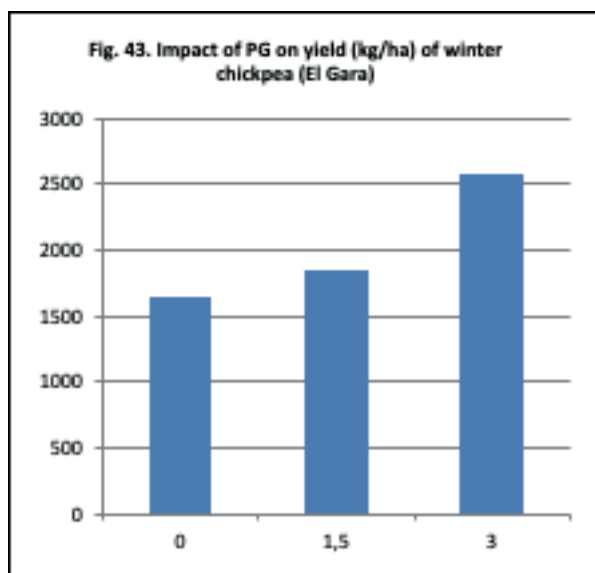


Fig. 46. Spring chickpea and lentils (Ain Sbit)
(Image courtesy OCP)



Fig. 47. Winter chickpea (El Gara)
(Image courtesy OCP)

1.4.3 PRIMARY CONCLUSIONS

1.4.3.1 RAPESEED

- The % increase in yield of dry matter (straw) at late-stage flowering/ seed setting is significant in PG treated plots vs control.
- PG application increased plant P uptake by dry matter at late-stage flowering/ seed setting through its direct contribution to P soil availability and indirect effect on availability of other nutrients, including trace elements as well as soil chemical changes. Therefore, PG contributed to enhancement of other benefits in addition to yield.
- P increases in treated plots with PG vs control ranged from 0-18kg P/ha with 1.5t PG/ha rate and 8-20 kg P/ha at 3t PG/ha rate. The increase in P uptake is equivalent to the quantity of P in 100kg DAP.
- S delivered by application of PG positively impacted both the rapeseed dry matter content at late-stage flowering but also the plant uptake of S by the rapeseed as a whole.
- Application of PG contributed to increased plant uptake of other nutrients, especially N, K, Ca and Mg. N and K uptakes as measured by dry matter at late flowering stage in PG treated plots were on the average 22-100 kg N/ha and 26-128kg K₂O/ha higher than uptake from the control plot.
- Applied as a fertiliser, PG had both direct and indirect benefits on increasing production of dry matter and plant mineral nutrients uptakes. These increases resulted from an enhanced water use efficiency and an improved plant availability and efficiency of nutrients in the soils.
- The trace element content in rapeseed dry matter analysed from samples taken at the later flowering stage were positively influenced by the application of PG.
- Maximum grain yield was obtained with the application of 1.5t PG/ha at El Gara (BK) and Ouled Saïd (OS) while at Aïn Ali Moumen (AA) and Jemaat Riyah (JR) maximum yield was attained with the 3t PG/ha rate. By contrast dry matter yield was highest at all sites at 3t PG/ha with the exception of OS where the maximum value was obtained at a rate of 1.5t PG/ha. Overall yield gains vs control varied considerably from site to site in the range of 21%-175% for grain and 11% to 90% for total dry matter or straw.
- Micronutrient contents in dry matter of rapeseed at flowering were also positively affected by PG application.

Yield increases due to PG were achieved through the increase of grain/pod, but also grain weight/total biomass. That indicates that PG had a positive impact on the contribution of produced biomass to grain filling.

- PG application increased the grain uptake of P, N, K, S and Ca
- Except for B, the grain uptake of trace elements (Zn, Cu, Mn, Fe) was increased by PG application
- PG application had a negligible impact on heavy metals uptake (As, Pb, Cd and Hg), hence presenting no problems for the quality of rapeseed production. Actually, PG even reduced plant Pb content (Table 8)
- The radionuclides analysis (Table 9) clearly indicated that there is neither accumulation in soil nor transfer to the plant in comparison with the control. In fact, levels of radionuclides in plant and soil after harvest had values under limit of detection (<LD)) (Table 9).

1.4.3.2 LEGUMES – CHICKPEAS AND LENTILS

- PG application increased the yield of winter chickpeas (Fig. 43, 47). The highest yield increase (30%) was achieved by an application rate of 3t PG/ ha. This result demonstrates the role of PG in increasing water use-efficiency under dryland conditions.
- PG application increased the yield of spring chickpeas by 50% (Fig. 44, 46) at both 1.5t/ha and 3t/ha PG application increased the yield of lentils by 27% at an application rate of 3t/ha (Fig. 45, 46)
- PG also enabled an increase in winter chickpea crop uptake of both macro- and micro-mineral nutrients. These included in particular N, K, S, Zn, Cu, Mn, Fe and B. There was no evidence of any increase in heavy metal uptake into the chickpeas.

Planting conditions for spring chickpea and lentils are shown in Fig. 46 and for lentils and winter chickpea Fig. 47.

1.4.4 NEXT STEPS NOW IN HAND

Conduct is underway of new field trials using PG as fertilizer under controlled conditions and in the fields using different combinations of crop and soil types and different rates of PG. Some trials are being carried out in partnership with the National Institute of Agronomic Research (INRA), the Ministry of Agriculture, Marine Fisheries, Rural Development, Water and Forests. Other trials will be carried out by the Innovation and Technology Transfer Center of Mohammed VI Polytechnic University.

1.5 VALORISATION OF PHOSPHOGYPSUM AS AMENDMENT FOR THE RECLAMATION OF SALINE/ SODIC SOILS: AGRONOMIC FIELD TRIALS - MOROCCO

AUTHORS

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Youssef ZEROUAL, OCP Innovation, OCP

1.5.1 INTRODUCTION

Soil salinity is an international scourge that contributes on a global scale to the deterioration of both soil and ground water quality while severely limiting crop yield. At a global level, somewhat surprisingly in view of the pervasive and very costly nature of the problem, there are no reliable statistics on the current extent and nature of the problem. An early analysis in percentage terms [49] put the global salt affected soil figure at some 50-60% of all soils in irrigated areas, though salinity and sodicity are themselves acknowledged variable in nature.

One of the most recent analyses, published in 2019, however concludes: “The total area of salt affected lands by our assessment is around 1 billion hectares, with a clear increasing trend” [50]. The management and remediation of saline soils is a high priority for both FAO and IAEA leading to the publication of a dedicated handbook for diagnostics [51].⁴³

These salt-affected soils are found mainly in irrigated areas in more than 75 developing countries with an arid or semi-arid climate and where food security is already at risk. In these countries, the use of marginal soil and water resources is at the same time, unavoidable and continuously increasing in order to meet the population's growing demand for food.

In arid and semi-arid conditions, salts accumulate due to intense evaporation, especially of water irrigation, and there is insufficient rainfall to wash the salts away from the root zone. This phenomenon, known as secondary salinization, affects several irrigated perimeters and soils in Morocco, particularly those in the regions of Doukkala, Tadla, Gharb, Souss-Massa, Moulouya, Loukkos, Tafilalet, Drâa, El Kelaâ des Sraghna, Bahira, Tassaout, Chichaoua but also affecting many others (Fig. 48). In fact, as elsewhere in the world, the salinization of water and soil is increasing and affects the quality of soils and their productivity. The surface area of saline soils in Morocco was estimated by the FAO in 1988 at 1.148 million ha [52].⁴⁴

Soils affected by salinity deteriorate due to changes in their physical properties (such as soil capping, crusting, hardening, swelling and dispersal of clays and loss of structure, run-off and erosion) which negatively impact the retention, availability and the movement or free drainage of water in the soil. Such changes have a direct effect on crops, by restricting their growth, yield and quality.

To remediate saline soils, different chemical, physical or biological approaches, separately or in combination, are used, including application of chemical amendments, addition of organic matter, tillage, but also the planting of salt-tolerant crops and varieties.

Chemical amendments such as sulphuric acid, hydrochloric acid and calcium polysulphide for the correction of soil salinity are used to provide Ca^{2+} (as gypsum, phosphogypsum, hydrated calcium chloride) or to solubilize precipitated calcite (CaCO_3) especially in calcareous soils. Increasing Ca^{2+} levels in both the solution and on the exchange complex of the soil improves soil particle aggregation and reduces crusting, thus improving the hydraulic properties of the soil.

1.5.2 STUDY OBJECTIVES

Using PG as either soil amendment, or fertiliser, or both, has a number of advantages: in addition to supplying Ca and S to soils deficient in these elements. PG contains available P and a range of other plant nutrients including micronutrients. The objective of this study was to evaluate in real field-conditions the effects of PG on (1) crop growth and yield and (2) the quality of saline soils in Morocco and (3) on radionuclides and heavy metals changes in soil and transfer to the plant.

1.5.3 MATERIALS AND METHODS

1.5.3.1 LOCATION AND CROP SELECTION

The field trials were carried out in the region of El Kelaâ des Sraghna, on the plain of Had Lamharra, precisely in the area of Sed El Masjoune (Fig. 49) which is known for its high levels of salinity in both soil and groundwater. The climate of the region is semi-arid with low precipitation. The principal crops grown are i. barley and ii. fodder maize for silage.

1.5.3.2 PLANTING AND TREATMENTS

Each trial plot received a basal application of phosphate in the form of DAP (Fig. 50, Fig. 51). Two (2) crops were planted, barley and maize. Treatments consisted of three PG treatments: a control with no PG application and two rates of PG. These PG rates were tilled in (Fig. 52) at 15t/ha and 30t/ha for barley and 20t/ha and 40t/ha for maize (Table 10).

42. For further detail on Mohammed VI Polytechnic University see Case Study 1.4 above and <https://www.um6p.ma/en>

43. See <https://link.springer.com/content/pdf/10.1007%2F978-3-319-96190-3.pdf>

44. See <http://www.fao.org/3/x5871e/x5871e03.htm#2.4%20Distribution>

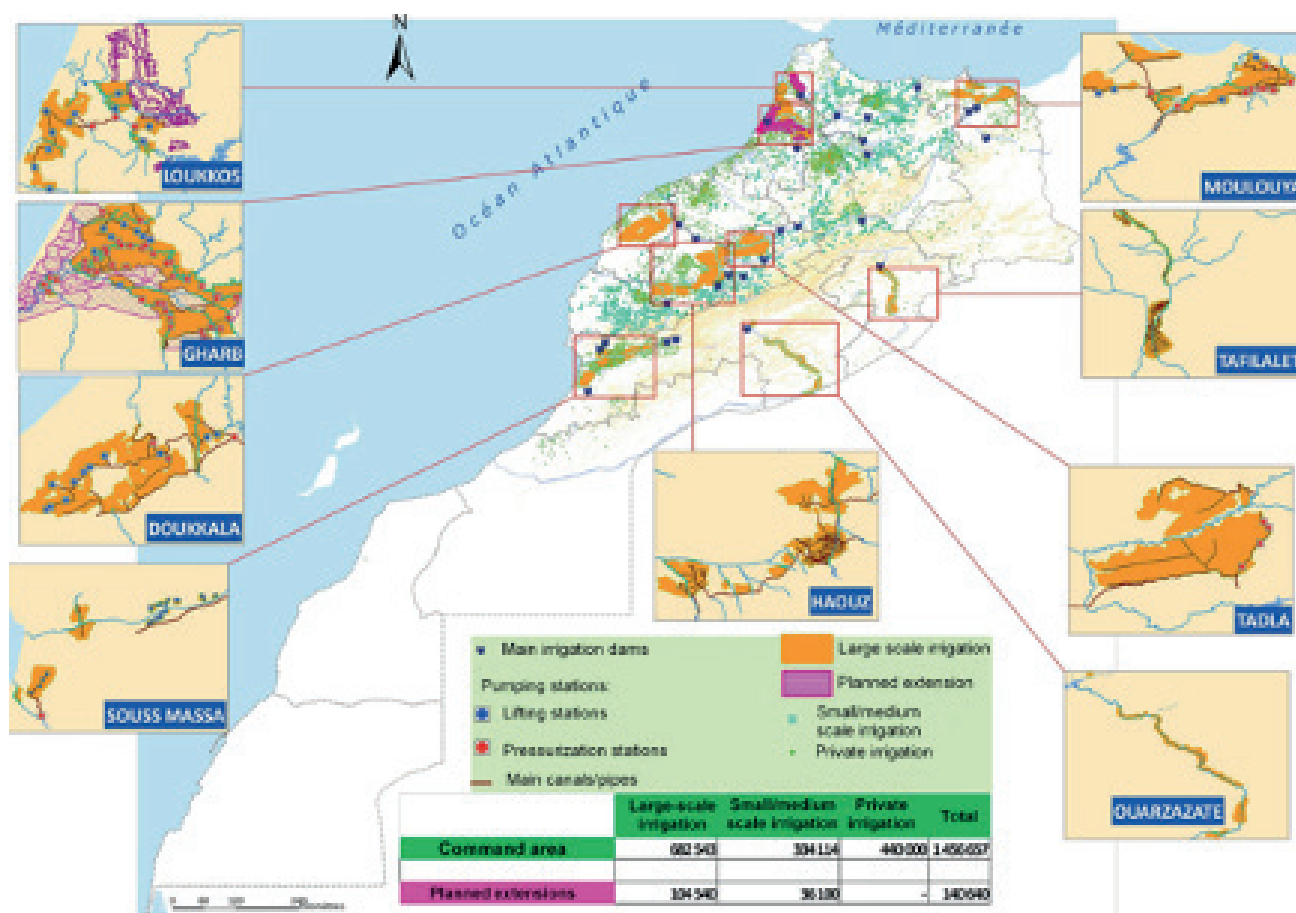


Fig. 48. Main irrigated regions of Morocco



Fig. 49. Field trial location

TABLE 10. Crops, control and treatments

CROPS	CHECK PLOT	TREATMENT 1	TREATMENT 2
Barley	0 t/ha	15 t/ha	30 t/ha
Maize	0 t/ha	20 t/ha	40 t/ha

**Fig. 50.** Trial plots, with control plot (Image courtesy OCP)**Fig. 51.** PG bagged and ready for application (Image courtesy OCP)**Fig. 52.** PG being tilled in on trial plots for barley and maize pre-treated with P application as DAP (Image courtesy OCP)

1.5.3.3 SAMPLING AND ANALYSIS OF SOILS AND CROPS

Soil samples were taken from all plots of the different treatments at a depth of 0-20 cm for maize and 0-20 and 20-40 cm for barley. The physico-chemical analyses carried out concerned the following parameters: granulometry (5 fractions), pH, soil organic matter (SOM), CaCO_3 , active Ca, Electrical Conductivity (EC: 1/5), plant-available P_2O_5 , exchangeable K_2O , exchangeable Na_2O , exchangeable MgO , exchangeable CaO , Fe, Mn, Zn, Cu, Cl, NO_3 and NH_4 .

For each trial plot, four (4) samples of forage maize were taken, weighed and dried, first in the open air and then in the oven. For each sample, measurements were taken for: weight of dry matter, the number of stalk and stems, the number of kernels (ears) and their weight, and grain weight.

For each treatment, the analysis of grain and corn dry matter (Table 11) were performed on a composite sample of four (4) subsamples. The analyses of nutrient content concerned: N, P, K, S, Mg, Ca, Na, Cl, Zn, Mn, Fe, Cu and B.

1.5.4 SUMMARY FINDINGS

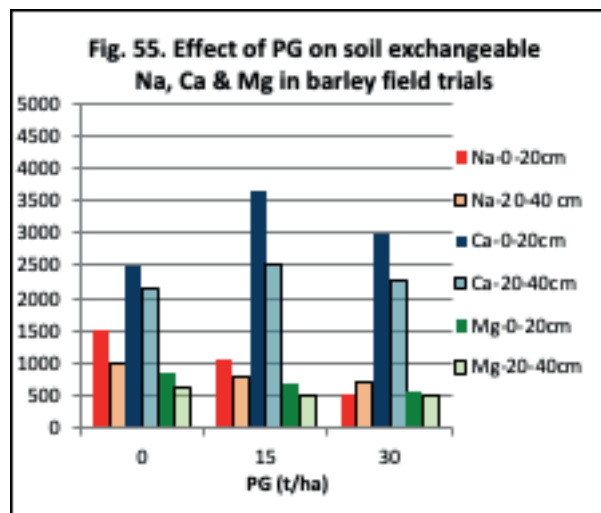
The soil of the trial plots was found to be (1) silty-clay, poor in SOM and with an alkaline pH (2) slightly calcareous at the surface (0-20cm) and moderately calcareous at depth (20-40cm) (3) rich in phosphorus, magnesium, manganese and in zinc, but poor to average in iron and calcium. The levels of sodium and of salinity were high. Phosphorus was added to both crops as a basal application to ensure that P was not a limiting factor.

TABLE 11. Soil physico-chemical analysis of trial plots under barley and maize

Planting (depth)	Dose of PG (t/ha)	Clay	Sand	Silt	K ₂ O	P ₂ O ₅	pH	MO	EC1/5	CaCO ₃	Ca Act.	Na ₂ O	CaO	MgO	Fe	Mn	Zn	Cu	Cl	NO ₃	NH ₄
		%			ppm	ppm		%	mmhos/cm	%	%	ppm	ppm	ppm	ppm	ppm	ppm	ppm	mg/100 g soil		
Maize (0-20cm)	0	39	31	30	497	138	8.1	1.89	2.99	7.7		2,894	4,032	1,082	10.55	61.82	2.37	1.96	497	138	8.1
Maize (0-20cm)	20	40	29	32	394	226	8.2	2.23	1.89	7.7		1,470	4,480	1,445	11.54	46.74	3.3	1.81	394	226	8.2
Maize (0-20cm)	40	36	33	31	525	205	7.9	2.4	5.75	6.8		4,552	6,888	1,602	12.84	84.94	3.63	2.06	525	205	7.9
Barley (0-20cm)	0	38	28	34	405	411	8.3	3.71	1.44	8.2		2,031	3,528	1,416	10.2	60.24	6.65	2.81	405	411	8.3
Barley (20-40cm)	0	41	25	34	466	148	8.5	1.79	1.02	11.3	6.4	1,375	3,052	1,034	5.66	21.86	1.63	1.53	466	148	8.5
Barley (0-20cm)	15	40	25	36	350	212	8.1	2.45	1.86	8		1,412	5,152	1,156	7.68	33.51	3.44	1.72	350	212	8.1
Barley (20-40cm)	15	44	27	30	359	42	8.5	1.22	0.85	11.7	6.8	1,078	3,528	835	5.81	13.65	0.54	1.34	359	42	8.5
Barley (0-20cm)	30	42	24	35	340	115	8.3	2.38	1.08	8.8		717	4,228	956	7.94	21.57	1.74	1.99	340	115	8.3
Barley (20-40cm)	30	38	27	35	320	25	8.8	1.12	0.48	14	8.3	937	3,220	821	5.54	9.1	0.44	1.08	320	25	8.8

1.5.4.1 BARLEY TRIALS

**Fig. 53.** Crop response Barley (L. control with no PG; R. PG plot marked with white envelopes, 30tPG /ha) (Image courtesy OCP)**Fig. 54.** Leaf burn reduced by PG application (L. control with no PG; R. 30t/ha PG) (Images courtesy OCP)



1.5.4.2 MAIZE TRIALS



Fig. 56. Maize with different doses of PG: Top L 0t PG/ha (control); Top R 20 t PG/ha (1); Bottom 40 t PG/ha (2) (Image courtesy OCP)

Fig. 57. Impact of PG on maize green matter (kg/ha)

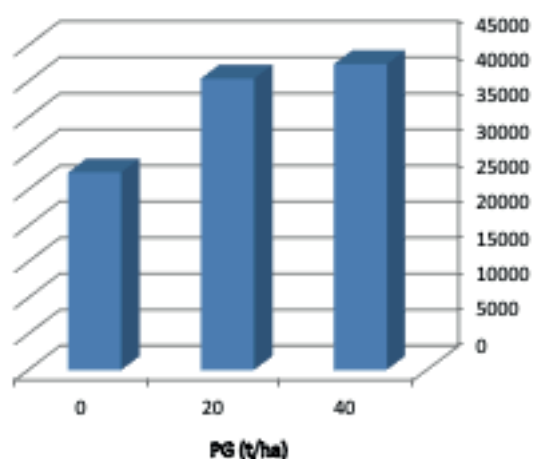


Fig. 58. Impact of PG on dry weight of maize grain (as % increase vs control)

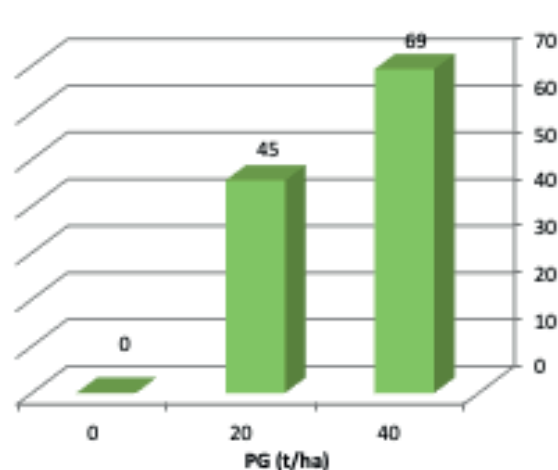


Fig. 59. PG effect on corn grain at milk stage, % yield vs control

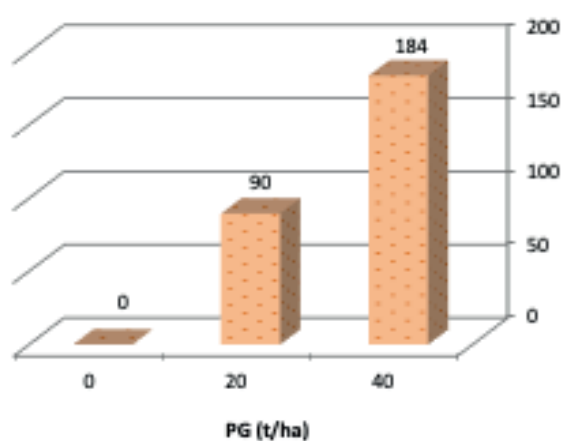


Fig. 60. PG effect of GP on kernel yield at milk stage, % yield vs control

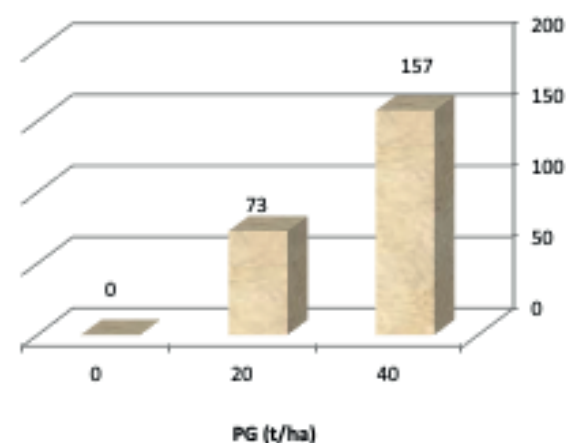


Fig. 61. Effect of PG on soil available P_2O_5 (ppm)

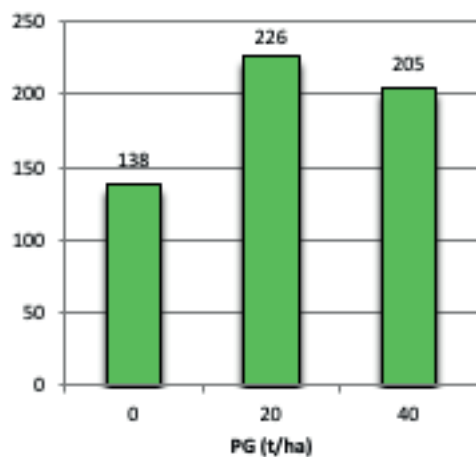


Fig. 62. PG effect on P uptake of forage maize at milk stage (kg/ha)

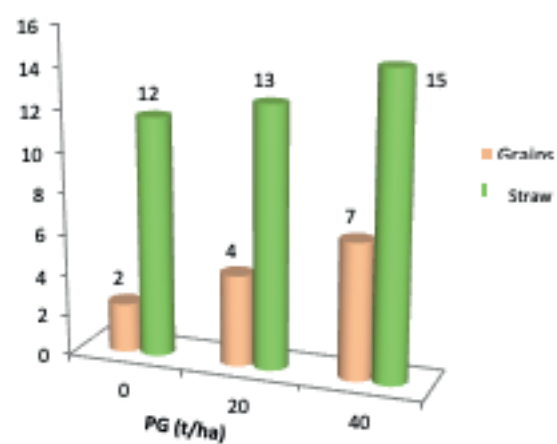


Fig. 63. Effect of PG on N uptake of forage maize at milk stage (kg/ha)

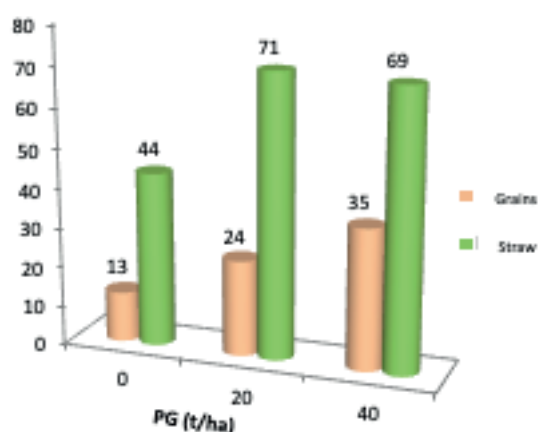


Fig. 64. Effect of PG on K₂O uptake of forage maize at milk stage (kg/ha)

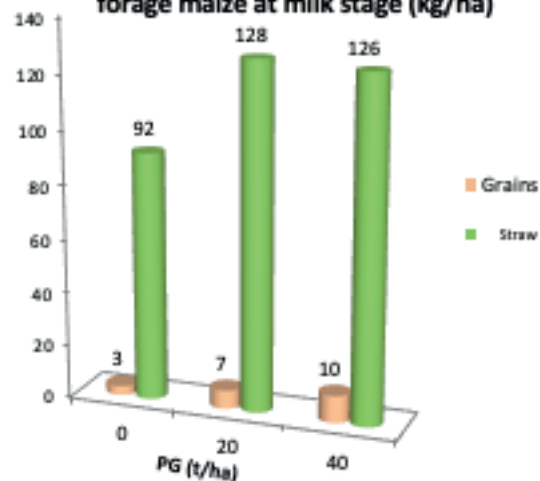


Fig. 65. Effect of PG on Mg uptake of forage maize at milk stage (kg/ha)

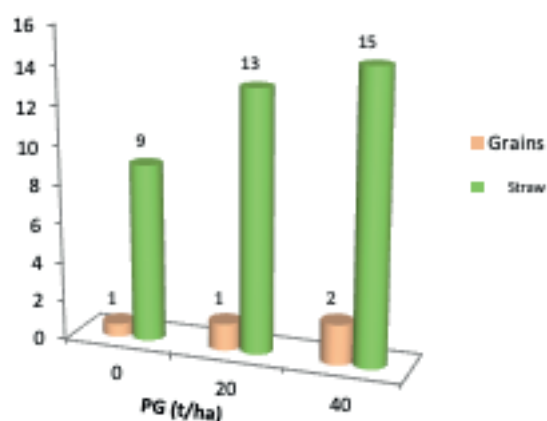


Fig. 66. Effect of PG on Ca uptake of forage maize at milk stage (kg/ha)

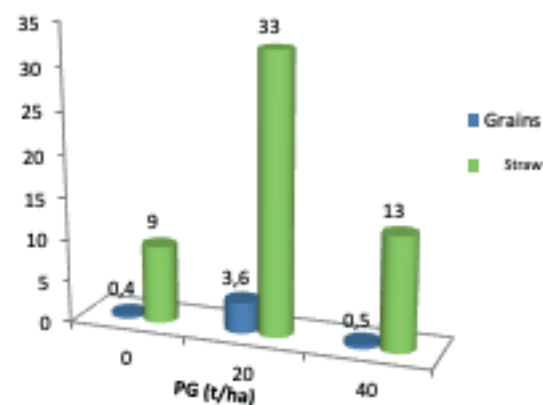


Fig. 67. Effect of PG on Zn uptake of forage maize at milk stage (kg/ha)

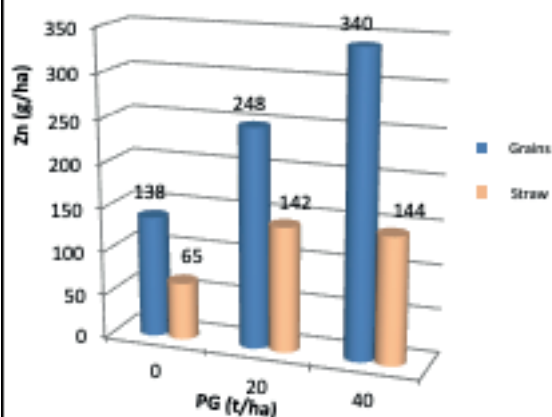
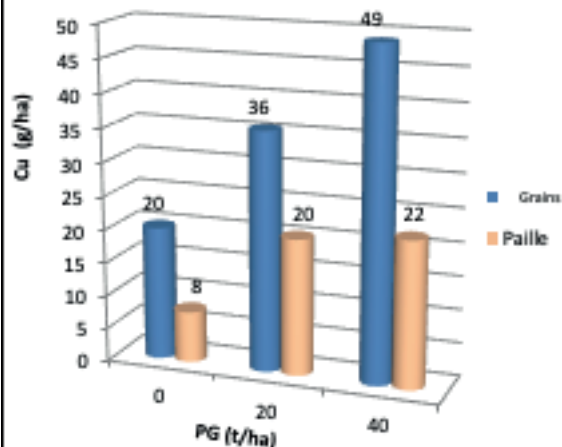
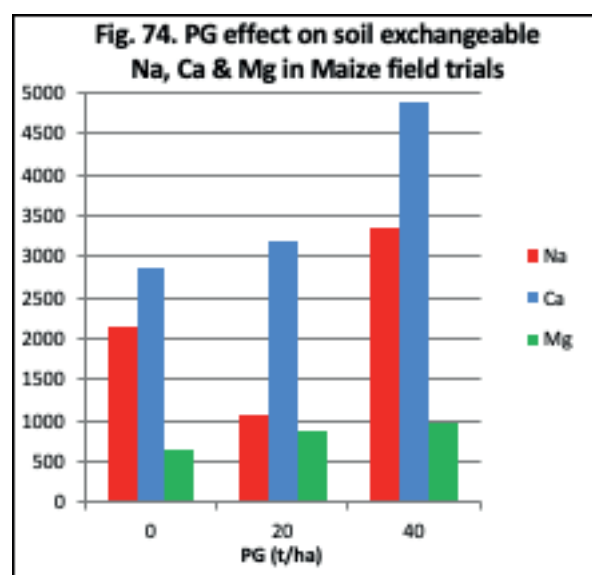
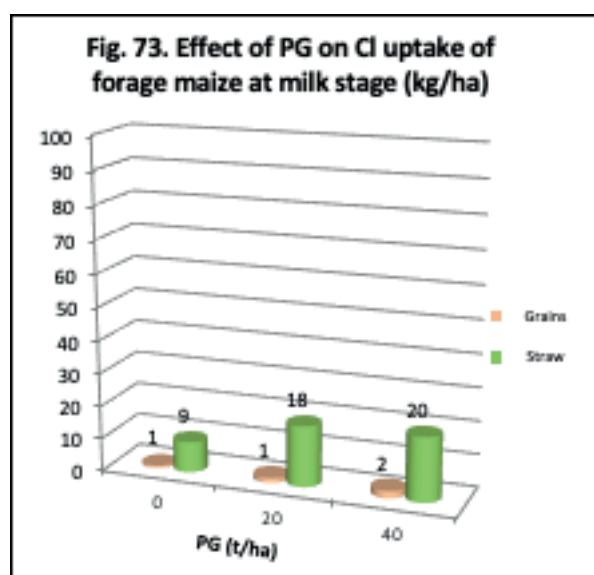
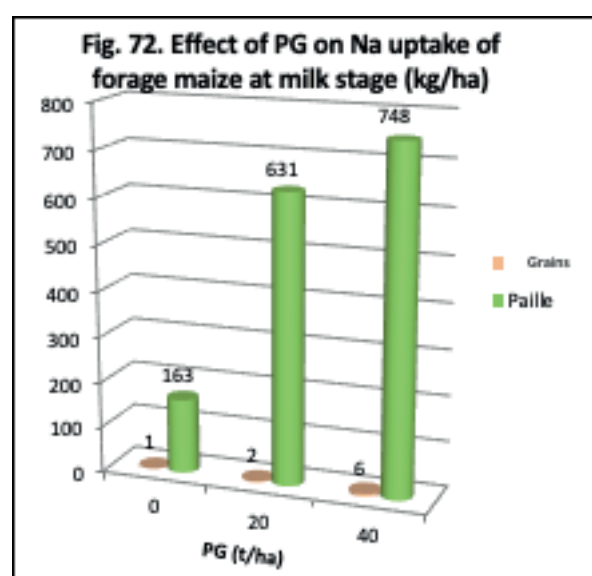
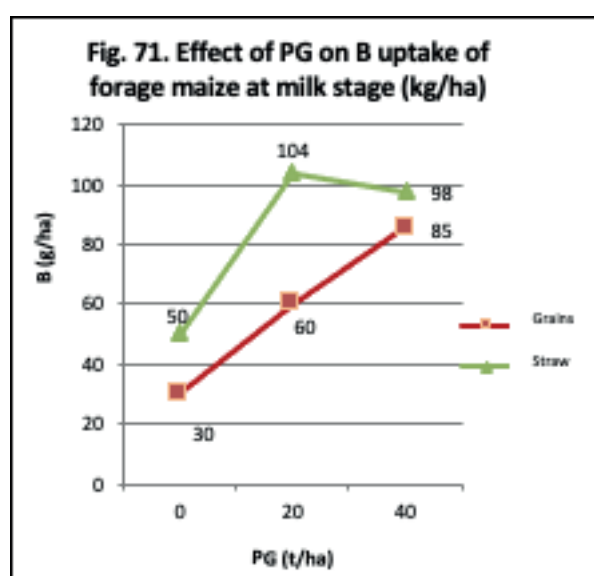
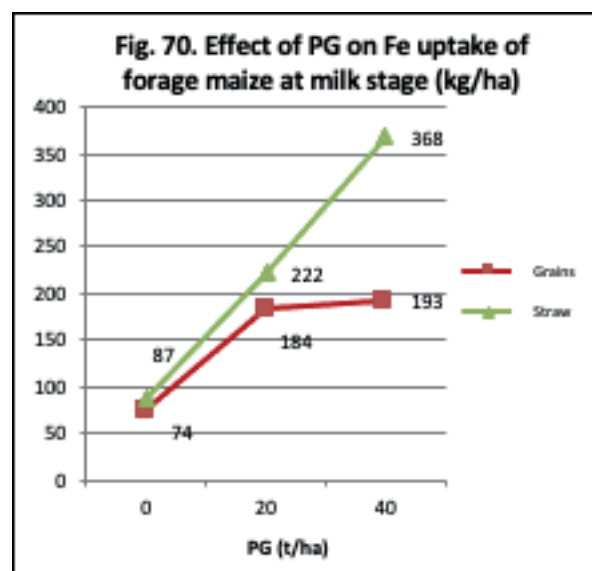
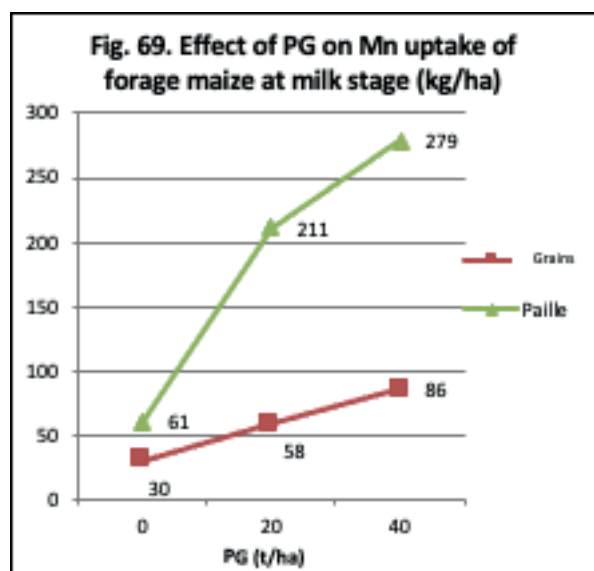


Fig. 68. Effect of PG on Cu uptake of forage maize at milk stage (kg/ha)





1.5.5 PRIMARY CONCLUSIONS

1.5.5.1 BARLEY TRIALS

- Yield on plots treated with 30t/ha is 40-50% higher than the control (no PG) (Fig. 53).
- Application of PG increased irrigated water use-efficiency because all the plots received the same amount of water but yields in PG treated plot were higher. The burning of the tips of leaves of barley were reduced in plots treated with PG at 30t/ha in comparison with the control (Fig. 54).
- The effect of PG application on soil exchangeable Na, Ca and Mg is shown in Fig. 55. Benefit to Ca uptake in the upper soil horizon (0-20cm) is most pronounced with benefits to both plant and soil condition.

1.5.5.2 MAIZE TRIALS

- Yield in terms of green biomass from plots treated with PG are significantly higher than that of control. This increase is mainly due to the increase in average weight per stalk/stem (Fig. 56, Fig. 57).
- Application of PG increased dry matter by 45% and 69% respectively for PG rates of 20t/ha and 40t/ha (Fig. 58, Fig. 59).
- Although the corn was grown for forage production and not grain, grain yield, even in the milk stage, was positively affected by the application of the PG (Fig. 60, Fig. 62).
- All trial plots were rich in phosphate. Therefore, P exports by dry matter were only slightly affected by the input of the PG (Fig. 61).
- The application of PG contributed to increased plant uptake of N (Fig. 63), K (Fig. 64) and Ca (Fig. 66). Nitrogen and potash uptake by straw from plots that received PG treatment was on average 70 kg N/ha and 127 kg K/ha compared to 44 kg N/ha and 92 kg K/ha from the control plot. Uptake of N and K by the seeds was low because they were still in the milk stage and would have probably increased due to translocation and grain filling. Because nutrient efficiency is typically related to water efficiency, PG application also increased the efficiency of nitrogen and potassium use. Nitrogen levels in the corn were almost the same for the different treatments, so there was no dilution or decrease in N content with increased yield.
- PG application increased the micronutrient content in the straw (Table 12). Imports of these micronutrients by the straw increased with the application of the PG through its positive effect on both straw yield and micronutrient content (Figs. 67, 68, 69, 70, 71).

TABLE 12. Forage maize mineral content of straw and grain from control and PG treated plots

MAIZE	PG (t/ha)	N	P	K	Mg	Ca	S	Na*1000	Cl	Zn	Cu	Mn	Fe
		%MS	%MS	%MS	%MS	%MS	%MS	%MS	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Straw	0	1.01	0.27	2.12	0.21	0.21	0.98	3775.3	2.15	15.03	1.77	14.07	20.15
Straw	20	1.17	0.21	2.11	0.22	0.54	0.76	10433	3.05	23.44	3.37	34.96	36.76
Straw	40	1.04	0.22	1.88	0.22	0.2	0.92	11204	2.92	21.53	3.28	41.71	55.02
Grain	0	2.25	0.43	0.61	0.12	0.07	0.68	184.55	0.13	24.67	3.58	5.41	13.25
Grain	20	2.27	0.42	0.65	0.13	0.34	0.9	234.73	0.14	23.46	3.37	5.5	17.38
Grain	40	2.23	0.42	0.64	0.13	0.03	0.87	360.58	0.14	21.5	3.09	5.41	12.17

- Despite an increase of exchangeable Ca (as CaO) (Fig. 66) and Mg (as MgO) (Fig. 65) in the soil, the difference in uptake between plots with and without PG remained small for Mg grain content. However, the uptake of Ca from plots dosed at the 20t/ha rate was higher than both plots which received the higher rate of 40t/ha but also those with no PG dose at all (Fig. 65). This is due to an increase in the Ca content of straw and grain.

- PG application resulted in an increase in micronutrient contents of straw. Uptake of the micronutrients by straw increased with increased PG rate without reaching the lower limit threshold of toxicity in any single element. As a result, PG had a beneficial impact on plant micronutrient availability, which is generally low in calcareous soils.
- PG application enabled an overall enhancement of Ca levels in soils but did not affect the magnesium content.
- Plant sodium uptake increased with the application rate of the PG, which may be due to a higher availability of the sodium displaced by the PG application (Fig. 72). Plant chlorine plant withdrawals follow the same trend but remain very low compared to sodium removals.
- Plant uptake of Na (Fig. 72) increased with increased PG rates, which may be explained by the impact of PG application in mobilising more available Na already, present in the soil through its displacement from the cation exchange sites. Plant Cl uptake followed the same trend (Fig. 73) but remained very low compared to sodium uptake.
- The effect of PG application on soil exchangeable Na, Ca and Mg in maize is shown in Fig. 74.
- Radionuclide transfer to plant in the PG-treated plots was similar to that of the control plots (Table 13).

TABLE 13. Effect of PG application as amendment on the activities of radioelements in grain and straw of forage maize (Sed El Masjoune)

	CORN STRAW			CORN GRAINS		
	PG: 0 t/ha	PG: 20 t/ha	PG: 40 t/ha	PG: 0 t/ha	PG: 20 t/ha	PG: 40 t/ha
234Th (Bq/kg)	<LD = 8	<LD = 9.8	<LD = 8.3	<LD = 7.6	<LD = 9.5	<LD = 9.9
226Ra (Bq/kg)	<LD = 4.5	<LD = 3.7	<LD = 4	<LD = 4.1	<LD = 4.5	<LD = 3.6
214Pb (Bq/kg)	<LD = 2.4	<LD = 1.6	<LD = 1.9	<LD = 1.2	<LD = 1.5	<LD = 1.5
214Bi (Bq/kg)	<LD = 3.1	<LD = 2	<LD = 1.2	<LD = 2.1	<LD = 1.7	<LD = 1.6
228Ac (Bq/kg)	<LD = 3.3	<LD = 3.1	<LD = 2.1	<LD = 4.1	<LD = 2.7	<LD = 4.6
208Tl (Bq/kg)	<LD = 2.2	<LD = 1.6	<LD = 1.9	<LD = 1.5	<LD = 2.2	<LD = 1.5
212Pb (Bq/kg)	<LD = 1.7	<LD = 1.9	<LD = 2.4	<LD = 1.5	<LD = 2.1	<LD = 1.9
212Bi (Bq/kg)	<LD = 1.7	<LD = 1.9	<LD = 2.4	<LD = 1.5	<LD = 2.1	<LD = 1.9
235U (Bq/kg)	<LD = 6.2	<LD = 4.4	<LD = 4.9	<LD = 5.7	<LD = 3.7	<LD = 4.4
40K (Bq/kg)	757.4 ± 48.6	198.4 ± 16.9	740.7 ± 39.1	379.1 ± 25.8	732.5 ± 37.4	268.9 ± 12.8

1.5.6 NEXT STEPS

The following next steps were agreed:

1. Conduct of new field trials with PG as soil amendment under controlled conditions and in the field (different soil types, crops, and with varying PG rates and sources, in partnership with INRA (Ministry of Agriculture, Marine Fisheries, Rural Development, Water and Forests) and Mohammed VI Polytechnic University (UM6P).
2. Production of salinity/ sodicity soil maps for different regions of Morocco, in partnership with the National Institute of Agronomic Research (Institut National de la Recherche Agronomique - INRA), Ministry of Agriculture, Marine Fisheries, Rural Development, Water and Forests, (Ministère de l'Agriculture, de la Pêche Maritime, du Développement Rural et des Eaux et Forêts).

2. CASE STUDIES: CONSTRUCTION MATERIALS

An overview of research and development work conducted into uses of PG as a construction material, for example for use as a retarder in cement, brickmaking and housing, may be found in IAEA SR78 10.5.2 and in PG1 Section 4. The case studies in this section show how investment in R&D can translate into business model innovation and sustainable commercial success, using PG as a “reusable raw material”.

2.1 PHOSPHOGYPSUM AND THE BUSINESS OF SUSTAINABILITY: BELGIUM

AUTHORS

Tibaut Theys, Thierry Garnavault, Prayon

2.1.1 PRAYON CONTEXT

Prayon has a long and distinguished history of managing and using PG as a commercial resource [53], the intellectual case for which was admirably summarised by Armand Davister in 1998 in his paper on PG to the IFA Technical Conference that year in Marrakech [54]. Prayon’s successful approach figures large in PG1 and it was natural for PG2 to build on this success, looking in greater detail as to its nature and origins. So to initiate the industry-wide consultation process accompanying the development of PG2, a working meeting was held at Prayon HQ, Engis, Belgium (March 21-22, 2018)⁴⁵ under the title **Phosphogypsum in the circular economy: Technical and policy options for enhancing market acceptance of PG**.

The circular economy aspects of PG are dealt with throughout this Report, reflecting the breakthrough significance of the Engis meeting in showing how easily PG use fits in to a circular economy framework. This section is Prayon-specific. It explores the more than forty-year journey Prayon has made to establish itself as a globally significant reference case in how to turn the “orphan” problem of PG as a “waste” into PG as a commercially viable, environmentally sustainable and socially acceptable co-product of wet process phosphoric acid production. This is exactly the case Davister set out [55] and as a tribute to his vision and perspicacity, PG production and sale is now, twenty years later, fully integrated into the Prayon working culture and business offering.

It is a measure of how dynamic the commercial and regulatory landscape within which PG is now situated that three years on from publication of PG1, Prayon is now selling ~100% of the PG it produces as compared with 80-90% in 2016. Reaching this point of equilibrium between production and use is a remarkable milestone. But over and above the commercial success, the range of positive attributes which Prayon can now list for its PG have amplified to include water use efficiency in agriculture, as prized by local farmers in Belgium who use Prayon’s PG as soil amendment, and as a promoter of bio-diversity. This last attribute was discovered accidentally when after depositing small quantities of PG on land near the Engis production facility and then not covering the PG with soil as had previously been the standard practice, it was noticed that returning or new species of both flora and fauna started to colonise the PG. To build on this success the regulator now requires the PG not to be covered when deposited on the soil.

2.1.2 PG AS EXISTENTIAL ISSUE FOR PRAYON

In opening the Engis meeting, Prayon Technologies’ General Manager Tibaut Theys cited the driving principle behind Prayon’s success: “Constraints sometimes drive creativity and innovation in a really positive way”. The constraints Prayon faced in the 1980s were existential: that PG discharge to the adjacent River Meuse was forbidden by the regulator and there was no more land available in Engis to store the fresh PG being generated at the Prayon plant.

So there was a simple, stark choice: stop production or come up with a radically innovative solution – to completely re-engineer the phosphoric acid production process to yield a PG that could be sold long-term, primarily into the construction materials market but also to local agriculture, achieving balance between production and use.

Forty-two years on, Prayon’s success can be judged in business terms by the 2018 PG results (Table 14).

TABLE 14. 2018 Results: Prayon PA and PG - Production and Sales

- Phosacid production in TPY P_2O_5 : 159,000 t P_2O_5
- PG production tpy: 790,000 t
- PG sales:

Agronomic use	60,000
Plaster and cement	708,000
TOTAL	768,000

A milestone in the resource progression of PG has

45. The meeting was held under the joint auspices of Prayon, Aleff Group, IFA and Fertilizers Europe, and with the participation of a representative of the United Nations Economic Commission for Europe.

therefore, now been reached where production (supply) and consumption (demand) have reached a point of sustainable business equilibrium, now also meeting UNSDG 12 concerning responsible production and consumption. In reaching this landmark achievement there has been and still is no subsidy, the process being conducted as a commercial undertaking but one with significant environmental and social benefits. Hence Prayon demonstrated the validity of the Nash economic equilibrium model of sustainability [55], that sustainability and commercial viability are fully compatible concepts.

How and why did Prayon succeed? Are the factors involved applicable more widely to PG producers around the world? In general, this Report illustrates that the factors are applicable beyond Prayon, even in situations where the volumes of PG produced are very significantly higher than those generated by Prayon. In particular, three “soft” factors stand out, which are the core principles for PG management identified for PG2 as a whole:

- Leadership
- Innovation
- Partnership.

2.1.4 INNOVATION

Contrary to the trend of the wet process PA industry since the 1980s towards centralised large-scale multi-unit production facilities each with approximate capacity of 1 million tonnes per year of PA, Prayon maintained a business model based on a “small is beautiful” concept. But it complemented this approach by diversification of its business offering not just in terms of downstream tangible product streams, but also based on its unique combination of tangible (equipment such as filters) and intangible (know-how, flow-sheet design, training, precise plant control based on big data management) engineering and chemical engineering capabilities which are in demand and/or use around the world.

2.1.3 LEADERSHIP

In addressing the PG issue Prayon in its leadership has been proactive throughout and has led from the top. This is nowhere clearer than in its long-held view that PG is a co-product of PA production – or even that the real co-product is actually PA of PG production. Its leadership strategy has also been developed and executed against a background of a clear, commercially sustainable, environmentally responsible and benign PG management strategy, one fully embedded in the values and operational good practices of the company. These aspects which set the context for the PG leadership approach are fully explained on its website under the following headings:

- Comprehensive and integrated resource management
- Industrial and public health and safety
- Energy and climate
- Major environmental projects
- Stakeholder engagement and communications

However large the volume of PG being generated a sustainable solution for its eventual storage, management and use must address all five of these aspects in a coherent and consistent manner.

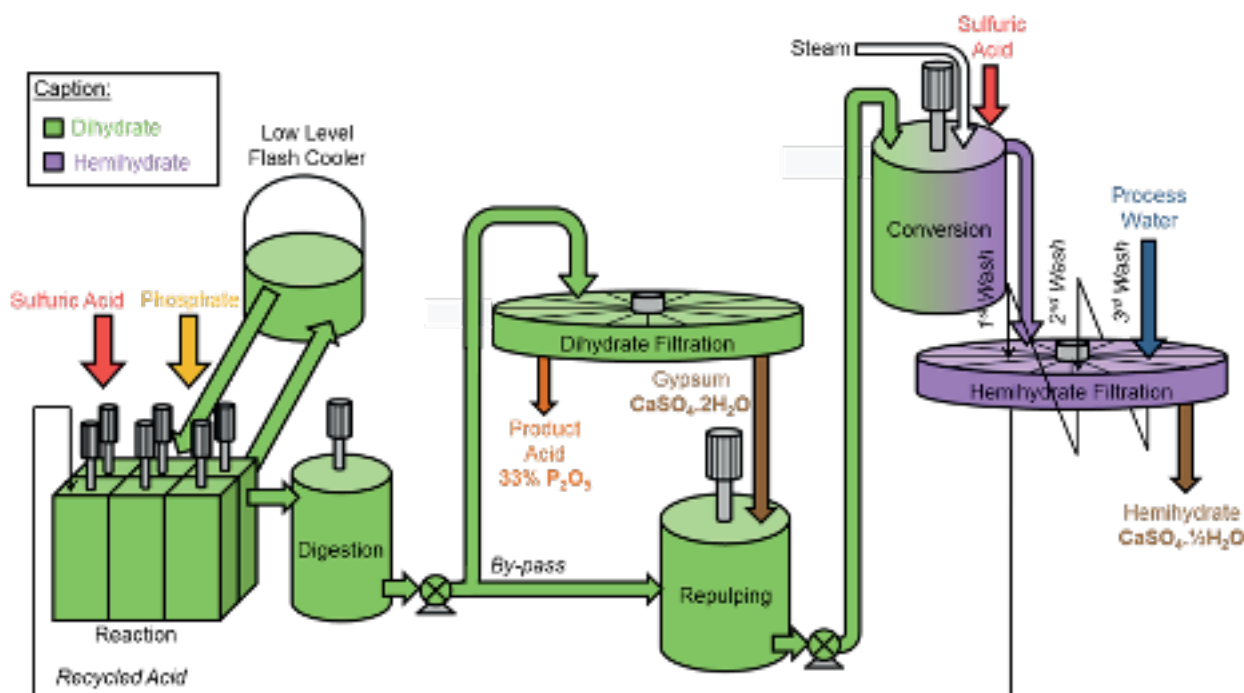


Fig. 75. The Central Prayon Process flowsheet (Image courtesy Prayon)

The innovative Central Prayon Process flowsheet (Fig. 75) summarises the Prayon response to the constraints it faced, and which is now the basis on which the whole PG process operates - innovate or close down. Prayon chose to innovate.

The features of the Central Prayon PG process are:

- High recovery efficiency, with reduced rock concentrate consumption resulting in saleable co-product with a consistent analysis and performance
- Enhanced P_2O_5 recovery to the filtered acid, with resultant reduced steam consumption and lower energy requirement
- A self-drying PG, requiring less fuel oil for processing
- Ability to accommodate a range of phosphate source rock types
- Environmentally friendly PG for interim storage, with higher societal and market acceptance
- Transformation of the model of a PG stack as a waste disposal device into a more “environmentally friendly” PG “quarry” (Fig. 78). As the gypsum in the quarry has been neutralised before interim storage leaching of impurities is negligible
- Using the reengineered post-1987 Central Prayon process results initially in a transition to the purer hemi-hydrate (HH) form of PG a purity partly derived from its use of phosphate rock from the Kola Peninsula⁴⁶ which is relatively low in both radionuclide and heavy metal content [2] [56] [57] [58].

2.1.5 PRAYON AND KNAUF MANUFACTURING FACILITIES

Prayon and Knauf manufacturing facilities are located on opposite banks of the River Meuse, close to the town of Engis (Fig. 76). The forest site now functioning as a PG interim storage area is also shown in Fig. 76.



Fig. 76. Prayon and Knauf manufacturing facilities on the River Meuse, close to Engis, with forest site of PG interim storage area (Image courtesy Prayon)

The HHPG is taken from Prayon as produced and carried across the river to Knauf by conveyor belt (Fig. 77) to a discharge point where it is temporarily stored. Over 28 days the HHPG then naturally reverts *in situ* with no further processing to its di-hydrate (DH) state before being processed by Knauf (Fig. 79) prior to shipment down river to the Knauf stucco plaster factory.



Fig. 77. The HHPG conveyor across the Meuse (Image courtesy Prayon)



Fig. 78. The PG “Quarry” (Image courtesy Prayon)

46. See below Case Study 3.1 where PhosAgro uses PG in road building also derived from “wet-processing” the phosphate rock of the Kola Peninsula.



Fig. 79. Turning DH PG into calcium sulphate for use in decorative stucco plaster manufacture (Image courtesy Prayon)

In 2018 some 89.6 % of production met Knauf specifications for the HH feedstock, while some 7.6% was used in agriculture leaving a small fraction of 2.8% to be moved to the interim storage area (ISA).

The process of innovation does not stop with reaching the point of equilibrium between production and use at Engis. It continues into the permanent quest for new solution like the new PG purification technology, “PureGyp” developed by the British company Carbon Cycle (Fig. 80)⁴⁷. The process dismantles the PG crystal lattice, releasing the impurities for separation, resulting in a bright white, highly marketable PG feedstock powder.



Fig. 80. Native HHPG (L) and when treated, shown as PureGyp (R) (Image courtesy Carbon Cycle)

2.1.6 PARTNERSHIP – CLOSE WORKING RELATIONSHIP WITH LOCAL REGULATORY AUTHORITY

Since the start of its new co-product PG strategy in the 80s, Prayon has enjoyed two long-term partnerships i) with the local regulatory authority and ii) with Knauf, and one intermittent collaboration with an independent technical-scientific centre of excellence, the nearby University of Liege. Each of these has been a “critical success factor”.

2.1.6.1 THE REGULATOR

Prayon has permanently developed a very close collaboration with the local regulatory authorities based on trust, mutual respect and a sustained effort to protect and improve the environment in which the plant operates. This relationship is partially reflected in a public environmental report available through a dedicated website⁴⁸ showing the present condition and the effort made to mitigate any negative operational impact.

This strategy permits Prayon in its dealing with the regulatory services to be engaged with them in a form of a constructive partnership allowing the development of science and evidence-based solutions that are proportionate to the level of environmental risk posed by Prayon’s phosphogypsum (“PG”). Regular quarterly meetings of a working group composed of the local authority and Prayon personnel allow an ongoing process of review and performance monitoring. When the practice of discharging PG to the river Meuse was forbidden in 1987, the practice of storage on land began (Fig. 81, Fig. 82). A formal permit was issued in 2001, with an initial expiry date of 2015. It has since been renewed until 2035.



Fig. 81. Prayon PG Interim storage area, unlined: Engis, Bois d'Engihoul, June 2019. PG movement by truck (Image courtesy Prayon)

47. See <https://www.chemistryworld.com/news/carbon-cycles-gypsum-purification-process-cleans-up-radioactive-fertiliser-waste/4010670.article>

48. For Prayon’s environmental reporting see the main Prayon web site (www.prayon.com) and the dedicated web page (<https://rapport-environnemental.prayon.com/>)



Fig. 82. PG storage piles, June 2019 (Image courtesy Prayon)

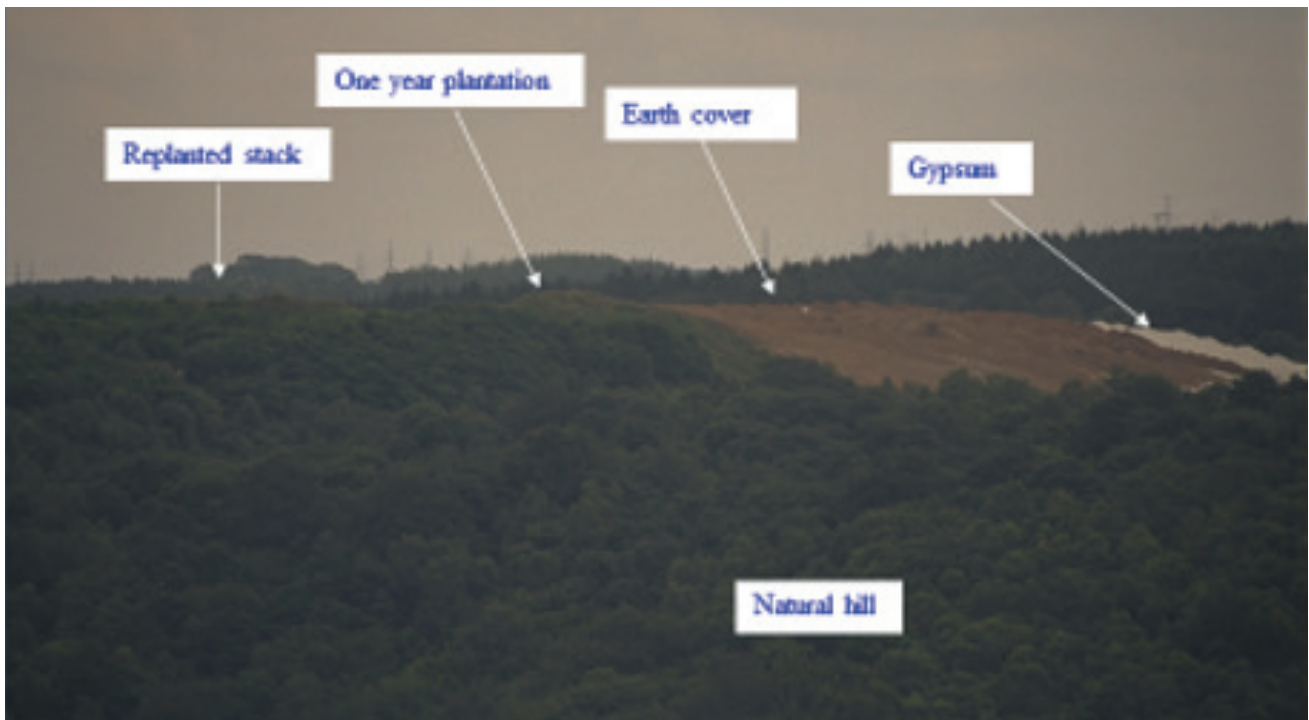


Fig. 83. Progressive integration of PG interim storage area with surrounding forest, Bois d'Engihoul (Image courtesy Prayon)

As shown in Figs. 81-83, the PG storage area is surrounded by the Bois d'Engihoul forest where its presence has naturally enriched the forest's biodiversity. PG stored in the forest has been observed over time to create a specific biotope (anthrosol) that has naturally favoured the establishment or re-establishment of wild plant species and other biota most of which were not hitherto seen in or had been lost to the area. On this basis, the Regulator, which quite independently was pursuing a policy of promoting biodiversity in the area, instructed Prayon to discontinue the previous regulatory practice of covering the PG with a top layer of soil, but simply to cover the top – primarily to reduce any unwanted visual impact – while leaving the flanks of the storage pile free for the further encouragement of biodiverse colonial species (Fig. 84).



Fig. 84. PG interim storage piles [8] – flanks left uncovered to attract new or re-establish old plant species and promote biodiversity (Image courtesy Prayon)

2.1.6.2 ENVIRONMENTAL IMPACT: THE NEED FOR AN HDPE LINER?

The Engis site has been used for PG disposal since 1987, the practice starting with a change in regulations to prohibit PG discharge direct into the Meuse. A formal permit was issued in 2001, with an initial date of 2015. In the meantime, in 2008 the regulator opened discussions about potentially mandating an HDPE liner⁴⁹ as a condition when the renewal permit was granted. As there were no clear regulatory guidelines available, the use of a liner remained a hot topic. To address it Prayon engaged with independent hydro-geological experts to consider what the case for and against a mandatory liner might entail.

The main focus of the regulator was on the management of surface water from the PG including:

- monitoring the pore water discharge stream
- monitoring the Meuse itself downstream of the stacks
- establishing a system for collecting and treating water run-off from the stack
- integrating into the water treatment system a water basin complex planted with macrophyte beds for bio-remediation
- monitoring groundwater
- agreeing mandatory intervention procedures if

- discharge limits for dissolved content were exceeded
- agreement that a mandatory HDPE liner would be installed if preventive measures were shown not to work.

Contextual requirements focused on the environmental impact of trucking reject PG to the stacks. Prayon was required to:

- regularly clean road surfaces from any PG spill
- cover all materials in transport
- monitor the performance of the roads used by the PG trucks, including mandatory financial contributions from Prayon for maintaining and strengthening the roads themselves.

Since 1987, the balance of unsold PG was stored on land adjacent to the plant, capped with a covering of earth and then planted with trees for landscaping⁵⁰ (Fig. 83). But more recently the regulator has changed the requirements in view of the empirical observation that leaving the top of the stack uncapped actually promotes biodiversity. PG in the surrounding eco-system behaves as an anthrosol, widening the range of flora and fauna that the habitat can support (Fig. 84). The explanation for this is simple. PG is “a sponge” which takes up and retains water.⁵¹ Local farmers in the Liège area of Belgium are well aware of this which is why they like to add PG as a soil amendment, reducing the need to irrigate. Because of PG’s water retention capability, plants that typically grow only in valleys in the Meuse region can colonise the PG “soil” on higher ground providing additional food and enhanced cover or habitat for other forms of wildlife.

2.1.6.3 KNAUF

More than 40 years ago Knauf established a plaster production plant nearby Prayon plant as the operational centre of its collaboration with Prayon. Both companies have developed a commercial collaboration based on trust and commitment. Production and Management teams of both companies regularly meet to discuss gypsum quality, quantity to be produced and commercial terms.

2.1.6.4 UNIVERSITY OF LIÈGE

When the initial regulatory framework for the stacked PG reject material considered the US practice of requiring an HDPE liner to prevent leaching to the ground and groundwater, an independent study by the University of Liège advised against this because of the risk of “funnelling” ie of concentrating PG in a limited area rather than allowing

49. This illustrates well the extent to which prevailing US regulatory practice has influenced PG management well beyond the US and under the 1989 PG Rule use of an HDPE liner is mandatory for stacking PG.

50. Recent Agrium [Nutrien] experience as reported at the IFA Technical Meeting Amman, March 2017, suggests that PG anthrosols are an ideal substrate for fast growing energetic tree varieties such as willow and poplar. This attribute can perhaps be tested in Engis.

51. Similar findings were established independently by the ICARDA team working in Aleppo, Syria which measured an ~70% increase in water efficiency in local soils amended with PG.

any negligible levels of leachate to be diluted naturally by spreading out into the eco-system. Of course, the capital and maintenance costs savings are very considerable when a) no liner is required and b) capping requirements with soil are either reduced in depth or not required at all.

In the meantime, the regulator opened discussions about potentially mandating an HDPE liner as a condition when the renewal permit was granted. As there were no clear regulatory conditions in place, the use of liner remained a hot topic. To address it Prayon engaged a highly competent consulting company for the impact survey, demand the advice of the University of Liège and involved the administration at an early stage prior to submitting the permit request through the creation of a specific committee. The survey covered dust emission, surface and underwater stream, water, public nuisance due to transportation, and biodiversity. From the different working sessions, it appeared that one of the main focal points was the management of surface water coming from the stack as it could contain P_2O_5 . As the gypsum is neutralized before being stored, heavy metal leaching levels are well below regulatory limits, a priority requirement for the regulator.

Taking into consideration the risk analyses performed by the experts as well as the advice of the University of Liège, the permit was granted provided subject to the following maintenance and monitoring measures:

- Regularly clean the road surfaces from any PG spill
- Cover material during transport
- Contribute to road maintenance
- Monitoring the pore water discharge stream
- Ground water quality in the numerous wells around the stack
- Monitoring the Meuse River downstream of the stack for detecting potential run-off
- Establishing a system for collecting and treating water run-off from the stack itself
- Integrating into the water treatment system a water basin complex planted with macrophyte beds for bioremediation.

It was agreed at the outset that mandatory intervention procedures would have to be followed if underground water concentration limits for various elements (sulphates, phosphorous) were exceeded, such installation of a HDPE liner. To date this eventuality has never arisen.

2.1.7 CONCLUSIONS

As had emerged from Tibaut Theys's comments during his Engis presentation (March 2018), perhaps the most remarkable part of the story was however, the most recent developments. Thierry reported that the strategy Prayon had adopted in its dealings with the regulator was to be engaged with them in a form of "constructive regulation

partnership", [59] anchored in agreement between them that the solution adopted needed to be science- and evidence-based and proportionate to the level of environmental risk posed by Prayon's PG (Fig. 85).



Fig. 85. The HH to DH holding area across the Meuse from Prayon at Knauf (Image courtesy Prayon)

From those principles, Thierry reported that the renewal of the permit, supported by the independent scientific work of the University and hydro-geology specialists, not only eliminated the need for a retro-fitted liner, it actually presented an environmental case for not having one to avoid the risk a liner might bring of funnelling potentially noxious leachate and hence concentrating its impact. It further advised that in light of the evidence showing an uncapped stack would promote biodiversity. The good practice that was further to be encouraged was to leave the tops of the stacks exposed rather than covered with soil.

2.2 CONSTRUCTION MATERIALS: CHINA

2.2.1 CONTEXT: "DEFINING THE FUTURE" OF PHOSPHOGYPSUM IN CHINA

The core values which have emerged as central to IFA Members' responses to the PG challenge - leadership, innovation and partnership - are clearly in evidence in the way the phosphate industry in China is facing a game-changing policy development, the regulator's demand for 100% use. Where 30 years previously the then dominant producer, the United States, in 1989 effectively prohibited the use of PG, for Chinese producers in 2020 the policy is to scale production of phosphoric acid to reflect the level of uptake of PG in the market. If 100% use of PG is not achieved, then PA production must be scaled back until the equilibrium point between production and consumption of PG is maintained - or maintainable.

2.2.2 IFA CHINA CONSULTATIVE GROUP

Not surprisingly, this was the dominant issue at the meeting August 27, 2019 in Beijing of the IFA China Consultative

Group (IFA-CCG) which had PG at the top and centre not just of its meeting but also of the conference which followed it August 28-29. In addressing the IFA-CCG meeting in his role as Coordinator, Mr. He, Chairman of Guizhou Chemical Company, the newly merged entity built from the two leading producers, Kailin and Wengfu, indicated that he believed the 100% use goal was achievable, but that to transition to meeting this goal would require five years.

Like Esin Mete, Mr. He has a long and outstanding record of leadership and innovation in PG use. These cover a range of applications from construction materials and building projects (PG1 Section 2.4 and 4.1-4.2) to application of an adapted Merseburg process for producing high quality ammonium sulphate and calcium carbonate feedstock from PG, with an added significant bonus of significant CO₂ sequestration (PG1 Section 8). Every 1mt of PG yields some 170,000t CO₂ sequestered. Likewise, many of the innovations supported by Mr. He and team have been developed in collaboration with independent centres of technical and scientific excellence, whether at universities or government research facilities. Such significant R&D investments will continue to be made. But as China is now the world's largest producer/consumer of both PA and PG, not just the industry in China but the global phosphate industry as a whole has a significant stake in working in partnership with China to reach the equilibrium point between production and consumption of PG that China's industry is required to deliver. The issue is existential but is not being faced for the first time. As is set out in the Prayon case study in PG2, Prayon faced the same issue 40 years ago, with success. So it was doubly appropriate that Mr. Yves Caprara, retiring Prayon Chairman, should be a participant in the IFA-CCG August 2019 Beijing meeting.

2.2.3 KEYNOTE PRESENTATION: DEFINING THE FUTURE

The keynote presentation for the meeting was given by Chairman Shousheng Li, the lead author of *Defining the Future*, (2018) [60], a co-publication of China Petroleum and Chemical Industry Federation (CPCIF) to which the Chinese fertilizer industry is affiliated, and McKinsey, China. Mr Li is also Chairman, CPCIF.

PG features prominently in *Defining the Future*, the PG numbers speaking for themselves. Annual PG production in China (reference date 2015) is ~80mt and as of 2015 utilization of PG was 26.5mt, equating to 33.3% which volumetrically certainly justifies the claim that China is in "a leading class worldwide"⁵². At the IFA-CCG meeting these figures were slightly modified in that by 2018 through plant rationalisation and the closure of small facilities annual

production of PG had fallen a little to some 77mt and consumption had risen to 39.7%, or 30.8mt. Legacy PG was estimated in aggregate in 2015 to amount to a holding of ~300mt. Assuming that the legacy has continued to build up but at the basis of 2018 figure a further 138.6mt will have been added, ie the legacy is now estimated at 438.6mt.

Defining the Future [60] recognises that having no as yet agreed solution to the long-term management and "comprehensive utilization" of PG is a "bottleneck" which puts the whole future development of the industry at risk. It goes further, noting that finding a sustainable environmental-economic equilibrium point PG is not simply existential for the fertilizer industry in China but it is also a touchstone for the approach China will take in future for the valorisation and use of all its secondary resources, from whatever extractive and processing industry produces them.

Exactly the same motivation led IAEA to develop SR78 [2], which also recognised that whatever solutions could be found for PG, especially in its guise as a NORM industry co-product, would transfer to other high volume residues such as red mud from bauxite or titanium processing, or slag from iron, copper and zinc smelting. That process of moving "wastes" out of the liability column and into the "resources" asset column is well aligned with the objectives of SDG 12, notably waste reduction or valorisation. It provides the business case, to pursue policies such as zero waste – hence 100% use of PG and no disposal - green chemistry, comprehensive utilization (referenced in PG1 as "comprehensive extraction", Section 2.4) industry 4.0 and the circular economy.

At the heart of the process of implementing a policy of 100% PG use is credible evidence that the materials are safe and beneficial to use and adhere, where available, to internationally agreed standards. "Enterprises lack comprehensive guidelines and standards"⁵³ comments Chairman Li. PG2 is designed to start the process of putting such standards in place for PG use. With the adoption of standards, and Quality Protocols, will come opportunities for valorisation and use of PG.

As Chairman Li made clear, innovation, partnership and leadership are the core values that will drive China's effort to meet Xi Jinping's demand of its heavy industry to work together to "accelerate the reform of the ecological civilization system and build a Beautiful China"⁵⁴. He then echoed Chairman Xi's remark by commenting of PG that "accelerating its comprehensive utilization" is a key aspect of implementing the reform of the industrial eco-system.⁵⁵

52. *Defining the Future* p.118.

53. *Defining the Future* p.126

54. Cited in *Defining the Future* p.127

55. *Defining the Future*, p.131.

2.2.4 GUIZHOU

As one of the early leaders in developing a comprehensive plan for PG valorisation, Wengfu Group and Kailin (see PG1 Section 4 and sub-sections 2.4.2, 8.2), now merged as Guizhou chemical company, have a wide range of decorative and structural construction materials available as illustrated below. These include ceramics, flooring, decorative wall cladding (Fig. 86) and building blocks (Fig. 87). As of the publication of this Report it is not clear how the industry in China will be able to meet the requirement of 100% use. IFA is committed to assisting phosphate fertilizer producers in China in meeting this important goal, both for the benefit of China but also because it will establish a pathway to 100% use which may be adapted for use by IFA member companies in other parts of the world.



Fig. 86. Product range 2020 - Ceramics from PG – flooring, tiles and panels (images courtesy of Charlotte Hebebrand)



Fig. 87. PG building blocks (image courtesy of Charlotte Hebebrand)

3. CASE STUDIES: ROAD BUILDING

An overview of the long history of pilot-scale uses of PG as a road-bed material, both in its own right and in combination with other industrial secondary resources such as fly-ash and red mud, can be found in IAEA SR78 Section 10.5.3 [2] and in PG1 Section 5 [1]. The case studies in this section mark the beginning of a new era in PG uses as road bed material. They bring together significant new or neglected scientific and technical aspects of PG's properties for road building applications with a key new market driver, the transition to a circular economy, based on the twin principles of conservation of primary resources and substitution where possible of available secondary resources.

3.1 INNOVATIONS IN ROAD CONSTRUCTION USING HEMI-HYDRATE PHOSPHOGYPSUM: RUSSIA

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3.1.1 CONTEXT

Over the past decade in Russia attention has been increasingly focused on use of innovative materials in road construction based on by-product and secondary resources [61] [62]. This case study sets out the successful history of road building in Russia 2008-2019 using hemi-hydrate phosphogypsum (HHPG) in roadbed. As factors such as primary resource conservation, waste reduction and transitioning to a circular economy have grown in significance in that time period, interest in using HHPG for this purpose has accelerated, accompanied by a detailed technical and scientific research and development programme undertaken by PhosAgro and its partners since 2015, as summarised in this case study.

An indicator of the success of the R & D work done is that road phosphogypsum has been recognized “a material with promising potential”. By no coincidence it was presented as “a cutting-edge development” at the 2018 Roads of

Russia Competition where the roadbed phosphogypsum (RBPG) produced by the Balakovo Branch of Apatit JSC was voted winner in the Category Innovation of the Year. Formal Technical Specifications (rev. 1) were approved in 2018 by the Russian Federal Road Agency for three years. The specifications authorise use of road phosphogypsum in construction and repair for roads categories 1 – 5, as provided for in the National Standard of the Russian Federation GOST 52398-2005. According to it, public roads are classified into five categories from highways and freeways (category 1, lane width 3.75 m, 4 lanes at least) to ordinary roads (categories 2 – 5, each respectively with a decreasing number of lanes from 4 to 1).

3.1.2 OBJECTIVES FOR PG USE IN ROAD CONSTRUCTION

Use of such secondary resources as PG in road construction is intended to respond to the following primary objectives:

1. achieving an operating life of general-purpose roads off at least 12 years without the need for interim repair
2. leveraging modern construction technologies using by-product materials to achieve reduction in capital costs for executing such construction projects by 20–30%
3. ensure the conservation of limited reserves of primary resources used as construction materials by substitution of modern materials for road construction derived from reusing secondary resources.

3.1.3 UNIQUE PROPERTIES OF PG IN ROAD CONSTRUCTION

This case study examines Roadbed Phosphogypsum (RBPG) as a construction material, unique in respect of its technological and consumer properties. As a roadbed substitute material, RBPG is yet to win universal popularity among road-building contractors. But as shown here it has considerable advantages compared to conventional materials of construction used for road building, such as sand and gravel.

3.1.3.1 REDUCTION IN SOIL-BEARING PRESSURE

According to the research conducted [63], the soil-bearing pressure of the stretches of road made with roadbed phosphogypsum is almost three times lower than measured soil-bearing pressure values on the stretches of roads built with layers of conventional granular materials. A layer of RBPG operates as an uncut, lightweight, cast-in-place slab, distributing its load over a large soil surface area and hence reducing point stresses in the soil (Fig. 88). Such reduction in the specific pressure on the soil makes the road less likely to exhibit local plastic deformation, so maintaining the level surface of the road for a significantly longer time [63].

56. This case study was originally published in Russian, as follows: Б. В. Левин, А. В. Кочетков, В. В. Талалай, С. А. Коротковский, А. В. Шибнев, М. В. Кузнецов. Дорожные инновации с применением фосфогипса. Мир дорог, 2019, 124, 110 – 113. (B.V. Levin, A.V. Kochetkov, V.V. Talalay, S.A. Korotkovsky, A.V. Shibnev, M.V. Kuznetsov. Road innovation using phosphogypsum. World of Roads, 2019, 124, 110 – 113). It has been adapted and edited for inclusion in this Report.

The application of the unifying principles of road structure and design to the engineering properties of the RBPG slab enable a precise calculation of the likely bending and stretching behaviours of the road. This ensures an optimum quantity and thickness of pavement layers, more efficient process operations, shorter construction times and a lower inventory of construction machinery. Applying road structure unification principles with RBPG also enables a full range of natural and climatic factors to be taken into consideration during design and construction, eliminating some negative impacts altogether and reducing the degree of impact of other negative factors.

3.1.3.2 HIGH STRENGTH

The higher strength properties of the layers RBPG compared to the layers of conventional granular materials allows for the construction of twin-layer road structures with higher load-bearing strength than that of conventional multi-layer construction. This effectively doubles the permissible axle weight limit for the road while allowing a significant reduction in the total thickness of the road structure. The outcome is a reduction by some 45-75% in the requirement for costly quality-certified mineral aggregates such as gravel and sand. A comparison between materials quantities, types and load bearing capacity for conventional road structures and designs using RBPG is given in Figs. 88 and 89.

3.1.4 CONSERVATION OF PRIMARY RESOURCES

Use of RBPG as an Anthropogenic secondary resource ensures that primary natural raw material is conserved. This not only cuts back on current road building costs but also significantly reduces upstream capital costs as incurred, for example, in prospecting and developing new deposits of primary materials, management and disposal of associated wastes when the primary material is processed or non-commercial fractions of gravel are disposed of as rejects/ tailings, or in restoring or backfilling pits and quarries when they are mined out.

At the same time, the fundamental technologies of road construction, such as specifications for natural base of the road are simplified. RBPG with its high-strength crystalline lattice bonds forms a cast-in-place foundation, resulting in uniform distribution of dynamic and static loading caused by road traffic. This minimizes longitudinal and transverse stresses which cause internal and external cracks to develop as well as deterioration of both bases and surface, result – a more durable road structure.

3.1.5 COMPARATIVE PERFORMANCE AND RESILIENCE

A Cast-in-place base using RBPG materials of construction determines both a PG road's resilience in seasonally varying temperature cycles, and the roadbed's structural resistance to freeze-thaw cycles, notably in the event of the top surface failure. This is due to the absence of water-absorbing pores in the road base, and, unlike construction

using gravel, elimination of material crumbling. Likewise, localised deformation, when the sub-soil subsides beneath certain sections is not seen, and there is no erosion of road pavement material.

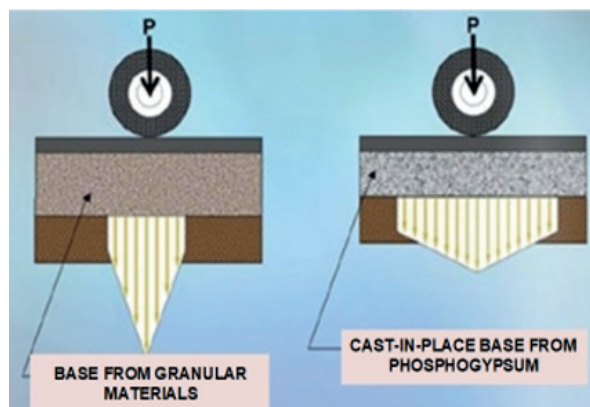


Fig. 88. Comparative stresses on sub-soil from road beds of gravel (L) and PG (R)

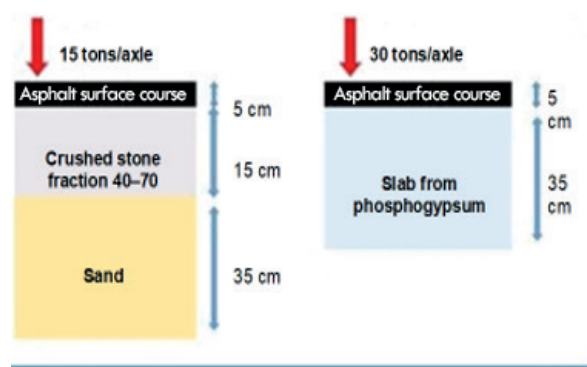


Fig. 89. Comparative load-bearing performance and base course depth – conventional aggregates (L) and compacted RBPG (R)

Crystalline structures in general are the strongest, the most water resistant and most durable, especially in conditions of high density and absence of large pores which may reduce structural resistance in freeze-thaw cycles [64]. It is exactly such structures that are formed by RBPG during the process of HH recrystallization into dihydrate whereby moisture is locked into the crystalline structure. To create strong road bases that can withstand dynamic horizontal and vertical stresses, it is necessary to create either a load-and stress-distribution system, as in the case of crushed stone and gravel, or close to a homogeneous matrix with a large margin of safety with respect to the forces and stresses involved. In the case of RBPG, this is achieved through crystalline bonds that create a strong spatial matrix. Static and dynamic impacts from moving vehicles reduce the strength of crystalline bonds, which avoids wedging pressures inside the matrix and the formation of cracks, unlike polydisperse systems with primary natural resources (sand, gravel) at the base of roads. In this case, stresses arise at the phase boundaries, which are reflected on the upper road structure by cracks, potholes, and chips. In the case of the use of RBPG, such phenomena are not observed even with prolonged operation of roads.

3.1.6 INVESTMENT IN R&D AND PILOT CONSTRUCTION PROCESS

In 2015, PJSC PhosAgro senior management took a decision to conduct a programme of scientific research combined with pilot practical applications using hemihydrate phosphogypsum (HHPG) in road construction. A streamlined PG-based construction process was developed and piloted for building foundation layers of roadbed for general purpose roads and for streets in urban residential neighborhoods with low traffic density using RBPG. The new construction process comprises the following operations, illustrated in sequence below, Figs. 90-9:

- Preparation including levelling the base-course with land grade for laying down a covering of RBPG (Fig. 90)
- Delivering and unloading the RBPG (Fig. 91)
- Spreading the material with a bulldozer (Fig. 92)
- Leveling off the laid surface with a land grader (Fig. 93)
- Roller compaction (Fig. 94)
- Spreading and compacting the gravel fraction 20–40, layer thickness 5–8 cm (Fig. 95).

The condition of the low-density road stretch (Category 4-5 type) only 24 hours after building the base is shown in Fig. 96.

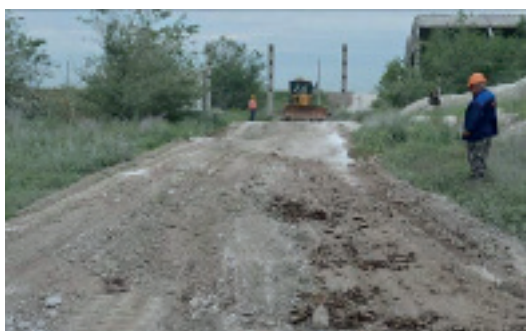


Fig. 90. Preparing the sub-base for laying down RBPG (Image courtesy PhosAgro)



Fig. 91. Delivering and unloading the RBPG (Image courtesy PhosAgro)



Fig. 92. Spreading RBPG with a bulldozer (Image courtesy PhosAgro)



Fig. 93. Leveling off the base course with a land grader (Image courtesy PhosAgro)



Fig. 94. Light roller compaction (Image courtesy PhosAgro)



Fig. 95. Spreading and compacting gravel course (Image courtesy PhosAgro)



Fig. 96. Condition of the road 24 hours after constructing the base (Image courtesy PhosAgro)

3.1.7 REGULATORY COMPLIANCE AND STANDARDS

A critical factor in road construction using HHPG is compliance with the regulatory specifications and performance standards. For example, the operation “Spreading and compacting the gravel fraction 20–40, layer thickness 5–8 cm” must be carried out directly after roller-compacting the RBPG. The applicable standard is STO 24406528-01-2018 Road Phosphogypsum⁵⁷ for construction of pavement structures. The technical specifications (rev. 1) were approved in 2018 by the Federal Road Agency, valid for three years. The standard authorises use of road phosphogypsum in construction and repair for roads of categories 1-5 (see Table 16). In parallel, the Russian Federation’s Ministry of Construction and Housing/Communal Infrastructure has adapted and approved the organization’s standard, specifically authorizing use of RBPG for road construction in metropolitan settings. This has opened a major new opportunity for repairing city roads without having first to rebuild the base course and replace the degraded or failed gravel. A RBPG layer 15–25 cm thick can be applied to failed or under-performing sections of the base on which can be overlaid the final asphalt concrete pavement layer. In the Customs Code TK-465 “Construction”, “ROAD PHOSPHOGYPSUM” is now formally registered as an approved road construction material. Equally significantly, Order No. 423 on Budget Norms and Rates of the Russian Federation’s Transport Ministry came into force January 1, 2018. For the first time this included specifications and rates applicable to construction projects using RBPG. The operational scope of Order No. 423 has since been extended and further elaborated to cover all the regions of the Russian Federation.

3.1.8 INVENTORY OF PILOT PG ROAD PROJECTS

As of the date of publication of PG2, a total area of RBPG roads, including experimental (pilot) stretches, comprising ~180,000 m² built surface has been constructed, with documented service lives to date of between 2 and 11 years (see Table 15).

In 2017, with the approval of Povolzhupravtdor Federal State Institution, a ~2,500 m² stretch of the Syzran – Saratov Federal Motorway, 83rd kilometer, was built in accordance with the requisite standard construction process flow diagram. Views of the “technical exit ramp for heavy duty vehicles on the Syzran – Saratov – Volgograd Federal Highway, 83rd kilometer, in the Khvalynsky District of the Saratov Region” from two angles across the junction are shown in Figs. 97 and 98. The initial base-course is moist chalk.

In parallel, a 3D model of the site junction was designed, including a 500m section of highway stretching in both directions away from the junction adjoining it (Fig. 99). This model helped establish, assemble and monitor the performance of the exit ramp and junction.

TABLE 15. Inventory of Built Road Stretches

FACILITY NAME	AREA (M ²)	BUILT
Stretch of Motorway Village of Bykov Otrog – Household Garbage Ground	900	2008
Stretch of Motorway leading to the Rolled Section Plant, Balakovo Severstal Publicly Traded Company	59,000	2013
Motorway Stretch Village of Kormezhka	9,000	2015
Motorway Stretch Village of Mayanga	2,000	2016
Pilot and Operating Stretches in the territory of the Balakovo Branch of Apatity JSC	20,000	2008-2019
Regional Motorway Balakovo – Ershov	80,000	2014
Federal Motorway Syzran – Saratov, 83-rd km – process exit ramp for heavy duty vehicles	2,500	2017
TOTAL: IN OPERATION FOR 2-11 YEARS		180,000m²

From 2012-2019, roads of regional importance (Categories 2-5) in the Saratov Region have been constructed using RBPG as follows:

- A stretch of the road connecting an industrial complex with the Village of Bykov Otrog in the Balakovo District of the Saratov Region was built and has been in service since 2014 (Fig. 100)
- A driver’s eye view of the street constructed using road phosphogypsum in the Village of Kormezhka, the Balakovo District of the Saratov Region is shown in Fig. 101
- The stretch of the road built in 2012 in the territory of the Balakovo Branch of Apatit JSC leading to the local ammonia facility is shown in Fig. 102. A drainage layer was not required. The base course was laid directly in a levelled trough.

3.1.9 SAFETY AND THE ENVIRONMENT

Various specialist organizations have carried out the requisite instrumentation audits and have each confirmed the full compliance with construction, environmental, safety and performance standards of roads made with the RBPG manufactured by the Balakovo Branch of Apatit JSC. Along with its technological and economic advantages, RBPG

57. Russian Standard, Phosphogypsum for road pavement construction Technical conditions (Amendment N°1), see <http://www.rosavtodor.ru/storage/app/media/uploaded-files/sto-24406528-01-2018-tssa.pdf>

possesses a unique set of physical and chemical characteristics allowing it to be classified as not just environmentally safe but also as a clean (“green”) material.

IAEA Safety Report 78 [2] has confirmed from a radiological and environmental perspective the safety of co-product phosphogypsum obtained by wet process digestion of Khibini apatite concentrates from the Kola peninsula deposit, by reacting them with sulphuric acid. This places Khibini apatite and its resultant RBPG at the lower end of the scale of relative radioactivity and heavy metals content of all PG produced commercially worldwide. Accordingly, Khibini phosphogypsum can be used without limitations for any application, such as agriculture requiring tonnage dose rates of 10-15t/ha or higher, road construction and industrial processing. Following the “graded approach” principles recommended by IAEA, such PG could even be safely considered “out of scope” for regulatory purposes, should the regulator choose to follow that course of action.

An overview of the extensive history of research and development including pilot application of the use of phosphogypsum for construction of automobile roads is listed in IFA Report Phosphogypsum: Sustainable Management and Use [1].



Fig. 97. Appearance of the built road stretch
(Image courtesy PhosAgro)



Fig. 98. Reverse angle view of the same stretch
(Image courtesy PhosAgro)



Fig. 99. 3D model of the built road, developed prior to construction (Image courtesy PhosAgro)



Fig. 100. A stretch of the road connecting the industrial complex with the Village of Bykov Otrug in the Balakovo District of the Saratov Region (Image courtesy PhosAgro)



Fig. 101. The appearance (road traffic view) of the street in the village of Kormezhka constructed using RBPG
(Image courtesy PhosAgro)



Fig. 102. A stretch of the road constructed in the territory of the Balakovo Branch of Apatit JSC (Image courtesy PhosAgro)

The cumulative effect of all this work done is that RBPG has been recognised as “a material with promising potential”, such that it was presented as “a cutting-edge development” in the Roads of Russia – 2018 Competition. The roadbed road phosphogypsum produced by the Balakovo Branch of Apatit JSC was voted winner in the Innovation of the Year Category. IFA PG1 [1] describes best practices in handling and using phosphogypsum in large quantities. The Russian experience is typified by use of pure phosphogypsum as a “promising material” based in particular on the reference case of using Balakovo phosphogypsum for road construction. Economic viability is achieved due to substitution of primary natural raw material with a secondary resource without diminishing the operating performance characteristics, assuming that the RBPG application methodology is strictly adhered to. Likewise, if correctly applied, RBPG does not have any negative impact on the operational zone adjacent to the automobile road, performance data corroborated by the results of long term many years’ observations with instrumentation tests on the automobile roads of the Saratov Region constructed using phosphogypsum. These results correlate well with findings from long-term study of a PG pilot road in Florida, Parrish Road, see IFA PG1 Section 5.

3.1.10 COST BENEFIT ANALYSIS

As a result of studies conducted by professional budget estimating experts in the road sector based on this performance data, calculations have been made to determine economic viability of using the new PG materials in road construction. The results of these studies are shown in Table 16 below setting out RBPG’s comparative economic viability against conventional materials of construction. It can be clearly seen that the construction technology developed has improved operating performance fundamentally by an order of magnitude not just by several percentage points (Table 17).

3.1.11 SUMMARY

In summary, the key advantages RBPG are:

- Tensile strength exceeding requisite benchmarks up to 10-fold
- Elasticity modulus exceeds the requisite benchmarks 2-fold
- When constructing roads, no sand drainage layer is required
- Effective performance maintained in marshy terrain
- Low propensity to heave during the winter (freeze-thaw) period of operation

- A Warranty operation period of the automobile road base no less than 12 years
- No negative impact on the environment.

In the context of a forecast restriction in the future availability of primary construction resources, most notably gravel, both in a physical (operational) and a financial (return on investment) sense, for the purpose of meeting the targets of the national project “Safe and High Quality Automobile Roads” RBPG is a unique, innovative material for construction of automobile road bases. It combines physical and price accessibility, simplicity and safety in handling, with high operational performance of the road, and environmental safety.

TABLE 16. The economic viability of using the “Roadbed Phosphogypsum”

ROAD CATEGORY	Cost per 1,000 m ² using RBPG Rbbls.	COST SAVING (%) RBPG vs conventional materials
Federal importance Category 1–2	1,634,000	21%
Federal importance Category 3	1,434,000	27%
Rural roads Category 4–5, capital type	926,000	35%
Rural roads Category 4–5, transitional type	550,000	100%

TABLE 17. Improvement of automobile roads operating performance after using road phosphogypsum

INDICATOR	Tests by road laboratory	STO 24406528-01-2018	SP 243.1326000.2015
Compressive strength, MPa	15.4	4.0–10.0	2.0–6.0
Bending tensile strength, MPa	4.4	1.0–4.0	0.2–1.0
Frost Resistance	F 25	-	F 15

3.2 AN INNOVATIVE APPROACH FOR PHOSPHOGYPSUM VALORISATION IN ROAD BUILDING, MOROCCO

AUTHORS

OCP Group in partnership with **Ecole Hassania des Travaux Publics** (Hassania School of Public Works (EHTP))⁵⁸, **Ecole des Ponts ParisTech** (National School of Bridge Building, Paris Tech (ENPC))⁵⁹, the **Centre National d'Etudes et de Recherches Routières** (National Centre for Road Research (CNER))⁶⁰, Morocco, and **Les Grands Travaux Routiers (GTR)/COLAS**, (Major Road Projects/ COLAS) France⁶¹.

3.2.1 ECONOMIC CONTEXT

In the past twenty years, Morocco has invested heavily in major infrastructure projects as a means of stimulating the country's economic development, in line with key strategic sectorial development objectives. This has resulted in opening up major communications axes to the country's major ports (Tangiers Med, Nador West Med, Kenitra Atlantic, Jorf Lasfar, Safi), airports, train stations (High-speed line Tangiers / Casablanca) and road networks (Fig. 103). From 1956 to date, the paved road network increased from 10,348 to 43,318 km of built infrastructure.

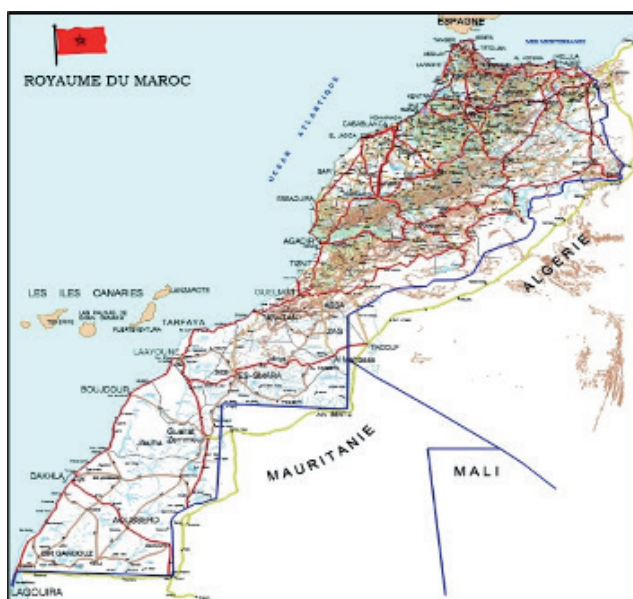


Fig. 103. Road map of Morocco with highway infrastructure

All of these infrastructure projects require significant amounts of raw construction materials, in particular sand and aggregates.

3.2.2 INCREASED NEED FOR BUILDING MATERIALS

The public works and building sector is the leading consumer of sand and aggregates for a range of uses as dwellings, bridges, dams, roads, railways and dykes. A typical medium-size dwelling requires 200t of sand, as compared with 3,000t for a hospital and 30,000t per lane/km of highway⁶².

In addition, Morocco's increasingly rapid urbanisation (30% in 1960, 62% in 2018 and a projected 73.6% in 2050), as estimated by the High Commission for Planning (Haut Commissariat au Plan (HCP)), has significantly increased the quantities of required materials, putting growing stress on the demand for these primary resources.

3.2.3 MOROCCO'S COMMITMENT TO THE ENVIRONMENT

In 2014, subsequent to the law adopted in 2008 relating to environmental impact studies (EIA),⁶³ the Kingdom adopted a National Charter for the Environment and Sustainable Development. The principal objectives of the Charter are to "Strengthen measures to protect and conserve natural resources and environments, biodiversity and the cultural endowment, to prevent and to fight against pollutions and nuisances".⁶⁴ The implementation of the Charter is being applied to the different business sectors.

3.2.4 AN EVOLVING REGULATORY CONTEXT

Morocco has 2,000 recognised quarries with a combined annual output of ~100 mm³. A new law regulating trade in these materials was passed in 2015 (27-13)⁶⁵ and came into effect at the end of November 2017. This law sets out the technical specifications to achieve the goal of controlling quarry products and determines quarries' opening and operating procedures. The law also dictates a given quarry's end of life requirements including guarantees in place for site decommissioning and remediation once it ceases business. Under the law quarry operators are obliged to produce mandatory annual reports on the quarries' environmental status and impact.

Simultaneously, in July 2015, the government adopted the

58. Ecole Hassania des Travaux Publics (EHTP), <http://www.ehtp.ac.ma/index.php>

59. Ecole des Ponts ParisTech (ENPC), <http://www.enpc.fr/>

60. Centre National d'études et de Recherches Routières (CNER), <http://www.equipement.gov.ma/Infrastructures-Routieres/CNER/Pages/Missions.aspx>

61. Les Grands Travaux Routiers (GTR)/COLAS, <https://www.colas.com/>, <https://www.colas.com/fr/presse-mediatheque/communiqués-de-presse/colas-direction-regionale-maroc-morocco-regional-management>

62. <http://www.planete-tp.com/granulats-chiffres-cles-a763.html>

63. Loi n° 12-03, <https://www.environnement.gov.ma/fr/152-Etudes%20d'impact%20sur%20l'environnement>

64. The original Charter texts reads as follows: « Renforcer la protection et la préservation des ressources et des milieux naturels, de la biodiversité et du patrimoine culturel, de prévenir et de lutter contre les pollutions et les nuisances ».

65. http://www.muat.gov.ma/sites/default/files/Rglementation/Loi-n-27-13-fr_0.pdf

law, dealing with coastal zones,⁶⁶ that provides rules for the protection and sustainable management of coastal areas, while introducing restrictions on resource extraction, notably sand and aggregates, with a commensurate influence on their prices.

Facing the dilemma of decreasing availability of traditional construction resources and at a time of significantly increasing demand, it was necessary to seek alternative resources for these purposes, notably from secondary resource stocks and supplies, especially those with lower environmental impacts.

This comes at a time when Morocco is beginning a transition towards the new perspective of a circular economy, whereby the integration of previously ignored or under-used co- and by-products from extractive industries into the construction eco-system can bring both economic and environmental benefits to the country, while conserving precious primary resources for future generations. Both goals are envisioned in the UN SDG 12 (responsible production and consumption). OCP also sees a potential synergy with the national “Blue Economy” initiative, launched in 2018,⁶⁷ and the role of protecting and enhancing the coastal and offshore marine environments in the economy.

3.2.5 THE PILOT PROJECT “VALORISATION OF PHOSPHOGYPSUM IN ROAD CONSTRUCTION” CONDUCTED BY OCP AT ITS SAFI PRODUCTION FACILITY

For many years, OCP Group⁶⁸ has implemented a policy of strong and active social and environmental responsibility,⁶⁹ with a commitment to sustainable development⁷⁰ as the foundation to its industrial development. This has given rise to major investment programs such as (i) a rational and optimized use of water resources, with the use of unconventional waters (desalination of sea water and reuse of treated wastewater), (ii) an innovative Energy program to reduce its carbon footprint, (iii) an operating approach guaranteeing an eco-responsible mining rehabilitation, etc.

Since early 2018, environmental protection and resource conservation have taken their position at the heart of OCP's own Circular Economy Program, leading to a conscious decision to build new industrial eco-systems

that allow the valorisation of co- and by-products of phosphate fertiliser production.

3.2.5.1A UNIQUE PARTNERSHIP AND A ROBUST METHODOLOGY

At OCP's industrial complexes, its production of phosphoric acid from phosphates generates a co-product Phosphogypsum (PG).⁷¹ In parallel, at both its mine and chemical processing facilities, there are significant holdings of phosphate mine tailings available for valorisation and reuse. PG and tailings share the attributes of offering technically feasible and economically attractive construction materials, *per se* or combined, notably for road building.

By adopting this perspective for PG and tailings use, both of which are readily available and affordable, but which may also be classed as “eco-materials”, a promising possibility of how to close some of the rapidly emerging national supply gap for primary construction materials is identified. At the same time taking such resources into beneficial use demonstrates in practice an exemplary way of closing points of resource loss in conventional linear models of materials flows, in such a way that circular resource-flow options take their place. This change of both perspective and operational practice cannot be achieved unless rigorously grounded in a robust scientific and technical approach.

Committed to implementing this transition, in early 2013 OCP group launched the first stage of its valorisation initiative for its co-product resources. This led to the establishment of an innovative road-building partnership between OCP and a range of respected institutions, based on circular economy and resource conservation principles, to build a pilot road with PG at its production complex in Safi. The partnership now draws on the combined expertise and resources of OCP, Ecole Hassania des Travaux Publics (EHTP), Ecole des Ponts ParisTech (ENPC), the Centre National d'Etudes et de Recherches Routières (CNER) (part of the Ministry of Equipment, Transport, Logistics and Water), and road-building specialists, Les Grands Travaux Routiers (GTR)/COLAS. This form of partnership may be seen in the context of UN SDG delivery to be an excellent illustration of SDG 17, partnership.

The PG road project at Safi was launched with the following distribution of roles and responsibilities (Table 18):

66. Loi n° 81-12 relative au littoral, <http://www.avnah.ma/avnah/Documents/Dahirs/Dahir-1-15-87.pdf>

67. « L'économie bleue : pilier d'un nouveau modèle de développement du Maroc », <http://www.ces.ma/Documents/PDF/Auto-saisines/2018/AS38-2018/Rp-AS38f.pdf>

68. See <https://www.ocpgroup.ma/en/our-strategy/our-industrial-and-commercial-strategy>

69. See <https://www.ocpgroup.ma/en/our-strategy/our-environmental-and-societal-strategy>

70. See Sustainability Report 2018, <https://www.ocpgroup.ma/sites/default/files/2019-07/Sustainability%20report%202018%20OCP.pdf>

71. For classification of PG as co-product" see IAEA Safety Report no. 78, 2013, https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1582_web.pdf

TABLE 18. Road Project Roles and Responsibilities

	EHTP	ENPC	CNER	GTR
Current state of knowledge about potential uses	Participant	Lead / Responsible		
Physico-chemical characterisation of PG and related co-products	Lead / Responsible	Participant	Participant	Participant
Formulation, mechanical and engineering characteristics of road building materials based on PG	Participant	Participant	Participant	Lead / Responsible
Environmental impact assessment / pollution potential from chosen formulations	Lead / Responsible	Participant	Participant	Participant
Construction of pilot road with monitoring instruments (test stretch)	Participant	Participant	Participant	Lead / Responsible
<i>In situ</i> monitoring of the mechanical performance of the pilot section	Co-Lead / Responsible	Participant	Co-Lead / Responsible	
<i>In situ</i> monitoring of the environmental performance of the pilot section	Lead / Responsible	Participant	Participant	Participant
Techno-economic lifecycle analysis and evaluation of likely performance limitations		Lead / Responsible		Participant

3.2.5.2 CURRENT STATE OF KNOWLEDGE ABOUT POTENTIAL USES

A detailed literature review enabled a better-grounded evaluation of PG's potential utility as a road construction material, whether used "as is" or in some way pre-treated (e.g. neutralisation), but also the constraints and limits of such uses. This preliminary step was an indispensable first step enabling the team to better target and optimise the subsequent stages of the project.

3.2.5.3 PHYSICO-CHEMICAL CHARACTERISATION OF PG AND RELATED CO-PRODUCTS

Next, a wide range of tests was carried out to detail the physico-chemical properties of the PG types produced at Safi in respect to key attributes such as granulometry, density, behaviour in water, chemical composition, pH, and content of trace elements. Summary findings from physico-chemical studies (Table 19):

TABLE 19. PG characterisation (Safi) with principal constituents and trace elements

Al ₂ O ₃	0.32%
CaO	30.34%
Fe ₂ O ₃	0.02%
K ₂ O	0.01%
MgO	0.19%
SiO ₂	1.69%
Na ₂ O	0.67%
SO ₃	40.71%
Density	2.59 g/cm ³

Other materials and co-products used in the treatment of / or with PG (cement, special binder, flyash) or in mix with PG (crushed sands, mine tailings)⁷² were also characterised.

3.2.5.4 FORMULATION, MECHANICAL AND ENGINEERING CHARACTERISTICS OF ROAD BUILDING MATERIALS BASED ON PG

Numerous formulations based on PG treated with cement, either with or without various additives, were tested in the laboratory according to the specifications required for the use of such materials in road building. The mechanical and engineering performance of these formulations both in short- and medium-term, allowed the selection of four variants which looked suitable for use in actual road construction conditions. Response values studied and corresponding Moroccan national standards, based on French national standards (NF), are shown in Table 20 below:

TABLE 20. Performance values and standards, PG-based road materials laboratory testing

METRIC	TEST TYPE	STANDARD
pd	Optimal density using Proctor Compaction Test	NF P 94-093
IBI	Immediate Bearing Index (suitability for immediate trafficking - penetration testing immediately after construction)	NF P 94 078
CBR	California Bearing Ratio (penetration testing after 4 d immersion and weight surcharge)	NF P 94 078
SV	Swelling Volume (after 4 d immersion and weight surcharge)	NF P 94 078
DCS	Diametral Compressive Strength (at 7 d, at 28 d and at 90 d)	NF P 98-232-3
E	Young's Modulus (at 7 d, at 28 d and at 90 d)	NF P 98-232-3
CS	Simple Compressive Strength (at 7 d, at 28 d and at 90 d)	NF P 98-232-1

The formulations (mixes) used for the pilot construction site comprised PG and cement with sand or tailings in different percentages. The % range for PG in the mixes was 57-93% (Table 21):

72. https://ec.europa.eu/environment/waste/mining/pdf/guidance_extractive_waste.pdf

TABLE 21. Summary performance results from three (3) different PG-based formulations

PG %	IBI (W_{OPM})	CBR (W_{OPM})	SV	DCS 7 d (MPa)	DCS 28 d (MPa)	DCS 90 d (MPa)	E 7 d (MPa)	E 28 d (MPa)	E 90 d (MPa)
93%	57	49	0.08%	0.09	0.27	0.35	1,100	3,400	5,000
65%	81	86	0.56%	0.28	0.66	0.85	6,070	7,100	10,400
57%	52	89	0.18%	0.28	0.71	0.90	5,700	7,200	10,500

3.2.5.5 ENVIRONMENTAL IMPACT ASSESSMENT: POLLUTION POTENTIAL FROM CHOSEN FORMULATIONS

In order to assess their potential for environmental pollution the mixes were submitted to various demanding tests of their polluting potential based on French Standard NF X 31-211, with focus on the risk of contamination from water run-off, passing over or leaching through the road bed materials to mobilise into the environment. The tests were largely conducted and evaluated on a comparable basis with applicable regulations in other countries notably those from the European Union⁷³ and India.⁷⁴

3.2.6 EXECUTION OF THE PILOT PROJECT

Once the laboratory tests had been validated from the engineering and environmental perspectives, in 2017 the project moved to the execution stage - the construction of a pilot road section inside the perimeter of the Safi production site, using four selected formulations for testing. Since the pilot was conducted within the site boundaries, additional permits were not required.

3.2.6.1 CONSTRUCTION OF PILOT ROAD WITH MONITORING INSTRUMENTS (TEST STRETCH)

In order to establish the technical feasibility for road construction for each of the four selected formulations and to characterise the *in situ* mechanical and environmental performance of each one, a straight ~1km length road was built. The pilot stretch was divided into five equal sections, constructed according to the four PG variant formulations selected from laboratory tests with a fifth control section for comparison. The cross-section profile of PG pilot road is given below (Fig. 104). The pilot road was then submitted to quite heavy traffic density using heavy goods vehicles (HGVs) of the road tanker type with a Dynamic Load [aggression] coefficient of 1.9, to accelerate wear and tear (traffic test at the intensity levels TPL3 - TPL4, the heaviest categories of truck on Moroccan roads).

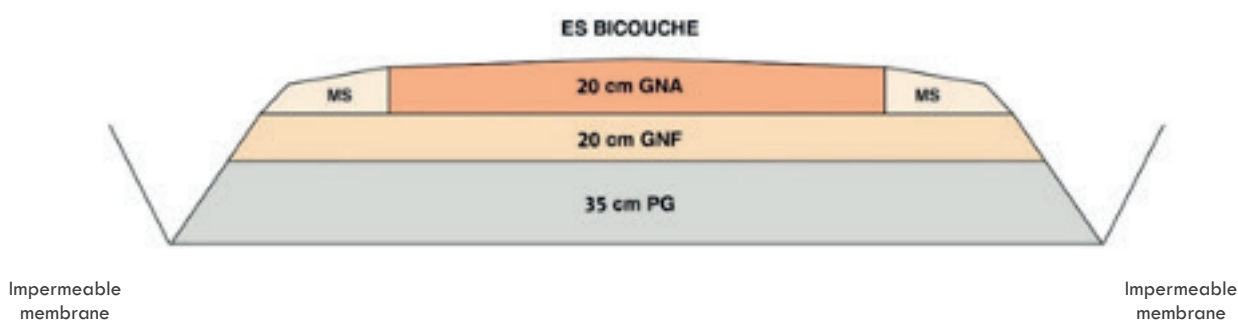


Fig. 104. Cross-section profile of PG pilot road, Safi (Image courtesy OCP)

An impermeable membrane (see edges of Fig. 104 and Fig. 105 below) was laid under the layer of PG to avoid any water infiltration into the base course. Lateral drainage systems were placed on side of the road, leading to five water collection basins to collect run-off waters. These waters were drained from the roadbed by special equipment built into the body of the road.

73. For European regulatory values see <https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000032275960&categorieLien=id>

74. For Indian regulatory values see http://www.indiaenvironmentportal.org.in/files/file/Final_Draft_Guidelines_for_Phosphogypsum.pdf



Fig. 105. Road construction with protective impermeable membrane overlaid on Safi naturally occurring soil base course and drainage system for collecting run-off water (Image sequence courtesy OCP)



Fig. 106. Pilot PG road at Safi facilities (Image sequence courtesy OCP)

3.2.6.2 IN SITU MONITORING OF THE MECHANICAL PERFORMANCE OF THE PILOT SECTION

The engineering performance of the pilot was measured *in situ* in part by counting and weighing the traffic passing over it and in part by using a pre-programmed LACROIX deflectometer.⁷⁵ These measurements were conducted by CNER.

Based on the obtained results to date, the estimated life-expectancy of the pilot stretch is 25 years. This is back-calculated using the ALIZE software tool from the deflection data measured on the experimental road. This indicates it will perform at a standard similar to, or even higher than a road built using conventional materials. A 20-year lifecycle is a standard metric for measuring the life-expectancy of a road before major repairs or resurfacing is required (see PG 1 section 5 reference case PG road, built 1985, Parrish Road, Polk County Florida, resurfaced after 21 years in 2006) so a 25-year life-cycle shows even more promise of reduced whole life-cycle cost.



Fig. 107. Deflectometer measurements of road performance (load bearing and compressive strength) (Images courtesy OCP)

3.2.6.3 IN SITU MONITORING OF THE ENVIRONMENTAL PERFORMANCE OF THE PILOT SECTION

The “Pollution Potential” tests conducted on the four different formulations used within the pilot road were broadly comparable in nature to both EU and Indian standards, findings being shown below Table 22:

TABLE 22. Heavy metals as detected in run-off eluates with reference standards, Morocco, EU (France) and India

Element	Maximum concentration measured in eluate	Moroccan standards	French Standards	Indian Standards (PG)
Cr	0.016 mg/l	2 mg/l	0.1 mg/l	0.1 mg/l
Cd	0.032 mg/l	0.25 mg/l	0.2 mg/l	2 mg/l
Pb	< 0.005 mg/l	1 mg/l	0.5 mg/l	2 mg/l
Hg	0.0001 mg/l	0.05 mg/l	0.05 mg/l	0.1 mg/l
As	< 0.005 mg/l	0.1 mg/l	0.1 mg/l	1 mg/l

It is planned to continue to monitor the road’s environmental impact for a further 3 years, sampling water run-off for chemical analysis to assess longer-term environmental performance and potential for build-up or concentration of mobilised elements causing pollution.

These measurements were complemented by radiation dosimetry monitoring (effective dose) assuming workers exposure time on site is equivalent to standard regulated working hours (8h/d x 5d/w). That shows a maximum annualised dose rate of 0.7 mSv/y, well below the exposure limits established by the regulator, IRSN,⁷⁶ France.

3.2.6.4 LIFE-CYCLE ANALYSIS AND EVALUATION OF TECHNO-ECONOMIC PERFORMANCE LIMITATIONS

A life-cycle analysis (LCA) comparing the different sections of the pilot is currently underway⁷⁷ which when completed will allow a multi-parameter evaluation of the overall performance and predicted “full cost of ownership” of the road over a 20-25 year lifespan. This in turn will not only allow a meaningful comparison between roads built with PG and those built with conventional materials, but also a better understanding of limits and constraints on the use of PG in similar projects.

75. <http://www.infralab.ch/wp-content/uploads/2016/10/Article-RT-Comparaison-HWD-et-Lacroix.pdf>

76. Institut de radioprotection et de sûreté nucléaire, <https://www.irsn.fr/EN/Pages/Home.aspx>

77. “Life cycle assessment of alternative road base materials: the case of phosphogypsum”, communication presented at SBE19 Graz, September 2019

3.2.7 PILOT STUDY OF PG USE IN ROAD CONSTRUCTION CROSSES OVER FROM SAFI TO JORF LASFAR

In 2019, a second pilot section of 200m length was built on Jorf Lasfar site. The project used PG produced at Jorf Lasfar itself and was implemented by the same team of partners. In this case the proportion of PG used was 65%.



Fig. 108. Pilot road at Jorf Lasfar (Image sequence courtesy OCP)

3.2.8 FUTURE DEVELOPMENT AND SCALE-UP PERSPECTIVE

In the light of the encouraging results obtained, new pilot roads using PG based materials are in planning and design trials across the national road network.

More ambitious cross-sections and new formulations combining PG with a range of locally available industrial co-products from the regions, starting with those available at Jorf Lasfar itself, will be considered for the new tests. The initial consortium will continue the work together and will be joined by staff from the Direction des Routes (Roads Directorate), Ministry of Equipment, Transport, Logistics and Water.

4. CASE STUDIES: INTEGRATED APPROACHES

4.1 PRODUCTION AND USE OF PHOSPHOGYPSUM IN EQUILIBRIUM: BRAZIL

AUTHORS

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Nancy Case – Mosaic Company

4.1.1 OVERVIEW

According to data published by Brazil's Associação Nacional para Difusão de Adubos⁷⁸ (ANDA) (National Agency for Fertilizer Development), phosphoric acid production in Brazil has reduced in recent years as a consequence of a national decline in rock phosphate mining, but also as a result of international investors buying out Brazilian phosphate producers (e.g. the acquisition of Vale Fertilizantes in 2018). In 2018 the phosphate sector produced 2.15mt of phosphoric acid used mainly for making Triple Superphosphate (TSP) and mono-ammonium phosphate (MAP). That level of production equates to an annual output of 8-10mt PG as co-product (~20% humidity).

4.1.2 FROM STACKS TO MINES: LEGACY PG COMING BACK INTO USE

Brazil still has a large legacy inventory of PG from many years of fertilizer production dating back to the 1970s, ie to the period before PG started to be consumed in large volumes for agricultural purposes. But it is estimated that this legacy holding will have been mined out by 2026/27 as the use of PG in agriculture as of 2019 at ~10 Mi tonnes yr⁻¹ is already outstripping current domestic production. This would make Brazil the first large-scale producer of PG not only to reach the point of equilibrium between production and consumption, but also to be in a position where to meet rising demand, PG “stacks” become PG “mines”.

4.1.3 ACIDIC SOILS IN THE CERRADO

Brazilian soils are predominantly acidic, presenting high levels of free Al³⁺ in solution across their profile. The Cerrado is a vast tropical savannah eco-system covering 21% of Brazil's surface area. As such, it is second only to the Amazon in terms of its size and significance among Brazil's many eco-systems.

The regional phosphate production centre is in Uberaba, Minas Gerais.

The use of PG for complexing Al in deeper layers and for transporting Ca through the soil profile to where liming is not effective (below 20 cm), has shown to be the best management alternative for ploughing in soil amending lime in most Brazilian soils, especially in the Cerrado region.

4.1.3.1 SULPHUR DEFICIENCY

In general, most Brazilian soils are likewise S-deficient as a consequence of having little or no organic matter content. Consequently, these soils have no capacity to retain sulphates (SO₄⁻²) in the mineral phase, taking into account the critical threshold level of 10 mg kg⁻¹ (extractor CaHPO₄ 500mg L⁻¹). This means that many crops require annual S addition for healthy development and good yields, whether by means of S rich fertilizers or by application of PG.

4.1.4 SOYBEAN

Among the crops most needy of S-rich fertilizer application is soybean, now the most widely cultivated cash crop in Brazil covering some ~36 Mi ha (equating to >50% of cultivated land area). But S is also in high demand for horticulture and fruit production, although on a much smaller scale. The main fertilizers used at present in Brazil with S in their composition are single super phosphate (SSP) and ammonium sulphate. PG is used as both soil amendment (up to 3 tonnes ha⁻¹) and as booster source of S, but in this latter case at much lower dose rates (300-500 kg ha⁻¹).

As competitor to, or perhaps complementing PG, Brazil has some natural gypsum mines (gipsite) in the Northeast region, mostly in Pernambuco State. Production of mined gypsum was 3.8 mt in 2018, reflecting a pattern of consistent growth in demand since 2013 when annual production was ~3.4 mt (Source: DNPM⁷⁹).

The main market for gipsite production is for manufacturing cement. Only a small amount (less than 20%) is used for agriculture. The reason is that the cost of transport over long distances to high-consuming agricultural areas such as Cerrado is uneconomic. In general, when the farm-delivered price is high (>\$50 US dollars/t) the farmers forego its use even when agronomically recommended. This is the situation in Mato Grosso state (west central Brazil) and other States located at long haul distances from the phosphate industry. Across the country, the economic threshold of \$50/t transport cost price is the demand limiting factor, both for natural gypsum and for PG.

78. <http://anda.org.br/history/>

79. Departamento Nacional de Produção Mineral (DNPM), <http://www.anm.gov.br/>

4.1.5 PG AS CO-PRODUCT

Phosphoric acid and PG production in Brazil is located in two specific places, on the coast of São Paulo State, processing rock phosphate (RP) coming shipped from other countries, and Uberaba (Minas Gerais State) where the majority of RP mined in Brazil is processed, transported from mine to processing plant by trains or trucks. Processing and selling PG from these production plants is outsourced to independent companies. These companies collect the PG from the storage areas (stacks), then dry and sieve it before application, ensuring it has good handling properties for field application and subsequent crop uptake.

Some companies are developing fertilizers with PG in their formulations, granulating or making composites of PG and elemental S together. The granulated product has pellets of the same size as fertilizer granules already sold into commercial agriculture and hence can be applied using existing equipment. This is one new option but is relatively more expensive than raw PG and hence comes at an

additional cost which farmers may not accept. In volume terms it represents a very small percentage of the PG currently consumed in Brazilian agriculture.

In terms of agronomic need, there is still considerable potential for increasing the use of PG in Brazilian agriculture, but demand is highly price sensitive. Until the time of publication of PG2 there are no government subsidies available to farmers, whether for fertilizer or soil amendment, so demand is completely determined by the market prices of both commodities and fertilizers/ soil amendments. The current trend for PG use, including legacy reserves, to be substantially or even completely absorbed by agriculture is likely to continue. Its use is environmentally friendly both to soils and to enable areas used for storing legacy PG to be returned to alternative more beneficial use. PG use is economically viable, and agronomically well suited for supplying essential nutrients notably Ca and S for the country's major crops, advantageously in plant-available form.

4.1.6 MAJOR PRODUCER: MOSAIC

In line with the trends noted above is the recent acquisition⁸⁰ by Mosaic of Vale's phosphate production facilities in both Uberaba and Cajati,⁸¹ PG production and use data from Mosaic⁸² (Table 23).

TABLE 23. PG production and consumption trends, Mosaic Uberaba and Cajati, Brazil

UBERABA					
YEAR	Gyp produced (t dry basis)	Gyp produced (t wet basis)	Gyp shipped (t wet basis)	Agriculture (t wet basis)	Cement plants (t wet basis)
2017	4,005,328	5,340,437	2,132,412	1,993,174	139,238
2018	4,109,299	5,479,065	2,734,338	2,571,142	163,196
2019 (up to October)	2,843,810	3,791,747	3,053,753	2,926,487	127,266
Total 2017 - 2019	10,958,437	14,611,249	7,920,503	7,490,803	429,700

CAJATI					
YEAR	Gyp produced (t dry basis)	Gyp produced (t wet basis)	Gyp shipped (t wet basis)	Agriculture (t wet basis)	Cement plants (t wet basis)
2017	1,111,383	1,389,229	965,928	221,639	744,290
2018	1,262,841	1,578,551	1,001,748	213,477	788,271
2019 (up to October)	678,023	847,529	950,838	277,516	673,322
Total 2017 - 2019	3,052,248	3,815,310	2,918,514	712,631	2,205,883

In Uberaba the striking volumetric characteristic is the heavy weighting towards agricultural use, understandable in view of the agronomic benefits mentioned above and the close proximity to the main Cerrado market. The 50% growth rate in use in agriculture from 2017 to 2019 seems likely to continue, but will also remain price sensitive, where transportation costs are a key factor.

80. Acquisition completed January 8, 2018, see http://www.mosaicco.com/Who_We_Are/4213.htm

81. For Mosaic P production worldwide see http://www.mosaicco.com/Who_We_Are/locations_directory_locations_by_facility_type_phosphate_production.htm

82. For Mosaic global locations including Uberaba and Cajati see Google Maps https://www.google.com/maps/d/viewer?hl=en&ie=UTF8&msa=0&ll=27.37176700000007%2C0.703125&spn=0.004764%2C0.007929&z=2&source=embed&mid=1mzd2Xi1gb270-710bzZokc_B_IU

For Cajati, equally striking is the volumetric weighting, but the mirror opposite of Uberaba, ie in Cajati weighted to cement. Again, geography is a key factor in that Cajati in Sao Paulo state is close to the coast and is much further from the key Cerrado market than Uberaba. A similar phenomenon is seen in India where market demand for PG correlates to close proximity of one or more cement plants.

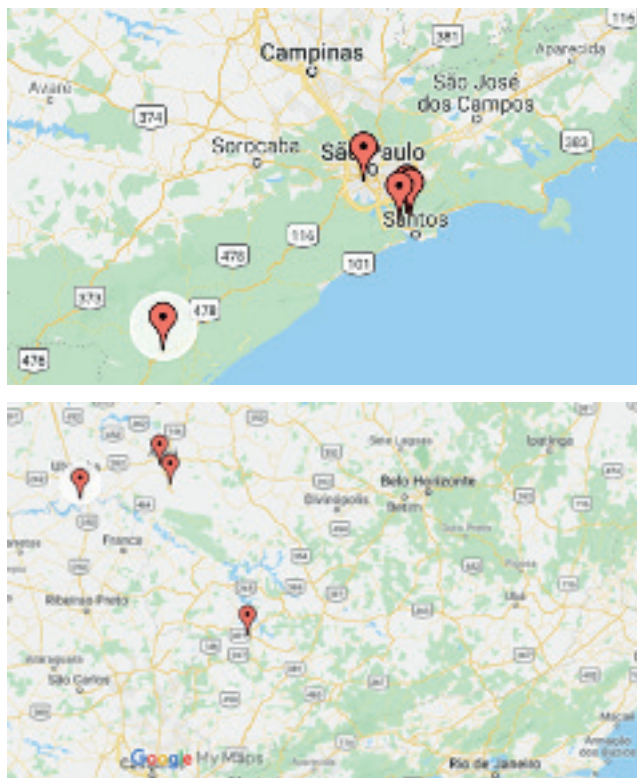


Fig. 109. Mosaic PG locations Cajati (L) and Uberaba (R)

4.1.7 BACKGROUND – PG R&D IN BRAZIL

While PG uses in agriculture and cement production now dominate the situation in Brazil as of publication date, historically Brazil has been a leader in the “constructive regulation” approach to PG use, based in particular on an active collaboration between regulators, operators, producers and universities or independent scientific centres of excellence. One key outcome was the publication by the national nuclear regulator CNEN⁸³ of Resolution 179/14 of November 2014 concerning Uses of Phosphogypsum in Agriculture and the Cement Industry.⁸⁴ A second, which has its origins in an international conference on PG uses hosted in 2006 in Belo Horizonte, was the decision taken by Vale management to develop a “business case” for PG use rather than disposal (or stacking) which culminated not only in commercial-scale use but, perhaps equally significantly,

the first known Sustainability Report by a global phosphate producer, published by Vale in 2012, with quantitative reporting for the first time of its PG use.

An overview of the very extensive research work done in innovative applications in Brazil, such as affordable housing,⁸⁵ high-strength gypsum board and other construction uses,⁸⁶ urban waste management, stack revegetation⁸⁷ and environmental impact assessment may be found in IAEA SR78 Section 10.5.2 and in PG1 Sections 4 and 7. A feature which this investment in R&D illustrates, as is reconfirmed in PG2, is that allowing a fruitful interaction between universities or scientific research centres, and producers such as referenced in Belgium, Canada, India, Morocco, is often (almost universally) the door-opener to commercial success.

4.2 USES OF PHOSPHOGYPSUM – AGRICULTURE, CEMENT, ROADS: INDIA

AUTHOR

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4.2.1 OVERVIEW OF PHOSPHORIC ACID AND PHOSPHOGYPSUM PRODUCTION AND USE

India’s phosphoric acid production has gone down during last two years due to closure of some plants. Phosphoric acid production in fertilizer year 2017-18 was 1.47 million tonnes equivalent to 7.8 million tonnes of phosphogypsum. There was generation of about 8 million tonnes of phosphogypsum (PG) in 2018-19 fertilizer year (Table 24). There is also an inventory of about 56.0 million tonnes at various locations in the country.

TABLE 24. Generation of Phosphogypsum and its Utilization in India (Data of 10 plants)

YEAR	Phosphogypsum Generation (mt)	Utilization of phosphogypsum (mt)*			
		Cement	Agriculture	Other	Total
2017-18	7.79	2.67	0.42	2.21	5.30
2018-19	8.27	3.96	0.59	1.82	6.37

(*estimated, mt=million metric tonnes)

4.2.2 CEMENT AND AGRICULTURE

Major use of PG in India is in manufacturing of cement which in 2018-19 accounted for about 4 million tonnes of PG, a rise of 30% on the previous year. India also has large resources

83. Comissão Nacional de Energia Nuclear, <http://www.cnen.gov.br>

84. USO DO FOSFOGESSO NA AGRICULTURA E NA INDÚSTRIA CIMENTEIRA <http://appasp.cnen.gov.br/seguranca/normas/pdf/Nrm488.pdf>

85. <https://www.teses.usp.br/teses/disponiveis/85/85131/tde-10072009-104349/publico/FreddyLazoVillaverde.pdf>

86. <http://livros01.livrosgratis.com.br/cp004818.pdf>

87. <http://www.smarh.eng.ufmg.br/defesas/272M.PDF>

88. Fertiliser Association of India, <https://www.faidelhi.org>

of natural gypsum which is used both for agriculture and manufacturing of cement. The production of mined gypsum in 2017-18 was 2.05mt.

Cement plants within a few hundred km of a phosphoric acid production facility commonly find it economic to use PG as a retardant (see CPCB specifications). In 2018-19 some 0.59mt was used in agriculture, also showing some 30% growth in demand. Wider use is constrained due to cost of transportation.

4.2.3 BUILDING MATERIAL AND ROAD USE

PG is also being utilized to a limited extent as building material. In spite efforts of the industry utilization of gypsum boards in civil construction has not achieved commercial scale. Use of PG in construction of roads is being experimented. The scale up of this use will be known only in next 2-3 years.

4.3 PG FERTILISERS AND ROAD CONSTRUCTION MATERIALS: TWO PG INITIATIVES OF PARADEEP PHOSPHATE LTD

AUTHOR

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4.3.1 INTEGRATED INITIATIVES IN PG USE BY PARADEEP PHOSPHATE LTD

This case study sets out two innovative and integrated initiatives taken by Paradeep Phosphate Limited (PPL),⁸⁹ Paradeep, Orissa, India for value-add uses of Phosphogypsum and potential for increased use of Phosphogypsum in India and neighbouring markets. These concern a major new pilot project for PG uses in road construction, and the development of a new S-rich PG-based fertiliser, Zypmite. In respect of partnership, the role of PPL leadership and the collaboration between PPL and the Central Road Research Institute as both partner and regulator are explored.

4.3.2 SALIENT OPERATING FEATURES OF PARADEEP PHOSPHATE LIMITED

Paradeep Phosphate Limited (PPL) is one of the large Phosphoric Acid producing plants in India. Salient operating features of PPL are:

- Current phosphoric acid production, 300,000 t/y
- Sources of phosphate rock: Morocco, Jordan, Egypt etc
- Rate of generation of Phosphogypsum (PG): 1.5 mt/y
- Current average value-add use of PG: 0.8 mt/y

Prominent areas for value-add use of PG:

- Cement (local manufacturers)

During the year 2011-2012, ~509,000 tons of Phosphogypsum was sold to cement plants and other use.

Major consumers are M/s Odisha Cement Ltd.; M/s Orrisa Agro Industries corporation) for:

- In-house production of Zypmite (low-cost, sulphur rich fertiliser (see Fig. 117))
- Sale to neighbouring countries such as Bangladesh and Nepal (apparently for application in agriculture & cement manufacture).

Challenges for increased use of PG:

- Transport bottleneck
- Non-availability of railway wagons - water transportation option being explored.

4.3.3 CENTRAL ROAD RESEARCH INSTITUTE (CRR): PROJECT OVERVIEW AND SUMMARY FINAL REPORT

Engineers and scientists of PPL & the Central Road Research Institute (CRR)⁹⁰ worked in 'hand-holding' (partnership) mode for more than a year to carry out a feasibility study on "The utilization of Phosphogypsum as road construction material". The project was entrusted to CSIR - Central Road Research Institute - by M/s Paradeep Phosphates Ltd., Odisha, India.

In order to assess its suitability as a road construction material a laboratory study was conducted, for which the broad scope of work was as follows:

- Characterization of Phosphogypsum
- Characterization of Soil /Flyash
- Use of phosphogypsum in road embankment and subgrade
- Use of Phosphogypsum in concrete roads
- Use of Phosphogypsum in Bituminous mixes of flexible pavements.

The tests carried out a characterization of PG in terms of its physical and engineering properties and to assess the possibility of using this material as such in road embankment and subgrade of a pavement. Studies were also carried out to determine the development of strength gain in local soil and flyash with the addition of phosphogypsum. In addition to the above, studies have also been undertaken to improve the strength of local soil with the addition of lime and phosphogypsum.

To carry out the study, locally available soil from the plant campus was collected. The site for collection of locally available soil was decided in consultation with the client. The soil selected for the study is fine grained soil and clayey in nature.

89. <https://www.paradeepphosphates.com/>

90. <https://www.crridom.gov.in>

In order to use phosphogypsum with flyash, several mixes of flyash and phosphogypsum were prepared in the laboratory to assess the strength characteristics of fly ash with addition of phosphogypsum.

To start the work phosphogypsum and soil samples were characterized in detail as per BIS standards. The properties determined included physical characteristics such as specific gravity, particle size distribution, consistency limits i.e., Liquid & Plastic limit, natural moisture content, etc. In addition to the above, the optimum moisture content (OMC) at which the sample can be compacted to its maximum dry density (MDD) were also evaluated for further casting of samples for strength determination. The strength and engineering characteristics of phosphogypsum alone and in combination with local soil, lime and flyash etc. were determined in terms of its shear strength (c, ϕ); Unconfined Compressive Strength and California Bearing Ratio (CBR).

In order to assess the efficacy of phosphogypsum for the purpose of stabilization, the soil was stabilized with phosphogypsum and phosphogypsum + lime separately. Strength gain was determined in terms of Unconfined Compressive Strength (UCS) and CBR. The durability tests were also conducted to assess the performance of stabilized soils when subjected to wetting and drying for simulating water logging and flooding situation at site.

Based on laboratory data, it was found that phosphogypsum as such when compacted at Optimum Moisture Content (OMC) & Maximum Dry Density (MDD), yields very high strength. The UCS value was good enough for its use in different pavement layers. However, when this sample was soaked in water for the purpose of determining durability, it was found to lose some strength but still it has sufficient strength for use in sub-base layer or as a capping layer over soft subgrade.

The local soil was also stabilized with different percentages of phosphogypsum up to 50%. The gain in strength was determined in terms of Unconfined Compressive Strength. It was found that with the addition of phosphogypsum, UCS increased but only up to 20% phosphogypsum. When the quantity of phosphogypsum was increased beyond 20%, the strength decreased. With addition of 4 & 6% lime UCS increased for both the 14- and 28-day curing periods. However, when the mixes of soil and phosphogypsum/ soil-phosphogypsum-lime, were subjected to durability tests, it failed after few cycles of wetting and drying and hence none of the stabilized samples could meet the durability test criteria.

The flyash was also stabilized with different percentages of phosphogypsum up to 50%. The gain in strength was determined in terms of Unconfined Compressive Strength.

It was found that with the addition of phosphogypsum, the UCS increased but only up to 40% phosphogypsum. When the quantity of phosphogypsum was increased beyond 40%, the strength decreased. However, when the mixes of flyash and phosphogypsum, were subjected to durability tests none of the samples could withstand the durability test criteria.

During the determination of unconfined compressive strength, it was observed that compacted specimen of phosphogypsum behaved like a semi-rigid material. It is evident from the fact that when the compacted mass of the same was subjected to loading in increment it behaved like a brittle material at its ultimate strength.

Based on laboratory studies, it was concluded that phosphogypsum as such can be used as a fill material and in sub-grade/sub-base layer of a road pavement. Local soil stabilized with 20% phosphogypsum can be used as subgrade /capping layer. Local soil stabilized with 20% phosphogypsum and 2 or 4% lime can also be used as subgrade/ capping layer. Flyash stabilized with 40% phosphogypsum can be used as subgrade /capping layer& sub-base layer. However, before recommending for large scale application, an experimental section should be constructed and monitored over a period of time to assess the performance of the road.

4.3.3.1 RECOMMENDATIONS:

1. Phosphogypsum as such when compacted at OMC and MDD, yields very high strength. The unconfined compressive strength (UCS) was good enough for its use in different pavement layers. However when this sample was soaked in water for the purpose of durability, it was found to lose some strength but still it has sufficient strength for use in sub base layer or as a capping layer.

2. The local soil was also stabilized with different percentages of phosphogypsum up to 50 percent. The gain in strength was determined in terms of Unconfined Compressive Strength. It was found that with the addition of phosphogypsum, the UCS increased but only up to 20% phosphogypsum. When the quantity of phosphogypsum was increased beyond 20%, the strength decreased afterwards. With addition of 4 and 6% lime UCS increased for 14 and 28 day's curing period. However, when the mixes of soil and phosphogypsum / soil-phosphogypsum-lime, were subjected to durability tests, none of the samples could withstand the durability test criteria. In tropical areas local soil stabilized with phosphogypsum/ phosphogypsum +4% and 6% lime can be used as capping layer/sub-base/layer.

3. The flyash was also stabilized with different percentages of phosphogypsum up to 50%. The gain in strength was determined in terms of Unconfined Compressive Strength. It was found that with the addition of phosphogypsum, the UCS increased but only up to 40% phosphogypsum. When

the quantity of phosphogypsum was increased beyond 40%, the strength decreased afterwards. However, when the mixes of flyash and phosphogypsum, were subjected to durability tests, none of the samples could withstand the durability test criteria. Flyash stabilized with 40% phosphogypsum can be used in capping/ sub-base layer.

4. During the determination of unconfined compressive strength, it was observed that compacted specimen of phosphogypsum behaved like a semi-rigid material. It is evident from the fact that when the compacted mass of the same was subjected to loading in increment it behaved like a brittle material at its ultimate strength. So, it may be used in lower layers of the pavement.

5. Based on laboratory studies, it is concluded that phosphogypsum as such can be used as a fill material and in sub-grade/sub-base layer of a road pavement. Local soil stabilized with 20% phosphogypsum can be used as subgrade /capping layer. Local soil stabilized with 20% phosphogypsum and 2 or 4% lime can also be used as subgrade /capping layer. Flyash stabilized with 40% phosphogypsum can be used as subgrade /capping layer & sub-base layer. However, before recommending for large scale application, an experimental section must be constructed and monitored over a period of time to assess the performance of the road.

6. 7% phosphogypsum can be used in bituminous concrete mixes. The optimum binder content (OBC) for bituminous concrete (BC) with 7% phosphogypsum and without phosphogypsum was found to be 5.8% by wt. of aggregate or 5.5% by wt. of mix. The use of 7% phosphogypsum increases the strength of mix and also increases the retained stability of mix indicating the reduced water induced damages of bituminous pavement.

7. The phosphogypsum can be used in semi-dense bituminous concrete (SDBC) mixes. The incorporation of 7% phosphogypsum in SDBC mixes provides higher retained stability in comparison to SDBC without phosphogypsum. The Optimum binder content for SDBC with 7% phosphogypsum was found 5.4 % by wt. of aggregate or 5.1% by wt. of mix. The stability, flow value, optimum binder content air voids and VFB of SDBC mixes with phosphogypsum as filler were found within the specified limits of MOSRTH.

8. The 7% phosphogypsum can be used in bituminous macadam (BM) mixes. The OBC for BM with 7% phosphogypsum as filler was found 3.6% by wt. of aggregate or 3.5% by wt. of mix. The optimum binder content BM mixes with 7% phosphogypsum as filler was found within the MOSRTH specified limits 3.3 to 3.5.

9. The 7% phosphogypsum can be used in dense bituminous macadam (DBM) mixes. The OBC for DBM with 5.5% as filler

was found 5.4 % by wt. of aggregate or 5.1% by wt. of mix. The stability, flow value, optimum binder content, air voids and VFB of DBM mixes with impure chalk as filler are found within the specified limits of MOSRTH.

10. The phosphogypsum has potential as filler for bituminous mixes and can be used in 7% by weight of aggregates in different bituminous mixes in base course such as Bituminous Macadam (BM), Dense Bituminous Macadam (DBM) as well in wearing courses, such as Semi Dense Bituminous Concrete (SDBC) and Bituminous Concrete (BC). The phosphogypsum can be used in SDBC and BM with emulsion, which can facilitate the construction without heating process and use of phosphogypsum in wet condition. The field trials are required to validate the preliminary laboratory studies and the field trials are required before its use in road construction.

11. No significant development of strength observed by replacing the cement by 10, 20 and 30% phosphogypsum at different w/c ratio for both Pavement Quality Concrete (PQC) and Dry Lean Concrete (DLC). The strength characteristics of the PQC mixes with 10% phosphogypsum as partial replacement of cement are comparable and almost equal at water binder ratios of 0.40 and 0.45.

12. The strength characteristics of the PQC mixes found reduced with higher dosages of phosphogypsum i.e. 20% and 30%.

13. The same trend was also observed for the mixes prepared for DLC.

14. For the preparations of standard concrete with grade designation M-40, M-35, M-30 and M-25 (as per IS 456-2000) 10% cement can be replaced by phosphogypsum with appropriate water binder ratio of 0.40 or 0.45. For DLC 10% cement can be replaced by phosphogypsum at OMC and MDD.

15. It is suggested that Phosphogypsum be treated with ~1% commercial lime for neutralization before use.

4.3.3.2 SITE CLEARANCE AND CONSTRUCTION

- > Length of the road: **500 m (5 x 100m sections)**
- > Width of the road: **5.75 m**
- > Site work commenced: **February 2017**
- > Construction completed: **April 2018**

See Figures 110, 111, 112, 113 and 114 below for a visual narrative of road clearance and construction.



Fig. 110. Cleaning (L) and stripping (R) site (Images courtesy Paradeep Phosphate Ltd)



Fig. 111. Application of sand course (Image courtesy Paradeep Phosphate Ltd)



Fig. 112. Development of embankment using neutralised PG (NPG) (Image courtesy Paradeep Phosphate Ltd)



Fig. 113. Clay as side cover, outer slope (Image courtesy Paradeep Phosphate Ltd)



Fig. 114. Testing in progress during road construction by scientists and engineers of CRRRI & PPL (Image courtesy Paradeep Phosphate Ltd)

4.3.4 NEW PRODUCT DEVELOPMENT - ZYPMITE

Chemical fertilizers such as diammonium phosphate (DAP), Urea and Muriate of potash (MOP) played a major role in the successful delivery of India's green revolution, which brought self-sufficiency in food production to the country. During the ensuing decades the crop nutrition focus was on increased application of the major nutrients N, P and K, a focus supported by a coordinated policy of the Government of India to provide significant levels of subsidy to encourage farmer uptake of these nutrients.

Worldwide, three products Urea, DAP and MOP have been the dominant, but also most cost-efficient mineral fertiliser sources of N, P and K respectively. But this macro-nutrient dominance has sometimes been at the cost of ignoring the critical role of micro-nutrients, such as magnesium and boron, in plant growth and yield. The relative neglect of micro-nutrients while formulating fertilizer specification and application policy, has resulted in progressive depletion of micro-nutrients in soil, a trend which is increasingly understood as the prime reason for a trend towards stagnation in agricultural productivity despite an overall increase use of NPK fertilizers. Micronutrients play a critical role as regulators of plant uptake of N, P, K, such that when they are not present in sufficient plant-available forms and quantities yields do not increase despite the application of higher levels of N, P and K nutrients.

PPL has been predominantly dealing with N, P and K, especially P. Its "NAVARATNA" brand is well established in most markets in its operating area. However, PPL now believes with stagnating yield and lower response to NPK time has come to look beyond NPK and start to look to the divergent demands of farmers. As a company committed to meeting its corporate social responsibility obligation, PPL is determined to propagate and popularize micronutrient-containing products which are cost effective and profitable to farmers.

Accordingly, PPL has developed a new product Zypmite, made by blending Phosphogypsum and Dolomite in varying formulations to create a cost-effective source of Sulphur (S), Calcium (Ca), and Magnesium (Mg). Before commercial launch, in the pilot phase of Zypmite development product samples were given to partners, Orissa University of Agriculture,⁹¹ for independent scientific trial. These were completed with satisfactory results. In parallel, PPL itself successfully conducted 408 field trials on various soils and crops, covering all its marketing territories. This allowed PPL to select the best performing composition resulting in the highest sustained increase in yield. Activities were then undertaken to commercialize Zypmite in the market.

4.3.4.1 PRODUCT FEATURES AND ADVANTAGES

Preparation of manually blended Mixed Fertilizers requires an exact knowledge of the nutrient formulations of the single- or macro-nutrient fertilizers, their mixing properties and optimal methods of blending them, knowledge which farmers may not possess. Even if such knowledge is available, farmers may have difficulty procuring the space and equipment required for efficient mixing and blending. Hence PPL has opted to market Zypmite in granulated form. Granulated products have the following advantages over manually blended products:

- > Every granule contains an identical formulation of macro- and micro-nutrients as specified for the product
- > Granules are free flowing and easy to apply
- > No product losses occur due to dusting during transport, handling and storage
- > There is less risk of unwanted commingling of extraneous nutrients
- > Nutrient 'leaching' and 'segregation' are reduced to a minimum
- > Release of nutrients to the soil is controlled and predictable.

Product formulations can be manufactured in various grades depending upon the nutrient content and balance required.

4.3.4.2 MANUFACTURING TECHNOLOGY

In the manufacturing process, different Gypsum, Dolomite etc in solid form are stored and proportionate quantities are drawn for neutralisation and processing. They are thoroughly mixed (Fig. 115) and fed to a Rotary Drum-type Granulator. Some 10 - 12% water is added in the drum. Due to moistening and to the agitating and tumbling action of the material in the granulator, granules are formed (Fig. 116).

The excess moisture in the material is removed in a dryer. Hot granules coming out of the dryer are fed to a cooler where they are cooled. The dried and cooled granules are screened to separate out oversize, undersize and finished product. Oversize material is returned to the granulation drum after crushing. Finished product in the range of 1 mm to 4 mm granule size is then packed.

This product thereafter is fortified with Boron and Zinc resulting in an S-rich product also delivering essential micronutrients through PG to the farmers.⁹² The Zypmite plant has a capacity of 200 t/d. and the finished product is marketed in 25 kg bags (Fig. 117).

Gypsum (PG) is also sold by PPL in both bag and bulk form.

91. Orissa University of Agriculture and Technology, <https://collegedunia.com/university/25764-orissa-university-of-agriculture-and-technology-ouat-bhubaneswar>

92. Zypmite https://www.paradeepphosphates.com/what_we_do/products/



Fig. 115. Neutralised PG powder after mixing with micro-nutrients (Image courtesy Aleff Group)



Fig. 116. Mixed powder after granulation (Zypmite) (Image courtesy Aleff Group)

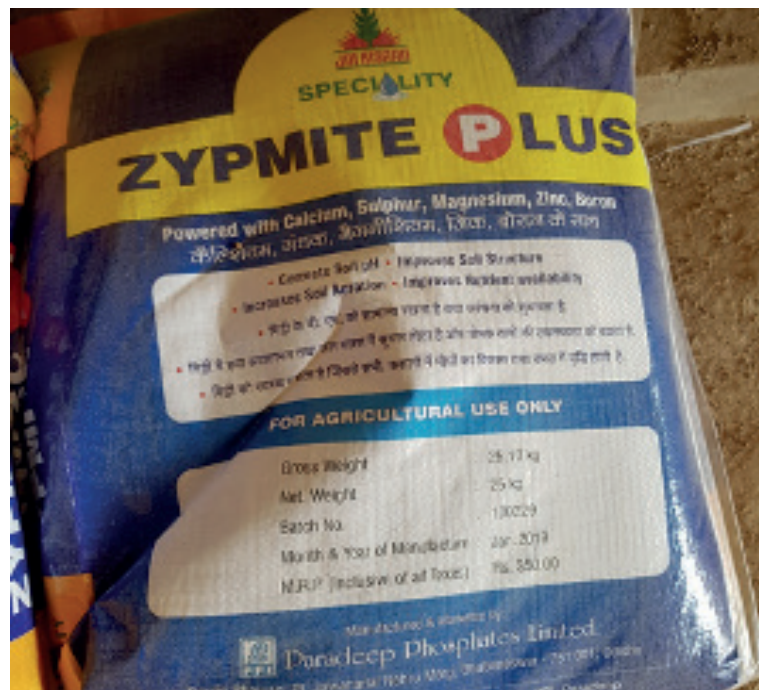
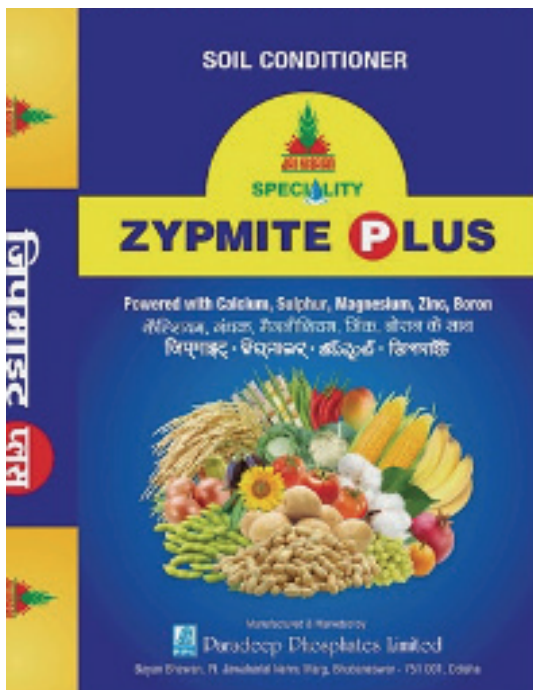


Fig. 117. Zypmite Plus Packaging (R) and Freshly Bagged Zypmite (25kg) prior to sale (L) (Images courtesy Paradeep Phosphate Ltd (L) and Aleff Group (R))

4.3.5 ZYPMITE APPLICATION TO CHICKPEA CROP

As an illustration of the widespread potential for PG use in S deficient soils in India, but also a further illustration of the benefits of knowledge sharing and partnership between academia and industry as PG value pathways are mapped out, brief reference is made to a recent publication studying field trials of Zypmite on chick-peas, a staple crop in many parts of India [65].

“A field experiment was conducted to evaluate the effect of Zypmite fertilizer along with di-ammonium phosphate (DAP) in study. The application of Zypmite exhibited in growth, yield, nutrients uptake and availability of nutrient in soil. [...] The sulphur availability in soil was significantly influenced among treatment and found maximum (23.0 kg/ha⁻¹) under 40 kg sulphur through Zypmite. It was observed that Zypmite and chemical fertilizers, enhanced yield and higher uptake of nutrient as well as improved soil fertility.”

The context for the study is as significant as its field-trial results. A key to the long-term solution for PG is high-volume use. Given how broadly applicable Zypmite is to key crops grown on India's soils, innovative products such as Zypmite have the potential for very high-volume use, both in India and in similar cultures where the chickpea also has staple food status.

4.3.5.1 PROTEIN SOURCE

“Chickpea (Cicer arietinum L.) is a most important pulse crop grown in India. Pulses can be grown on a varied soil series and climatic environments, and play important role in crop rotation, mixed and inter-cropping and maintain soil fertility through nitrogen (N) fixation in soil. Pulse crops are major source of protein among the all vegetarian in India, and having essential amino acids, vitamins and minerals, [66] They contain 22 to 24 per cent protein, which is just about double in wheat and three times in rice. [67] It is an integral part of the cropping system of the farmers all over the country, because this crop fits well in the crop rotation and mixed cropping. It has multipurpose use and ability to grow under the condition of low fertility and varying conditions of soil and climate.

4.3.5.2 COST-BENEFIT VS CEREALS

A 2014 study concluded that good agronomic management practices, awareness campaign of integrated pest management (IPM) and use of high yielding varieties (HYV), pulses are more economic as compared to cereals [68]. Dry land areas comprise virtually 64% of the total cultivated area and recorded 42% of total food grain production in the Indian agriculture. In Chhattisgarh state about 803.03 ha area under chickpea cultivation

(ICRISAT Annual Progress Report 2011-12).

4.3.5.3 SULPHUR AS KEY NUTRIENT

Sulphur is now recognised as major plant nutrient, along with nitrogen (N), phosphorus (P), and potassium (K). Poor nutrient management is vital rationale of low productivity of chickpea. Phosphorus is an important fertilizer in chickpea production [69] [70] [71]. Phosphorus has a positive effect on nodule formation and nitrogen fixation in legume crops.⁹³

Sulphur constitutes the main element of amino acids such as cysteine and methionine, which are of essential nutrient value. In addition to these functions, ferro-sulphur proteins play an important role in nitrogen fixation. This element positively affects nodulation in legume crops in particular. It is essential for the growth and development of all crops, without exception. Most of the plants requirement of Sulphur is absorbed through the roots in the form of sulphate (SO₄⁻²). Sulphur deficiency is becoming more critical with each passing year which is severely restricting crop yield, produce quality, nutrient use efficiency and economic returns on millions of farms. Like any essential nutrient, sulphur also has certain specific functions to perform in the plant. Thus, sulphur deficiencies can only be corrected by the application of sulphur fertilizer. Due to continuous cropping and imbalanced use of fertilizers, the deficiencies of secondary nutrients are also coming up. The continuous use in India of S-free fertilizers has also aggravated the problem of widespread S-deficiency in India's soils. Zypmite is a new source of S which contains 15% S and can be a beneficial to different crops”[65].

4.4 REGULATORY STATUS OF VARIOUS PG VALUE-ADD APPLICATIONS - INDIAN REGULATORS

AUTHOR

TK Haldar, Aleff Group, India

The Case Study is based on a) an invited visit to PPL site to see the pilot road and visit the Zypmite plant, b) experience of the author in Government of India service working with both the regulatory body and the phosphate industry on regulatory aspects of phosphogypsum use and c) presentations by Ranjit Misra (PPL) at the IFA New Orleans meeting, April 8, 2019.

93. Deo, C. Khaldelwal, R.B, Effect of P and S nutrition on yield and quality of chickpea (Cicer arietinum L.) [2009] <http://agris.fao.org/agris-search/search.do?recordID=IN2011000199>

4.4.1 CURRENT OPERATING CONTEXT OF PHOSPHOGYPSUM MANUFACTURE

Presently, most phosphoric acid plants in India are disposing Phosphogypsum within the plant premises in storage facilities. Depending on the demand, the phosphoric acid units sell the PG for different applications which include (i) for use as soil conditioner (for alkaline soil); (ii) as sulphur-rich fertilizer in agriculture; (iii) in cement manufacturing to control the settling time of cement (ie as a retardant); and (iv) in the production of plaster, plaster boards, gypsum fibre boards, and gypsum blocks (see Table 24).

Utilisation requires handling and transportation of phosphogypsum by rail or road (mainly in trucks/tractors). While in the years 2013-16 fertilizer use was low at a constant rate of only 1500t/y, cement production rose through the same period from 3.2 mt/ to 3.8 mt/y [72].

The utilization of phosphogypsum depends on the degree of impurities such as fluoride, phosphoric acid and radioactivity which depends on (i) type of imported source rock used, (ii) the acidulation process adopted or (iii) the pre-treatment given to phosphogypsum, eg neutralisation (see road and Zymite study above), but also (iv) cost of transportation. Proximity of phosphoric acid plants to cement producers makes PG an economically attractive feedstock, but where the haul distance from phosphate complex to cement producer is long or compromised by transportation bottlenecks there is little current option but to store it on site. There is, however, clearly a market opportunity to expand use as soil amendment and for road building.

4.4.2 STIPULATION OF REGULATORY AUTHORITIES IN INDIA ABOUT VALUE-ADD APPLICATION OF PG

The operation of Phosphoric acid plants and management of their residues, notably PG, are monitored by two separate national agencies. While risks from conventional physical and chemical contaminations and emissions are regulated and monitored by Central Pollution Control Boards (CPCB), risks from radioactive contamination and radiation protection are regulated and monitored by Atomic Energy Regulatory Board (AERB)⁹⁴.

4.4.2.1 AERB GENERAL PRINCIPLES

1. AERB approval is not required for selling phosphogypsum for its use in building and construction materials provided the activity concentration of Ra-226 in it is less than or equal to 1 Bq/g. [If Ra-226 concentration in phosphogypsum is more than 1 Bq/g, it is to be mixed with other ingredients such that the Ra-226 activity concentration in bulk material is less than or equal to 1.0 Bq/g.]

2. AERB approval is not required for manufacturing and use of phosphogypsum panels or blocks provided they have Ra-226 activity less than 40 kBq/square metre area of any surface of the panels/blocks.

3. There is no restriction for use of phosphogypsum in agricultural applications from the radiological safety considerations.

4.4.2.2 SALE OF PHOSPHOGYPSUM BY FERTILISER PLANTS

AERB approval is not required for selling Phosphogypsum for its use in building and construction material provided the activity concentration of Ra-226 in it is less than or equal to 1 Bq/g. [If Ra-226 concentration in Phosphogypsum is more than 1 Bq/g, it is to be mixed with other ingredients such that Ra-226 activity concentration in bulk material is less than or equal to 1 Bq/g].

4.4.2.3 MANUFACTURING AND USE OF PHOSPHOGYPSUM PANELS AND BLOCKS

AERB approval is not required for manufacturing and use of Phosphogypsum Panels and Blocks provided they have Ra-226 activity less than 40 kBq/square metre area of any surface of the Panel/Blocks).

4.4.2.4 USE IN AGRICULTURE

There is no restriction for use of Phosphogypsum in agricultural applications in respect of radiological safety considerations.

4.4.3 POLLUTION CONTROL BOARD

Progress on phosphogypsum valorisation in India was significantly enabled by the decision of the Central Pollution Control Board (CPCB) to reclassify it as a non-hazardous waste rather than as previously as a hazardous waste. Use is subject however, to CPCB specifications and an array of national standards as follows:

As far as possible, the phosphoric acid plants should put efforts to utilize the generated phosphogypsum for beneficial purposes such as plaster board manufacturing, in cement manufacturing as substitute for natural gypsum, recovery of by-products such as ammonium sulphate, sulphuric acid as well as reclamation of the alkaline soils. For utilization of the phosphogypsum, following guidelines are required to be followed:

(i) *All the phosphoric acid plants may explore possibilities of recycling of the phosphogypsum in plaster/ gypsum board manufacturing through their own establishment as an integral part of the phosphoric acid plant or any other small-scale unit.*

94. For AERB Directive No. 01/09 see <https://www.aerb.gov.in/english/acts-regulations/safety-directives>

(ii) All the Plaster, Blocks or Gypsum Boards manufacturing industry shall utilize phosphogypsum waste (Specifications: low radioactivity, low in organic matter and sodium content) as raw material for manufacture of Plaster, Putty Blocks or Gypsum Boards after reduction in impurities to the specifications as given in Indian Standards IS: 12679-1989, Reaffirmed 2010 (Requirement of By-product Gypsum for Use in Plaster, Blocks and Gypsum Boards).⁹⁵

(iii) As far as possible, Cement manufacturing unit (s) shall use the phosphogypsum (Specifications: less than 0.05% co-crystallized and soluble P_2O_5 less than 0.05% soluble F) in place of the natural gypsum as a regulator for setting time of cement, at the rate of 4 to 5% in its composition. Phosphogypsum used for manufacture of cement retarder (Table 25) shall necessarily conform to the specifications, as given below:

TABLE 25. PG specification for use as cement retarder

SERIAL NO	PARAMETER	SUGGESTED LIMIT %
1	Insoluble P_2O_5	0.50 to 1.00
2	Insoluble fluoride	0.40 to 0.65
3	Insoluble P_2O_5	0.02 to 0.10
4	Soluble fluoride	Up to 0.02
5	Moisture	Less than 15 %

(iv) Any entrepreneur who wishes to manufacture ammonium sulphate from the phosphogypsum waste as per the following reaction may approach the concerned State Pollution Control Board (SPCB) / Pollution Control Committee (PCC) for obtaining consents as required for establishment of such recycling industry.



(v) Any entrepreneur who wishes to recover or manufacture sulphuric acid from the phosphogypsum waste may approach the concerned State Pollution Control Board (SPCB) / Pollution Control Committee (PCC) for obtaining consents as required for establishment of such recycling industry.

(vi) The low-grade phosphogypsum may be used to reclaim alkali soils and saline –alkali soils with high sodium ion concentration. Fertiliser (Control) Order (FCO) has also approved the use of phosphogypsum as Fertiliser in view of its nutrient values, therefore, Fertiliser industry may maximise the use of phosphogypsum as 'Fertiliser'. For this purpose, the Indian Standard specifications for By-product Gypsum as stipulated under IS: 10170-1982,⁹⁶ reaffirmed 1999

need to be followed. For use of low-grade gypsum for conditioning alkaline soil, as a manure in agriculture mainly for correcting black alkali soil, BIS specifications for gypsum for agriculture use should be followed (i.e., IS:6046-1982 (First Revision; reaffirmed 2008).

(vii) Neutralized, stabilized or suitably treated phosphogypsum (not more than % to be decided) and free from fluoride, cadmium, lead, arsenic and mercury content as per limits suggested below and after blending with suitable binding material as well as bentonite and having coefficient of permeability not less than 10⁻⁷ cm /sec shall be permitted for construction of highways and access roads except in residential areas in consultation with the respective SPCB or PCC.

Further, in case of use of phosphogypsum as sub-base/ Sub-grade for road making, it shall meet the following specifications (Table 26):

TABLE 26. PG specifications for use in road-bed – heavy metal content

PARAMETER	TESTING METHOD	RECOMMENDED LIMIT (NOT EXCEEDING)
Fluoride	Toxicity characteristic Leaching Procedure (TCLP)	150 mg/l
Cadmium	TCLP	1 mg/l
Lead	TCLP	5 mg/l
Arsenic	TCLP	5 mg/l
Mercury	TCLP	0.2 mg/l
Moisture	Free moisture	15 %

These specifications are subject to a general requirement on industry to monitor PG use on a regular basis, for example soil sampling and inspection to ensure that there is no unforeseen accumulation of either heavy metals or radionuclides.

4.4.4 PROSPECTS AND TRENDS

Systematic characterisation of Phosphogypsum generated by major phosphoric acid plants and objective assessment of their potential for value-add application - commensurate with their characterisation data, respective regulatory guidelines and local market scenario needs to be taken up for acceleration in the efforts for increased use of generated PG. Expertise is available in India and this can be achieved in collaboration with academic institutions and reputed government agencies. Wherever required, assistance of international experts can also be availed.

95. <https://law.resource.org/pub/in/bis/S03/is.12679.1989.pdf>

96. http://www.questin.org/sites/default/files/standards/is.10170.1982_0.pdf

The regulatory framework in India encourages value-add application and thus promotes increased use of PG in appropriate applications. Positive response from international agencies and organisations such as IAEA, EU, IFA and recent results of large-scale PG use in different countries has created promising background for expanding fields of application.

Experience of road construction at PPL using PG and results of environment monitoring/performance analysis over three monsoons need to be widely published and major PG manufacturers to be encouraged to launch similar programmes for local and regional applications. This has the potential not only for large scale use of PG in infrastructure projects but also conservation of primary/natural resources in line with United Nations Sustainable Development Goals.

Focussed study on use of other industrial residues such as fly-ash and red mud for neutralisation and stabilisation of PG need to be taken up. FAI along with concerned government agencies can play a major role in this.

India has high potential for large scale use of PG in agricultural applications. Use of PG as soil conditioner or as low-cost fertiliser (in line with the initiative taken by PPL, 'Zypmite') need to be encouraged for:

- (i) Existing farmland having soil with high alkalinity or high sodium content
- (ii) Use as landfill for land area presently not covered by agriculture for developing social forestry for employment and income generation in rural India, and
- (iii) Reclamation and re-forestation of land affected by desertification due to loss of topsoil.

PARTNERSHIP

INTRODUCTION: KEY STEPS IN THE PATHWAY TO PG VALORISATION AND COMPREHENSIVE USE

The 40-year journey referenced in Section 1 that PG has taken from “waste” to “resource” and “co-product” can be traced in a sequence of stages as shown below.

STAGE 1. FLORIDA - BEGINNINGS OF SYSTEMATIC SCIENTIFIC EXPLORATION OF PG USES

When the Florida Institute of Phosphate Research (FIPR) was founded in 1978 by the State of Florida Legislature, funded by a severance tax from the phosphate mining industry in the state, then the epicentre of global phosphate production, it was the only publicly funded research centre in the world dedicated to the needs of the phosphate industry.

Led by founding Director David Borris and Director of Research, Mike Lloyd, who is still active, it quickly set about sponsoring a comprehensive set of studies, scientific meetings and publications covering valorisation of PG as a “by-product” of phosphoric acid production (see Fig. 118). The evidence base assembled in the FIPR library during the 1980s and 1990s, some seminal parts of which are listed by Gary Albarelli in his contribution below, remain unrivalled in both depth and coverage. It reflected the many and diverse partnerships between FIPR and its stakeholders, whether universities, consulting firms, phosphate producers, environmentalists or educators. It is good to see FIPR in its new guise as part of Florida Polytechnic University coming back into the PG picture.

STAGE 2. SOUTH-WEST SPAIN - ASSESSING ESTABLISHED PG USE IN AGRICULTURE

At the end of the 1990s, in south-west Spain, unbeknown to FIPR, the practice of discharge of PG to the rivers Odiel and Rio Tinto just before they merge and flow into the Atlantic was stopped on environmental grounds. This brought to a

head a challenge from environmentalists to the long-standing practice in that part of Spain, starting in the early 1950s of applying PG as soil amendment to the saline marshy soils of the neighbouring Guadalquivir delta.

Initially in the 1950s the marshlands of the delta were treated with high volumes of PG to create new soils. These have since become some of the most intensively farmed and fertile soils in the European Union supplying high-value crops such as strawberries and tomatoes all over Europe. The farmers applied periodic top-up PG doses to neutralise the soil pH, maintain its physical condition and remediate progressive salt-build up.

A court injunction was granted in 2000 temporarily halting the practice. Then, under judicial supervision, the Universities of Seville and Huelva, led by a team formed by Prof. Rafael Garcia Tenorio conducted an independent 5-year scientific assessment of whether or not the practice was harmful, based on a 3-year field trial. The outcome was positive from a farmer-perspective and in 2005 PG was granted official status as a fertiliser under Spanish law. The practice of use was allowed to continue. The legacy for PG was invaluable – a body of peer-reviewed publications showing conclusively the advantages of PG as soil amendment.

STAGE 3. KAZAKHSTAN - PG AS SOIL AMENDMENT ON DEGRADED SOILS

In the mid-2000s, the environmental regulator of Kazakhstan ordered the removal on environmental grounds of PG stockpiled next to the phosphoric acid production facilities in the country. The independent research body ICARDA, then headquartered in Aleppo, was commissioned to find uses for this material in agriculture. ICARDA established that it would likely function as an excellent soil amendment for the badly degraded soils in W. Kazakhstan which had been seriously exhausted by intensive farming for cotton production during the Soviet period. The results of a 3-year protocol-driven, peer reviewed trial, funded by Asian Development Bank were highly positive increasing yields by up to 270%, providing at the same time independent confirmation of results from work in SW Spain by Tenorio and team. At the time neither U Seville nor ICARDA knew of each other's work. The project manager was Dr. Manzoor Qadir who now works at UN University.

STAGE 4. INDIA - LEADERSHIP FROM GOVERNMENT AND REGULATOR

At more or less the same time Fertiliser Association of India, guided by FAI Technical Director Dr. S. Nand was working first with the Atomic Energy Board and then the Central Pollution Control Board to formulate a policy and regulatory framework for removing unnecessary obstacles to market uses of PG in India, notably in cement manufacture. The process was formally launched in 2008 with a statement indicating

that there was no radiological reason to prevent use, allowing PG to be reclassified from hazardous to non-hazardous. The regulation of heavy metals took until 2015 to complete with the Guidance on Phosphogypsum Management and Handling.

STAGE 5. VIENNA - THE INTERNATIONAL ATOMIC ENERGY AGENCY REVIEWS PG RADIOLOGICAL RISKS AND SAFETY

In parallel, closely linked to the FIPR funded project Stack Free by '53 (2005-2011) the IAEA launched a process of compiling what has become Safety Report 78 concerning the Phosphate Industry as a NORM industry, including PG. In 2013 this Report was published with Prof. Tenorio as one of the lead consultants. SR 78 was the first attempt to compile a comprehensive synthesis of all the previously unrelated efforts. Among the IAEA officers involved in the review and editing of SR 78 was Hari Tulsidas, who now works for the Economic Commission for Europe, at the UN Geneva office.

STAGE 6. SANTIAGO CHILE AND ISTABUL - IFA ENGAGES

IFA takes the decision to formalise the IFA NORM/Phosphogypsum *ad hoc* task force into an IFA NORM/Phosphogypsum Working Group, reporting to the Technical Committee. Inaugural meeting Santiago, April 2013.

An *ad hoc* IFA meeting meeting in Istanbul September 2013, hosted by Toros Agri, sets the objective of compiling and publishing IFA PG1 Report as industry response to IAEA Safety Report 78.

STAGE 7. NEW DELHI AND PARIS - RELEASE OF IFA PG1

On the occasion of the annual IFA Technical Symposium, March 2016, in New Delhi IFA releases PG1.

STAGE 8. UN GENEVA - PG CLASSIFIED AS ANTHROPOGENIC RESOURCE

In 2018 the UN Economic Commission for Europe formally classified PG as an “anthropogenic resource” issuing specifications for reuse of such resources under the United Nations Framework Classification.

STAGE 9. BEIJING - GOAL SET OF 100% PG USE IN CHINA

In response to a “comprehensive utilization” PG policy brought in by the provincial authorities of the major phosphate producing provinces in China, PG is given top priority of all issues currently facing the fertiliser industry in China by decision of the IFA-China Consultative Group, August 2019, Beijing.

STAGE 10. IFA PARIS - RELEASE OF PG2

In the wake of COVID-19 pandemic, the April release of PG2 in Delhi was deferred to July and moved online. The event was marked by the first IFA PG webinar.

VISION STATEMENTS

Vision statements are personal perspectives on the future, and related aspects of the past, of phosphogypsum as a resource. The authors are all leading figures in the phosphogypsum pathfinder network and have been instrumental in forming, leading and financing some of the most significant projects in the field.



MIKE LLOYD:

Comprehensive consumption of all phosphogypsum legacy stacks and annual production worldwide

AUTHOR

G. Michael “Mike” Lloyd Jr, Former Director of Research, Florida Industrial and Phosphate Research Institute

At the Annual Meeting of the PG WG New Orleans, April 8, 2019 G. Michael “Mike” Lloyd on the occasion of his 90th birthday was honoured as a “Giant” of PG on whose mighty load-bearing shoulders works such as this Report are proud to stand. This honour was endorsed that day by the whole IFA Technical Committee meeting under the chairmanship of Mr. Yasser Albassi.

MY PG JOURNEY AND FUTURE PERSPECTIVE

As a newly graduated chemical engineer in the early 1950s, like most new professionals, my prime motivation was involvement with meaningful, interesting and gainful employment. Being raised in a household supported by the fertilizer industry, I recognised its vital importance for the well-being of mankind. However, during my early years in the industry, it became exceedingly clear that my chosen field would provide a lifelong focus in easing the scourge of world hunger. This has been my principal driving force to this day.

During my many years of service managing operations at phosphate fertilizer production facilities, phosphogypsum issues were never a concern. In Florida, the wet process of phosphoric acid production did not become widespread until the expansion of fertilizer production in the 1960s. Phosphogypsum was stacked and that was considered an accepted part of phosphoric acid production. It was not until the 1970s, with the growth of the environmental movement and influx of population into Florida, that it became

recognised that rapid accumulation of phosphogypsum was going to become a real issue for the industry moving forward.

In response to the growing environmental concern related phosphate industry activity in Florida, in 1978 the Florida Legislature established the Florida Institute of Phosphate Research (FIPR)⁹⁷ to study and develop technologies to address these concerns. Among the charges to the Institute stipulated in law was to address “phosphogypsum disposal and utilization.” I came to FIPR as its first Chemical Processing Research Director in 1980 and quickly recognised that finding uses for the rapidly growing stockpile of phosphogypsum would be the primary focus of my work [73]. I credit FIPR’s first Executive Director, Dr. David Borris, with giving me free rein to pursue these investigations. From the start, it was evident to me that phosphogypsum had enormous potential as a co-product of the manufacture of phosphate fertilizers. It became my mission to see that its widespread utilization as such could fully consume all production and accumulated stockpiles so that stacks could be completely eliminated. This eventually led to my support for and engagement with the project Stack Free by ’53 which ran from 2005 – 2011 under FIPR’s sponsorship and is still a major factor in the many successes described in this Report and in PG1.

At the time I arrived at FIPR, Dr. Borris was organizing the First International Symposium on Phosphogypsum held in November of 1980 to bring together the world’s collective expertise on utilization and disposal of phosphogypsum [74]. This symposium would define the framework for FIPR’s phosphogypsum research program, as well as foster the relationships that would begin contracting with FIPR, a funding body, to build this program. The symposium served as the ideal marketing forum to present FIPR as the central funding resource for applied research in this area. It also served to reinforce my firm belief that direct interaction with professionals and experts in a given field is the most valuable venue for knowledge exchange and advancement of the body of knowledge, even more so than publication.

This initial exposure brought Dr. Wen Chang from University of Miami to FIPR. Dr. Chang, an expert in road construction techniques, had the strong conviction that phosphogypsum would prove to be an ideal cost-effective road base material. FIPR funded Dr. Chang’s work that led to publication of a widely-referenced book “Engineering Properties and Construction Applications of Phosphogypsum” [75] and construction of two demonstration roads in Florida, one at Parrish Road, Polk County Central Florida and the other close to the White Springs production facilities in N. Florida then operated by PCS, now known as Nutrien. Dr. Chang’s

97. For FIPR I see <http://www.fipr.state.fl.us/>

research led to vital advances in this area. The roads have held up very well over the 30+ years since their construction and details with photos can be found in PG1, Section 5 as well as in IAEA SR78.⁹⁸

The next application attacked was sulphur recovery. At the time (early 1980s) rising sulphur prices due to supply/demand imbalance led the phosphate industry to consider alternative sources of sulphur other than the Frasch process of recovery from sulphur deposits [76]. I worked closely with Davy McKee to develop a novel patented process that showed great promise when compared to the previous art, the Müller-Kühne process, which had grown out of favor as inefficient and costly. The so-called “Circular Grate Process” would produce a 9% sulphuric acid compared to 6% of the Müller-Kühne. It also had the added advantage of producing an aggregate material, rather than the problematic calcium carbonate produced in the Müller-Kühne. However, just as the Circular Grate process was being successfully demonstrated, new requirements to remove sulphur from oil and gas at refineries led to a dramatic increase in the availability of sulphur and with it, a steep decline in sulphur prices, thus rendering the Circular Grate Process uneconomical.

Another unintended consequence of the removal of requirements to remove sulphur from fossil fuels was the impact to agriculture. Since sulphur was no longer being deposited from the atmosphere, arable soils were becoming deficient in this key nutrient. The “canary in the coalmine” was the dramatic decrease in yield experience in the U.K. rapeseed crop, a commodity with high sulphur requirement. This led to research into the agricultural advantages of utilizing phosphogypsum to compensate for the atmospheric deposition of sulphur. PG is now widely used globally for this purpose.

By the time of the Third International Symposium on Phosphogypsum in 1990 [77], nearly all the work presented was from studies conducted or sponsored by FIPR and FIPR was firmly established as the global leader in phosphogypsum research. Unfortunately, FIPR’s work in this arena came to a grinding halt with the issuance of the EPA NESHAPs rule requiring PG to be stacked and prohibiting nearly all uses and putting severe restrictions on research activity.

Throughout the 1990s my efforts focused on bringing evidence to bear to convince the EPA that the basis for the PG rule had been overstated and faulty. After many encounters with EPA representatives, public hearings and applications for waivers to the rule for PG for various projects, it became apparent that these efforts were not going to be fruitful.

Meanwhile, environmental events occurring at Florida PG stacks in the 1990s also made it very evident that stacking would not be a sustainable situation. This was brought to a head with the 2002 bankruptcy of Mulberry Phosphate leading to the abandonment of their facilities, resulting in the State’s emergency remediation of the stack and pond water system. With FIPR I took the lead in forming a Pond Water Advisory Committee to investigate solutions for the enormous potential long-term liability of the ultimate treatment and disposal of stack pond water.

About this time, Julian Hilton of the Aleff Group approached FIPR with a proposal to assess the global phosphogypsum regulatory status, production and utilization efforts, with the goal of ridding the planet of PG stacks within fifty years. The so-called “Stack Free by ‘53” project, funded by FIPR, was to be a multi-year effort to determine whether gathering of evidence regarding safe, environmentally sound uses of phosphogypsum throughout the world could be brought to bear in changing the regulatory intransigence.

I am very pleased to hear that that effort has yielded great success in fostering the acceptance of phosphogypsum as a commodity and secure in the knowledge that my work is carrying on and in the hands of enthusiastic and capable experts. Upon my retirement from FIPR in 2012, I have felt very gratified knowing that my efforts in establishing a knowledge base that others are able to build upon to develop widespread use of phosphogypsum around the world. I continue to have a part-time presence at FIPR to lend my experience to their effort, especially where phosphogypsum is concerned.

It is my firm belief that it is inevitable that the growing body of evidence, as well as the real value swing from liability to asset, that favors PG use over stacking will be impossible for the United States EPA to ignore. It is my great wish that I will see the fruits of over 30 years of my professional life contribute to having PG widely accepted for use here in the U.S.

Although it may be jurisdictional intervention that provides the initial impetus for bringing this valuable co-product into widespread use, the evidence provided through these efforts will yield proof of commercial viability as a commodity. It is this viability that will bring about the consumption of all phosphogypsum stacks and production worldwide.

98. See <https://patents.google.com/patent/US5049198A/en> / <https://patentimages.storage.googleapis.com/e4/e9/e1/e63a512e096681/US5049198.pdf>



Fig. 118. Display of FIPR Phosphogypsum Publications (1980s) – FIPR I Library (Image courtesy FIPR I)

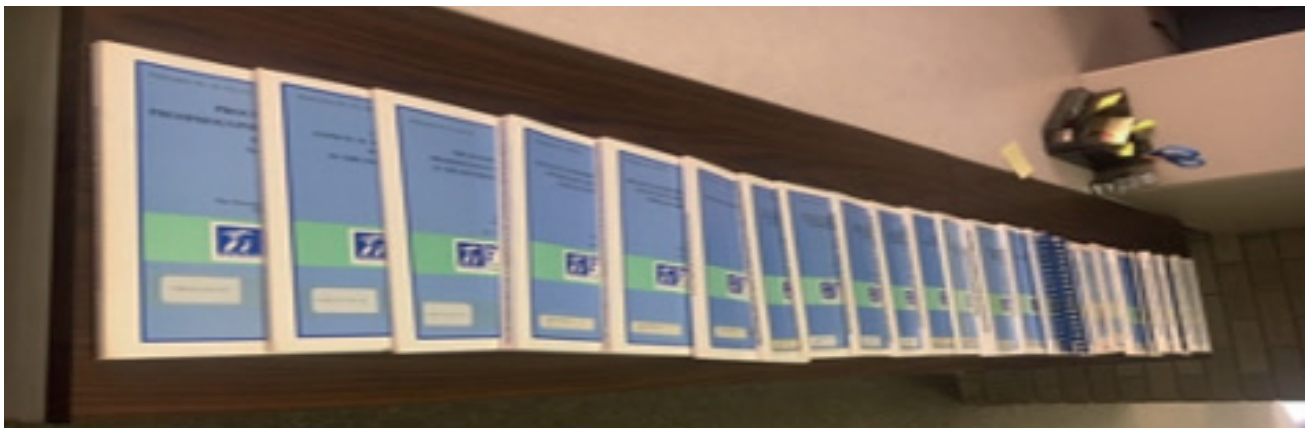


Fig. 119. Display of FIPR PG Publications (1990s-2000s) – FIPR I Library (Image courtesy FIPR I)

GARY ALBARELLI:

FIPR's History as a Global Center of Knowledge and Information on Phosphogypsum since 1979

AUTHOR

Gary Albarelli is Communications Director, Florida Industrial and Phosphate Research Institute, Florida Polytechnic University

The 1978 Florida Statute creating a Florida Institute of Phosphate Research explicitly stipulated that one of its primary charges would be to find acceptable uses for phosphogypsum. From its first days, phosphogypsum utilization research has been a cornerstone in the Institute's mission (Figs. 118, 119)). The research conducted and funded by the Institute has provided a firm foundation on which the global knowledge base in this area has been built. It has also been a springboard for further research into phosphogypsum utilization globally.

SEMINAL PG PUBLICATIONS AND REPORTS

A sample of the Institute's seminal publications and reports on PG are:

- Phosphogypsum for Secondary Road Construction, Wen F. Chang, 1989

- Engineering Properties and Construction Applications of Phosphogypsum, Wen F. Chang and Murray I. Mantell, 1990
- Gypsum as an Ameliorant for the Subsoil Acidity Syndrome, Malcolm E. Sumner, 1990
- Environmental Monitoring of Polk and Columbia Counties Experimental Phosphogypsum Roads, Gordon D. Nifong and Jon K. Harris, 1993
- Behavior of Radionuclides During Ammonocarbonation of Phosphogypsum, William C. Burnett, et al., 1995
- Microbiology and Radiochemistry of Phosphogypsum, William C. Burnett, et al., 1995
- Proceedings of the Phosphogypsum Fact-Finding Forum, 1996
- The Economic Benefit of Phosphogypsum Use in Agriculture in the Southeastern United States, Greg Traxler, 1996
- Development of Economically Stabilized Phosphogypsum Composites for Saltwater Application, Kelly A. Rusch and Roger K. Seals, 2005

In support of the Institute's phosphogypsum research program, its library has accumulated and indexed a vast repository of the world's literature on phosphogypsum. This repository formed the baseline for the efforts of the FIPR-funded "Stack Free" program that has resulted in widespread success in the acceptance of phosphogypsum as a commodity of great value. The repository continues to undertake this role. As such, the Institute stands ready to support international efforts and research in furtherance of the "Stack Free" objectives.

In addition to the science, technology and engineering involved in the various applications of phosphogypsum utilization, the Institute has conducted and funded research into the radiological aspects and risks of these applications. Any jurisdictions requiring information to address any such concerns can be assured that this information is authoritative and science based. This knowledge base is also ready to support efforts to safely utilize this valuable co-product.

In its current incarnation as Florida Industrial and Phosphate Research Institute, the Institute is an integral research component of Florida Polytechnic University. FIPR will be central to the development of the nascent university's research program and FIPR will leverage the university's faculty, students and facilities (and vice versa) to reinvigorate and extend its work as world-renowned PG research center.

RAFAEL TENORIO:
Europe...why so late?

AUTHOR

Rafael García-Tenorio, is Director, Spanish National Accelerator Centre and Professor of Applied Physics, University of Seville, Spain

Some twenty years ago, my research group, the Applied Nuclear Physics of the University of Seville, was commissioned by the Government of Andalusia to perform some very detailed and structured scientific field studies over a five year period to evaluate the environmental and social impact of the use of phosphogypsum (PG) as a soil amendment to enhance the use of saline soils in local agriculture and to increase both crop production and yield. This research was commissioned in response to the pressure from and needs of some local stakeholders opposed to the practice. Since the 1950s local farmers had been using the phosphogypsum produced in Huelva

as an amendment in their saline salt-marshes to restore their soils' fertility but in the late 1990s they began to experience difficulties obtaining supplies of PG because of pressure from local interest groups. This pressure started shortly after the introduction by the European Union (EU) of Council Directive 96/29/Euratom of 13 May 1996 laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation⁹⁹ the scope of which included regulating NORM industries. The Directive was first implemented it was in a very conservative way, leading to what we now know to be an unjustified level of caution on the part of the regulator, an impact which spilled across into negatively impacting public perceptions of risks from NORM industries, including PG. Likewise, the regulatory process took no account of actual ongoing practices of use of PG, which in the case of agriculture in Spain has already been in place for some 50 years. Other uses in construction and engineering were also overlooked.

In fact the regulatory focus was almost entirely on PG discharge to the Atlantic, a practice disallowed under the OSPAR Convention¹⁰⁰ and which quickly led to either the substitution of discharge to land in "stacks" or to the closure of phosphate production facilities as happened in many countries such as France, the Netherlands and the United Kingdom.

The findings of our research programme, published in leading peer-reviewed journals, were that the risks from PG whether to the environment, the farmers themselves or to the wider public were negligible and that the benefits of use far outweighed those risks. The government and regional courts accepted our findings and for a time the farmers regained access to PG. Similar findings were also known to us from other research groups around the world, though our research scope was among the more comprehensive and systematic that had yet been undertaken concerning PG in agriculture and the environment. In part this was simply because there has been no concern about the practice prior to 1996 and hence there was no need to justify it on scientific grounds. With the wider impact of the OSPAR convention of marine discharge of PG, the phosphate industry in Europe overall was significantly cut back. So, for the few countries that continued to produce phosphoric acid the PG issue effectively stopped being a pan-European one and became very much a local concern. In respect of the situation in Spain, while phosphate fertilisers continue to be produced, phosphoric acid production stopped in

99. <https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1414575518651&uri=CELEX:31996L0029>

100. For the OSPAR Convention see https://www.ospar.org/site/assets/files/1290/ospar_convention_e_updated_text_in_2007_no_revs.pdf

2010 under continued local stakeholder pressure.

Overall, however, phosphoric acid production worldwide was growing so the issues we had faced, and our various publications, came to the attention of the International Atomic Energy Agency (IAEA) which was engaged in an extensive project to produce safety reports concerning NORM aspects of a wide range of industries, of which phosphate production was one. Because of its international remit, IAEA was able to convene working groups with memberships from a wide range of countries who could meet to share knowledge and experience of NORM in what was at that time still a relatively unknown and little-explored field.

Different technical coordination and expert consultation meetings were organized by IAEA first to assess the body of evidence available, including our studies, and then as findings became clear, to prepare clear messages about the safe, beneficial uses of the PG produced around the world under the “graded approach”. These were first peer-reviewed and then disseminated by the Agency through its normal channels. Then after approval by its Member States, the process was brought to a conclusion with the publication of IAEA Safety Report 78 [2] devoted to the Phosphate Industry. In SR 78 a full chapter is dedicated to PG, defining it as a “co-product” of phosphoric acid production, with sections devoted to health, safety and environmental aspects, guidance for regulators. An extensive range of case studies is referenced setting out options for use notably in agriculture, road building and construction.

This 2013 IAEA Safety Report [2] was a very important milestone that paved the way for the clear involvement and support of the International Fertilizer Association on the subject of PG in recent years, with its own milestone Report PG1 published in 2016. But perhaps because at the time of publication much of the European phosphate industry had already been closed down European regulators were slow to move away from their previous alignment with the very restrictive constraints imposed by the United States Environmental Protection Agency in 1989, mostly because they had no pressing need to.

Nowadays, the situation in Europe is radically changed. Policymakers have become aware of just how vulnerable the European economy is to uncertainties about security of supply of many critical materials, among them phosphate rock, which is now classed as “critical”. And under the circular economy Action Plan there is now growing pressure to conserve primary resources and where possible substitute “reusable raw materials” such as PG instead of primary resource alternatives. So misguided policies on PG since the 1990s have caused a chain of

events that have inflicted much unnecessary and largely avoidable damage to industries we now realise we need to protect. But this knowledge of hindsight comes too late. My reflections focus on my own and my team’s experience in Europe for the obvious reason that our, scientific, cultural and social lives are lived in European society... but I hope we can convey some lessons we have learned the hard way to prevent other countries from making the same mistakes. This is especially true in countries where the phosphate industry is one of the main pillars of the economy, as is the case among many of our neighbours in the Mediterranean basin and where PG has many roles to play as a reusable resource for agriculture and construction. Science tries always to be balanced and neutral, but I have learned that sometimes it has to convey acidic and critical messages not just even-handed ones.

MANZOOR QADIR:

The state of phosphogypsum in 2070
A world without phosphogypsum stacks

AUTHOR

Dr. Manzoor Qadir is Deputy Director, Institute for Water, Environment and Health, United Nations University

With the landmark scientific risk assessment on the fate of phosphogypsum, the Phosphate Industry Safety Report [2] did not consider phosphogypsum a waste anymore, rather classified it as a co-product of phosphoric acid production. This clears a major roadblock in the use of phosphogypsum in different sectors.

With the reclassification of phosphogypsum as a co-product, it is increasingly considered as a resource for a range of valuable uses and contributions to the current global sustainability processes, such as the 2030 Sustainable development Agenda, the Paris Agreement to address the threat of climate change, the United Nations Convention to Combat Desertification and the Convention on Biological Diversity aiming at the protection and conservation of biodiversity.

While the world at large is making progress to mainstream use of phosphogypsum in different sectors, particularly agriculture, we are still far from using all the phosphogypsum produced annually, leaving aside the existing phosphogypsum stacks. Currently about one-third of the phosphogypsum produced annually is used while most of the remaining two-thirds still contribute to the phosphogypsum stacks. However, as shown in IFA PG1 [1] there are bright spots of the phosphate industry using major part of the phosphogypsum they produce. Looking ahead, there are two major pathways to deal

with phosphogypsum management opportunities. First, minimizing the production of phosphogypsum per unit of phosphoric acid produced; and second, planning and implementation towards maximizing the use of phosphogypsum that it overtakes the annual production and subsequently starts clearing up the phosphogypsum legacy stacks.

Estimates suggest that by 2006, about 2.6-3.7 billion tonnes of phosphogypsum had been accumulated in stacks worldwide. With major part of annually produced phosphogypsum still being added to stacks at 109 million tonnes per year [1] the phosphogypsum stacks as of today could have grown to approximately 4.0 to 5.1 billion tonnes; possibly around 4.5 billion tons on the average.

The use of phosphogypsum in agriculture remains just 8% of the total use while the major uses are in construction (40%) and other options (52%) such as construction materials, landfill, and roads. Given the demonstrated benefits of using phosphogypsum in agriculture and afforestation [35] [39], there is a need to increase the share of phosphogypsum being used in agriculture.

The use of phosphogypsum in agricultural and forestry systems may be extended through its use:

- (1) as a soil amendment for rehabilitation of salt-affected degraded lands resulting in agricultural productivity, carbon, land value, economic and livelihoods gains
- (2) as a major material to create anthrosols leading to high-yielding afforestation plantations to sequester carbon, potential use for green energy or wood chips, and ecosystem diversity
- (3) as a water quality protection substance in saline water irrigation systems to mitigate salinity effects in crop production and agroforestry systems offering saving water for other uses, carbon sequestration in soil, renewable energy, farm produce, and crop diversification options
- (4) as a base material for developing value-added fertilizer
- (5) as an agricultural land protection material to create embankments and protections around soils prone to erosion
- (6) as a catalyst to provide benefits to a range of other sectors such as phosphate fertilizer industry, transportation sector, marketing entrepreneur,

infrastructure industry, and trade industry dealing with agricultural commodities and farm machinery.

Seeing a world free of phosphogypsum stacks and associated benefits by 2070 is possible, but to see this happening on the ground there is a need to promote and implement aggressively a commercially beneficial model of using phosphogypsum in agriculture, agroforestry, land development and protection, construction and construction materials, roads, among others.

S. NAND: The PG Opportunity

AUTHOR

Dr. S. Nand is Technical Director, Fertilizer Association of India

SULPHUR DEFICIENCY IN SOILS

There is widespread deficiency of sulphur in Indian soils. According to latest estimates published in May 2019, 40% of Indian soils are deficient in sulphur [78].

The importance of sulphur for oil seeds and pulses crops is well known. Application of sulphur in India takes place through various sulphur-carrying fertilizers. Prominent amongst these are single super phosphate (SSP), ammonium phosphate sulphate (APS) complexes and ammonium sulphate (AS). Mineral gypsum and phosphogypsum are used both as soil amendment and as source of sulphur. In the fertilizer year 2018-19, application of sulphur in Indian agriculture was ~0.75 million tonnes. There is considerable headroom in the market for growth. Even if 50% of sulphur required is supplied through PG to Indian soils, it will create annual demand of more than 2 million tonnes of PG in agriculture.

At present there is subsidy of Rs. 3.56 per kg of sulphur in a fertilizer product. PG has at least 150 kg sulphur per tonne. Equivalent amount of subsidy on PG will help to defray the cost of granulation. Granulated PG (see Zypmite, Section 4.2.5) will be easy to transport and apply in fields.

Government of India approved the following specifications of phosphogypsum for use in agriculture (Table 27) on a provisional basis, subject to periodic monitoring every three years by suppliers and farmers.

TABLE 27. Phosphogypsum (Granular)

1.	Moisture per cent by weight, maximum	15.0%
2.	Sodium content (as Na), percentage by weight, maximum on dry basis	0.75%
3.	Colour	Light Green
4.	Particle size	Not less than 90% of the material shall pass through 4 mm IS sieve and shall be retained on 1 mm IS sieve. Not more than 5%, shall pass through 1 mm IS sieve
5.	Sulphur (as S) per cent, by weight, minimum on dry basis	13.0%
6.	Calcium sulphate dehydrate content per cent, by weight, minimum on dry basis	70.0%
7.	Fluoride (as F) per cent, weight, maximum	1.0
8.	Heavy metal content, (as mg/kg), maximum	
	Lead (as Pb)	100.0
	Cadmium (as Cd)	5.0
	Chromium (as Cr)	50.0
	Nickel (as Ni)	50.0
	Arsenic (as As ₂ O ₃)	10.0
	Mercury (as Hg)	0.15

LOCATIONS AND LOGISTICS

All phosphoric acid plants except one are located on the coast. The consumption areas are in the hinterlands of the production facilities. Transportation of phosphogypsum is a challenge both in terms of handling, storage and cost which impedes market growth. Granulation of phosphogypsum for ease of transportation and application in agriculture is one possibility, see for example Zypmite, which also contains micronutrients needed by the plants, but it also adds to the cost, which farmers may not readily accept. One of the factors for this is that the main sulphur carrying fertilizers are subsidized by the central government. Several state governments extend subsidy to use of natural gypsum. But no subsidy is provided by central or state government on PG for use in agriculture.

MARKET AND REGULATORY CONSTRAINTS

Any imported material will face the same problems to higher degree. There is already very high inventory of phosphogypsum at various locations in India. Therefore, import of phosphogypsum may not be economically viable proposition. Moreover, there may be need for specific permission for import of phosphogypsum into India. Further, any product which is meant to be used as fertilizer in agriculture has to have prior approval and inclusion in Fertiliser Control Order (FCO). At present imported phosphogypsum is not permitted for agriculture use. Therefore, regulatory aspects have to

be sorted out before import of phosphogypsum or any value-added product containing phosphogypsum.

POLICY LEVERS

There is potential for increasing utilization of PG in agriculture and as construction material. A policy support by the central/state government can accelerate the use of this natural resource and will encourage the circular economy.

HARI TULSIDAS:

Value creation and compliance with UN Sustainable Goals: the pathway to 100% Phosphogypsum Use?

AUTHOR

Hari Tulsidas is Technical Officer with the UN Economic Commission for Europe (UNECE), Geneva

CONTEXT

I have a special interest in classification and management of anthropogenic resources such as phosphogypsum as before moving to Geneva for seven years I was a Technical Officer with the International Atomic Energy Agency (IAEA) Vienna and was one of the IAEA team responsible for Safety Report 78, including the chapter on phosphogypsum [2].

My IAEA colleague Shaun Guy was present at the landmark meeting of the IFA PG/NORM Working Group in Tashkent, 2012, and on that occasion introduced the draft of Safety Report 78 to those attending in pre-publication form. I was working as a Technical Officer for IAEA at that time and was one of the internal team responsible for its final review and publication. Given the strong encouragement in that report for beneficial uses of PG it is a particular pleasure for me to contribute to this latest IFA Report as it shows what progress industry has made since IAEA SR 78 publication in 2013 towards the “stretch goal” of 100% use, both of current and future annual production but also of legacy PG.

It is also admirable to see the way the leadership signalled in the speech of Mrs. Esin Mete in Sharm el Sheikh in January 2014 has been heeded, especially as from a UN perspective she set the framework for meeting the goal of PG use within the context of the forthcoming Sustainable Development Goals. So, against that background I strongly encourage the industry to continue on its ambitious path towards full use of PG. The UN will do what it can to assist including finding appropriate ways to partner with industry on suitable large-scale projects.

PG AND TUNNEL VISION

The reason why PG is not routinely used for hundreds of productive uses is tunnel vision about risks unjustifiably ascribed to PG due to the small levels of naturally occurring radioactivity it contains. In most cases the level of radioactivity is equivalent to, or sometimes even less than, natural soils. If the reasoning about risk was consistently applied we would have to remediate vast areas of soil in their natural state or simply shy away from agriculture altogether. The International Atomic Energy Agency (IAEA) for which I worked before moving to UNECE, promotes a graded approach to NORM management and exempts any material with less than 1 Bq/g from any need for regulation. Regulators can simply declare such PG as “out of scope” of regulation. Even having radioactivity slightly above 1 Bq/g does not make it unsuitable for productive use, the 1 Bq/g value is simply a threshold at which regulators may consider regulation. Only a small proportion of PG anywhere in the world exceeds 1 Bq/g and when higher levels such as 1.1 Bq/g or 1.2 Bq/g, such material can qualify for regulatory exemptions according to IAEA Basic Safety Standards [6].

DISCOVERING LONG-TERM VALUE IN PG

Our planet faces many challenges such as climate change, degrading ecosystems, receding water bodies and rising inequality. But the most significant difficulties of all revolve around the nexus of food-energy- water (FEW). How can we ensure security and accessibility of food, water and energy supplies equally to every inhabitant of the planet and all the co-dependent eco-systems? Can PG as an abundant anthropogenic resource¹⁰¹ be brought into service to fix some of these fundamental issues?

Ensuring food for about 10 billion humans by 2050 and trillions of animals is a vast challenge in which PG surely has a role. PG does not just provide the plant nutrients, but also restores or substitutes soils.

PG can be a soil amendment to increase the productivity of some soils or a soil substitute to restore areas that are impacted by severe soil erosion.

Could climate warming be addressed by costly switching to renewable energy or planning a trillion trees?¹⁰² India and Ethiopia recently proved a few hundred million trees could be planted in a single day. If the wasted land could be reclaimed with PG, the tree planting campaign

could get a head start. PG supported green belts and parks could come up in cities and urban centres. Rising global temperatures drive out soil moisture and promote desertification. PG has better water retention capabilities that can be used to arrest desertification. It can be used for large scale ecosystem restoration to rebuild water bodies and swamps. Water purification and storage could be possible through the clever use of PG. Access to clean energy still plagues large populations in the world. Increased production of fossil fuel-based energy could bedevil the climate mitigation plans, whereas PG based bioenergy production could be carbon-negative.

INNOVATIVE RESOURCE MANAGEMENT TOOLS FOR VALUE CREATION

UNECE embraces the same three core principles as IFA members when making its contribution to finding the sustainable solution to PG, leadership, innovation and partnership. Cooperation through innovative public-private partnership is underpinning the development of the United Nations Resource Management System (UNRMS) to address the need for a better framework for global resource management, including secondary resources such as PG, be it at a strategic programme level or tactical project level.

This framework applies to all resources and can be easily adapted for the phosphate life-cycle management. The example of a redesigned PG pathway is shown in Table 28.

The pathway provided in Table 28 can be simultaneously a decision-making and resource-progression framework but also the instrument for capital allocation. In capital markets, investors are withdrawing from traditional tools and switching more and more towards impact investments such as “green bonds” or “climate bonds”. PG utilization focused on its application to the FEW nexus could be an opportunity to attract such funding. Cooperation between the UN and industry is needed at a higher-level to quantify the commercial opportunities and identify the social and environmental benefits of PG utilization. This includes having an accurate inventory of all PG available worldwide, analysis of possible use scenarios in solving FEW challenges and information on the possible outcomes. Such a study will help the industry to rediscover PG and create wealth from its positive utilization.

101. United Nations Economic Commission for Europe classifies PG in the UN Framework Classification as an “anthropogenic /secondary resource”, https://www.unece.org/fileadmin/DAM/energy/se/pdfs/UNFC/Anthropogenic_Resources/UNFC_Antropogenic_Resource_Specifications.pdf.

102. Want to Fight Climate Change? Plant 1 Trillion Trees. <https://www.livescience.com/topics/climate>

TABLE 28. RESIGNED PHOSPHOGYPSUM PATHWAY¹⁰⁴ [79]

STEP	PATHWAY TO MARKET PARTICIPATION	CORE INSTRUMENTS	COMMERCIAL EVALUATION	PRINCIPLES AND OBJECTIVES OF PPP PROJECTS
1.	TECHNICAL FEASIBILITY	PG utilization scoping study in FEW areas	Disruptive or value-add (optimization) potential; initial laboratory appraisal and single or batch testing	Improve sustainability , and/or comply with SDG goals, e.g. cutting CO ₂ emissions to move to a green economy; combat desertification; advance the FEW objectives
2.	REGULATORY AND SOCIAL ACCEPTABILITY	Life-cycle management flow-sheet and related materials flow analysis compliant with the "graded approach" to risks, notably from radionuclides and heavy metals	In-depth laboratory appraisal - replicability/ normalization, reliable characterization compliant with safety limits, continuous testing	Engage all stakeholders , either directly involved in the PPP project or who might be affected directly or indirectly in the Social Licence to Operate or Informed Consent
3.	COMMERCIAL VIABILITY/ INDUSTRIAL CAPABILITY	Project readiness checklist/ with resource progression and capital investment decision- gate flow sheet, including SDG compliant market studies (e.g. pre-feasibility) and business model innovation	Proof of concept – commercial scale: the Pilot project to scalable level (4,000 hours) in the advanced or finished state, defined performance standards can be met	Be replicable , so that PPP projects can be scaled up and achieve the transformational impact required by the 2030 Agenda. This criterion also needs to take into account whether the local staff and governments have received the necessary training to do similar projects going forward
4.	POLITICAL DESIRABILITY	Detailed feasibility study – planning and conduct of the new commercial-scale project	Validated commercial potential (shovel ready); RD3 stage 4, engineering and procurement specifications in place, construction contract available for tender; investment secured, measurable value potential (CAPEX (asset) and OPEX (cash flow)), decision gate 4	Increase access and promote equity , which means that access to essential services, such as water and sanitation, energy etc. should be increased to people, especially to the socially and economically vulnerable. Furthermore, people-first PPPs should aim to promote social justice and make essential services accessible without restriction on any grounds, e.g. race, creed etc. to all
5.	MARKET PARTICIPATION	Industrial benchmarking, replicable projects and good practice	In market (sustainable business) ; customer base/ reliable off-take agreement(s); actual value release; return on asset (equity growth) and / or return on investment (positive cash flow)	Improve (demonstrate) project economic effectiveness , projects must be successful, achieve value for money and have a measurable impact by removing a barrier or creating a new mechanism by integrating groups into the global market

HIDDEN TREASURE: REDESIGNING THE PHOSPHOGYPSUM PATHWAY

Short-termism, or the excessive focus on immediate benefits, could be a paradigm that was shaped by life's evolutionary past. With no excellent brain capacity to remember far into the past or look far ahead into the future, immediate actions for survival were all that mattered. When faced with a threat, a short cut to escape the situation was ideal, rather than a long contemplation of the root causes. Genes that prompted immediate actions progressively increased and dominated. Modern human brains are equipped to do better, such as studying general patterns, looking at causes and effects, and undertake planning to get the desired benefits. Being a toolmaker itself marked the beginning of futuristic thinking. However, the evolutionary artefact of short-termism still dominates human actions.

SHORT-TERM LINEARITY TO LONG-TERM CIRCULARITY

A race for quick results is desirable in many situations. However, they often leave behind problems that take a long

time to reveal themselves. The systems-thinking approach includes delay as a necessary component. Take the example of the quickest path available to the desired goal that could require expending a bit more energy. In the long term, when this task is repeated countless times, the additional energy requirement could become life-threatening. The production of industrial wastes is an example of a short cut, which has blighted our civilization since the start of the industrial revolution. All the problems we face today, be it environmental pollution or global warming, are the result of short-term thinking that ignores small consequences and fails to take into account the delays.

Making phosphate rock into water-soluble products that can be quickly taken by plants was a miracle of the industrial revolution. There are several options to achieve the water solubility goal, of which perhaps the shortest and most scalable is "wet process" sulphuric acid digestion. The resultant 1:5 proportions of PA and PG would probably never have caused any difficulty for the industry had PG's status been formalized from the outset and used as a co-product.

103. See HILTON, J., et al, (2018) https://www.unece.org/fileadmin/DAM/energy/se/pp/unfc_egrm/egrc9_apr2018/ece.energy.ge.3.2018.7_e.pdf

But it was discarded, typically at the outset to water, but eventually also on land, where it rapidly accumulated into being a problem. Even that might not have been a problem had the concept of “interim storage pending eventual use” been built into the resource management system. But it was not. PG got piled up in managed disposal stacks or pumped out in the ocean.

There are, however, no wastes in natural materials flows. The products and by-products of one cycle become the resources for another cycle. Food left uneaten becomes manure, providing nutrients for further food production. Nothing is lost, everything feeds into another cycle, and this is the basic design of circularity.

TOWARDS 100% PG USE: NEXT STEPS?

MEETING THE UN SUSTAINABLE DEVELOPMENT GOALS – A KEY ROLE FOR PG 2020-2030 AND BEYOND

In late 2015, 193 Heads of States agreed to put in action the 2030 Agenda for Sustainable Development (2030 Agenda), which includes the 17 Sustainable Development Goals (SDGs). 2030 Agenda has its roots in the renowned Brundtland Commission report, “Our Common Future” (1987) [81], Agenda 21 (1992) and the Rio Declaration (1992) and is a follow-up of the Millennium Development Goals (2000-2015).

As mentioned by Esin Mete in 2014, the SDGs provide an excellent opportunity for the fertilizer industry to be part of the sustainable development movement by contributing to resource use efficiency and earning the social licence to operate. To a large extent, this is achieved by resolving the PG indefinite stacking and disposal issue in favour of use, indicating a more general transition of the mineral fertilizer industry into a focal point for sustainable development.

While recognizing the apparent challenges in finding solutions to 100% phosphogypsum use, it cannot be discounted that only a concerted and continuous endeavour with the total partnership of the industry and public institutions will make this possible. The UN system today has 2030 Agenda as its core mission, which is also a call for action to all stakeholders, the policymakers, regulators, industry, civil society organizations and the communities. The UN system stands ready to support all initiatives in utilizing phosphogypsum, especially those that contribute to food productivity, decarbonization, and combating desertification. As the world races towards the last lap towards the SDGs, it is imperative that the industry and the public institutions together take a bold step in agreeing to a committed roadmap for total phosphogypsum use before 2030. The history will be judging how the industry leaders

and governments will be committing to this transformative step today.

A COLLABORATIVE PROJECT BETWEEN INDUSTRY AND UN?

A combination of policy and regulatory pressure is growing worldwide to plan for and deliver 100% PG use, resulting in the eventual circular economy goal of zero waste and zero harm to people or planet. How might the scope of such a project be formulated and implemented?

From a phosphate producer’s perspective, it is easy perhaps to forget that there is more than one kind of process-residue gypsum. Of these the most widely produced is a by-product from coal-fuelled energy production, flue-gas gypsum won from flue-gas desulphurisation (FGD). In China alone, combustion of fossil fuels for energy produces nearly one hundred million tonnes of FGD gypsum per year which (see case studies) makes the ~80mt/y PG produced in China look more modest by comparison. How will PG in China take its place in the market for secondary resource gypsum? Does it have advantages for some markets, such as its P_2O_5 content which might give it a competitive advantage?

While still regulated as a waste in some of its processed forms, gypsum, whether from the phosphate or the coal-fired energy industry, is abundant and has the potential to play a role in some of the greatest challenges the world now faces, for example to transform extensive areas of desertified or degraded soil into fertile soil for arable crop production or growth media for afforestation (case studies 1.1, 1.2, 1.3, 1.4).

Soil conditioning and repair of damaged sodic soils for agriculture are accomplished by treatment with gypsum (see case studies 1.4). There are countless other applications for PG including road construction (case study 3.1, 3.2, 4.2.2), construction materials (case study 2.1, 2.2), innovative fertilizers (case study 4.2.2), wallboard, sulphur recovery, marine barrier construction, and ceramics (case study 2.2).

All processed gypsum resources, notably PG and FGD, must be properly managed by reference to validated protocols for use to optimize social, economic and environmental benefits. Such scientific, evidence-based management is unknown or disregarded in many regions and fragmented at its best in others, especially when examined globally. PG2 sets out to bring some higher degree of coherence and consistency to the knowledge-based available to commercial producers and their customers as to what works, what is safe and what can be regarded as a good practice.

FILLING KNOWLEDGE GAPS

The challenge of knowledge gaps concerning contemporary science and technology is not simply one faced by producers and consumers. Regulators are often

ill-informed and hence tend to over-regulate in response, breaching the IAEA core principle of proportionality as set out in the Basic Safety Standards (BSS) [82]. Incongruities and inconsistencies between local and regional governments and international advisory or regulatory bodies such as IAEA are problematic enough, but to date different industrial producers of distinct types of gypsum have tended to operate in silos partly as a result of the lack of interaction of their core businesses, partly through fear of the stigma of radioactivity (NORM) which has been attached to PG, which has been compounded by the unwarranted designation of PG as hazardous. These barriers are difficult to bridge.

Every source of gypsum has its detractors. FGD gypsum results from combustion of fossil fuels and contains residual heavy metals as well. Even natural gypsum cannot escape similar notoriety. Natural gypsum contaminated with sulphites responsible for a widespread gypsum wallboard controversy involving structural and health consequences in the USA.

INTEGRATED MANAGEMENT OF ALL GYPSUM RESOURCES

Gypsum resources, primary and secondary should ideally be managed as a single resource continuum. Decisions on appropriate use will be based on characterization and the graded approach and depend on the particular characteristics of the gypsum from each primary deposit or mine, or each energy production or chemical processing site. Sustainability planning will be based on accurate quantification of stored and produced quantities, and regional needs for gypsum matched with to appropriate applications and transportation logistics. Efficient management requires continuously updated databases of the physical, chemical, and radiological characteristics of the gypsum continuum; quantities, application rates, and gypsum specifications by application; and spatial data of areas where gypsum is available in relation to where it is to be used.

Databases must be accompanied by detailed application Quality Protocols and peer-reviewed manuals of best available technologies for the most common, high-volume gypsum applications. It is likely that the existing stockpiles or production of PG for example may be blended with gypsum from other industries to produce the best gypsum for a particular use. It is also likely that primary production flowsheets will be modified to produce gypsum more suitable for one or more applications as is practiced by Prayon in the phosphate industry (case study 2.1). Mixtures of gypsum and other co- or by-products, such as red mud from bauxite and alumina processing, will find a niche in the new circular economy.

A good first step would be to convene a congress of industry

associations engaged with issues concerning gypsum production and use to raise awareness of the types and quantities of gypsum produced annually, as well as to air the concerns of the various producers. The main producers are expected to be natural gypsum miners, the energy sector, and phosphate fertilizer producers.

Here are some examples of the information needed to match gypsum sources to appropriate applications and use locations, based on the graded approach.

ANNUAL INVENTORY GYPSUM PRODUCTION AND PROJECTIONS

The global inventory of all gypsum resources should be updated on an annual basis.

1. Types of gypsum (natural, FGD, PG) produced by country and company
 - a. Tonnes per year by country and company
 - i. Current
 - ii. 10-year projections supply/ demand.

STOCKPILED INVENTORIES

Transitioning to a system-wide management procedure of PG as a reusable raw material within a circular economy will be greatly facilitated by taking a detailed inventory of available PG. Data parameters for such an inventory include:

1. Thorough protocol-based sampling and characterisation
2. Tonnes in storage facilities/stockpiles should be inventoried by gypsum type and location
3. Spatial profiles of legacy holdings in closed stacks to be assembled by coring and analysis.

PHYSICAL CHARACTERISTICS

1. Gypsum crystal structure (using scanning electron microscopy)
2. Solubility
3. Thatching, filtration.

CHEMICAL AND RADIOLOGICAL PROPERTIES

1. Radiological profile
 - a. Ra-226, Th-232, K-40 in Bq/g
 - b. Measure using HPGe
2. Trace metals and metalloids
 - a. Pb, Cd, As, Mg, Hg, Cr, etc. in ppm, ppb or ppt
 - b. Measure using ICP-MS
 - c. Compounds of interest such as phosphate or sulphites.

PRIMARY APPLICATIONS

1. Sodic soil repair (especially suited to PG holdings with elevated P_2O_5 content, ie above 0.5%)
2. Road construction
3. Construction materials (especially suited to PG holdings with 0.5% or lower).

REGIONAL NEEDS

1. Named regions matched to applications
2. Proximity to needed quantities of suitable gypsum sources
3. Application of artificial intelligence techniques to optimize sources and blending according to applications, use locations, and logistics:
 - a. Optimize gypsum characteristics for applications
 - b. Optimize transportation costs
 - c. Optimize beneficial outcomes according to social, economic and environmental criteria.

INFORMATION RESOURCES REQUIRED

Once compiled, a “living” web site of databases, manuals, and application tools can be developed and maintained for global users of all types of gypsum and associated resources.

Considering the global social, economic and environmental benefits of gypsum applications as a whole, it is evident that the effort of building and nurturing a global Gypsum Resource Management System should be considered. Applying the core principles of this report, the implementation should take the form of a collaborative and innovative partnership between the major stakeholders, the industry, appropriate UN bodies and international centres of excellence and regulators / policy makers concerned with one or more aspects of standards and best practices for gypsum use. Points of departure are evident in the trends of policy-making and regulation are shown in Table 1 above and across all the case studies in this report.

CONCLUSIONS

The major changes in both policy and regulatory frameworks which directly or indirectly impact PG, such as SDG compliance, transitioning to the circular economy, climate action or zero waste, are only likely to make the goal of 100% PG valorisation and use more achievable, whether commercially from market demand or even as a regulatory requirement. But plotting a practical and commercially sustainable pathway to that goal will require a substantial and sustained effort on both the part of government – policy makers and regulators - and industry to deliver it in a timely manner without causing damaging degrees of transitional stress to operators. Nowhere is that more the case than in China, the world's biggest PG producer, where the wholly achievable goal of comprehensive utilisation of PG is now required, but currently within an as yet undefined operational framework.

Regulators are however, starting to learn how to regulate PG not just from a safety, health and environmental perspective, but also as a major reusable resource within a circular economy, and to do so in partnership with operators. If there is one lesson learned from the closures of the majority of European phosphate producers in the 1980s and 1990s it is perhaps that a regulatory regime based on flawed science and lack of consultation with industry can lead to unnecessary destruction of jobs. The outcome is now evident: the creation of economic conditions whereby phosphate resources have had to be classed as a “critical material” for the EU economy. Such an outcome should be avoided elsewhere. As the EU regulators acknowledge with their 2019 Circular Economy Action Plan, within the new “circular” economic model even what the purposes of regulation are, need to be rethought. This means first engaging with all stakeholders to ask how the economic imperative of circularity

can best be delivered while fully respecting the regulatory precepts of zero waste and zero harm. The answers must be based on shared values and an implementation process delivering transparent and equitable shares in the benefits to People, Planet and Prosperity of zero waste and zero harm.

The answers must also be grounded in facts and evidence. In that vein, operators, starting with thorough sampling, characterisation and analysis conducted in partnership with independent centres of excellence, are assembling the technical and scientific evidence-base on which their plans of reaching 100% use are founded. From that investment come the associated Safety Data Sheets, and Quality Protocols which show that industry and their partners have the capabilities and technologies to deliver and sustain 100% safe, beneficial use. Operators also recognise they must continue indefinitely to monitor the environmental and social impacts of what they have done. The case studies set out in PG2 on agriculture/forestry, construction materials, road-building show a level of maturity of knowledge and method in assessing opportunities for high volume applications, but also successful strategies for partnering, that leaves no doubt these documentation tasks, with appropriate reference examples, can be accomplished.

There is now broad agreement across all mining and processing industries that they need to craft a new narrative. The International Fertilizer Association's (IFA) PG Working Group responsible for PG2 reached that position already at its April 2018 annual meeting in Madrid. The first step in creating such a narrative was for industry to talk to itself about PG in a new way. PG2 shows it is now doing that, redefining PG's future, and doing so in a spirit of trust, confidence and realism.

This process remains ongoing. In the forty-year journey to date that precedes the publication of PG2, enormous investments of both intellectual and financial capital have been made. Now, as PG2 shows, the scale and nature of the multiple returns on that investment are clearly emerging. PG's inherent utility and value as a co-product and resource is established. The wider opportunity PG valorisation offers is to return precious land, long lost to PG storage or disposal to productive uses.

When the true externality cost to future generations of not taking these steps now is factored in, there is only one present option for defining the future – seize the opportunity of comprehensive use.

ABBREVIATIONS & ACRONYMS

AFA	Arab Fertilizer Association (http://www.arabfertilizer.org/)	FE	Fertilizers Europe (https://www.fertilizerseurope.com)
ALARA	As Low as Reasonably Achievable	FEW	Food-Energy-Water Nexus
Bq	Becquerel	FGD	Flue-gas desulphurisation (of coal to make gypsum)
BSS	Basic Safety Standards (IAEA) (https://www-pub.iaea.org/MTCD/publications/PDF/Pub1578_web-57265295.pdf)	FIPR	Florida Industrial and Phosphate Research Institute (http://www.fipr.state.fl.us)
Ca	Calcium	FSA	Fluosilicic acid
CaCO ₃	Calcite	FSP	Fundamental Safety Principles
CBA	Cost-Benefit Analysis	GHG	Greenhouse Gas
CBR	California Bearing Ratio	H ₃ PO ₄	Phosphoric acid
CEC	Cation Exchange Capacity	HAP	Hazardous air pollutant
CO ₂	Carbon dioxide	HDPE	High density polyethylene
CPCB	(India) Central Pollution Control Board	HF	Hydrogen fluoride
CRRI	(India) Central Road Research Institute	HSE	Health, safety and environment
CSR	Corporate social responsibility	IAEA	International Atomic Energy Agency (https://www.iaea.org)
CRR	Comprehensive Resource Recovery	ICRP	International Commission on Radiological Protection (http://www.icrp.org)
CX	Comprehensive extraction	IFA	International Fertilizer Industry Association (https://www.fertilizer.org)
DAP	Diammonium phosphate	IMO	International Maritime Organisation (http://www.imo.org/en/Pages/Default.aspx)
EC	Electrical conductivity	IPCC	International Panel on Climate Change (https://www.ipcc.ch)
EC	European Commission	IRP	International Resource Panel (https://www.resourcepanel.org)
EFCA	Environmental Full Cost Accounting	ISA	Interim Storage Area
EMP	Exchangeable magnesium percentage	ISF	Interim Storage Facility
EOL	End of Life	K	Potassium
EOW	End of Waste	LCA	Life-cycle Analysis
ESIA	Environmental and Social Impact Assessment	LNT	Linear No-Threshold
EU	European Union	MAP	Monoammonium phosphate
FA	Fly ash	MDD	Maximum dry density
FAI	Fertilizer Association of India (https://www.faidelhi.org/)	MFA	Materials Flow Analysis
FAO	Food and Agriculture Organization (http://www.fao.org/home/en/)	Mg	Magnesium
		MOP	Muriate of potash
		MSDS	Materials Safety Data Sheet (see SDS)

mt	Million (metric) tonnes	UCS	Unconfined Compressive Strength
NORM	Naturally Occurring Radioactive Material	UNECE	United Nations Economic Commission for Europe (http://www.unece.org/info/ece-homepage.html)
ODT	Oven dried tonnes	UNFC	United Nations Framework Classification (https://www.unece.org/energy/welcome/areas-of-work/unfc-and-sustainable-resource-management/unfc-documents.html)
OHS	Occupational health and safety	UNRMS	United Nations Resource Management System
OMC	Optimum moisture content	UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation (https://www.unscear.org)
P	Phosphorus	UNEP	United Nations Environment Programme (https://www.unenvironment.org)
P ₂ O ₅	Phosphorus pentoxide (phosphoric acid) industry term for H ₃ PO ₄	USEPA	United States Environmental Protection Agency (https://www.epa.gov)
PA	Phosphoric acid		
Pb	Lead		
PG	Phosphogypsum (calcium sulphate CaSO ₄ •nH ₂ O)		
PGWG	Phosphogypsum Working Group		
Po	Polonium		
PR	Phosphate rock		
QP	Quality Protocol		
Ra	Radium		
REE	Rare earth elements		
S	Sulphur		
SD	Sustainable development		
SDE	Sustainable Development Equilibrium		
SDG	Sustainable development goal		
SDS	Safety data sheet ¹⁰⁴		
SFA	Substance flow analysis		
SO ₂	Sulphur dioxide		
Sv	Sievert		
TBL	Triple Bottom Line		
TFI	The Fertilizer Institute (https://www.tfi.org)		
Th	Thorium		
TSP	Triple superphosphate		
U	Uranium		

104. MSDS has been replaced by SDS, a standardised, universally adopted 16 part format for Safety Data Sheets compiled in compliance with the UN Globally Harmonized System of Classification and Labeling of Chemicals (GHS), for details of which see <https://www.osha.gov/Publications/OSHA3514.html>.

GLOSSARY

ACTIVITY. The quantity A for an amount of radionuclide in a given energy state at a given time, defined as: $A(t) = dN/dt$ where dN is the expectation value of the number of spontaneous nuclear transformations from the given energy state in the time interval dt . The SI unit for activity is reciprocal second (s^{-1}), termed the becquerel Bq [82].

ACTIVITY CONCENTRATION. The activity per unit mass or volume typically measured as Bq/g or Bq/l. The term is used for any situation where the activity is in the form of contamination in or on a material [82].

ANTHROSOL. Literally “man-made” or “designer soils. “Soils with prominent characteristics that result from human activities” (FAO).¹⁰⁵

ARISING. Material forming the secondary, residue or waste products of industrial operations.

BENEFICIAL USE. The desired outcome of the application of the Waste Hierarchy to materials under consideration for disposal is that beneficial use is found for them. This requires that the use should be technically feasible, environmentally neutral or benign and proportionate in regard to cost. It also requires consideration of use “as is” or “made useful” by further treatment or processing.

BY-PRODUCT. An incidental or secondary product made in the manufacture or synthesis of something else.

CALCISOL. Soil characterised by a layer of translocated (migrated) calcium carbonate – whether soft and powdery or hard and cemented – at some depth in the soil profile. They are usually wet-drained soils with fine to medium texture and they are relatively fertile because of their high calcium content. Their chief use is for animal grazing.

CALCIXEROLL. Soil which 1. has a calcic or gypsic horizon that has its upper boundary within 150 cm of the mineral soil surface; and 2. in all parts above the calcic or gypsic horizon, after the surface soil has been mixed to a depth of 18 cm, either are calcareous or have a texture of loamy fine sand or coarser.¹⁰⁶

CARBON CREDIT. a tradable permit or certificate that provides the holder of the credit the right to emit one tonne of carbon dioxide (CO_2) or its equivalent.¹⁰⁷

CARBON FOOTPRINT. The total emissions caused by an individual, event, organization, or product, expressed as carbon dioxide (CO_2) equivalent.

CARBON SEQUESTRATION. a natural or artificial process by which carbon dioxide (CO_2) is removed from the atmosphere and held in solid or liquid form.¹⁰⁸

CARBON TRADING. Sometimes called emissions trading, is a market-based tool to limit greenhouse gases.¹⁰⁹

CATION EXCHANGE CAPACITY. A measure of the soil's ability to hold positively charged ions. It is a very important soil property influencing soil structure stability, nutrient availability, soil pH and the soil's reaction to fertilisers and other ameliorants.¹¹⁰

CATION EXCHANGE MECHANISM. As applicable to the use of PG as soil amendment the cation exchange mechanism substitutes Calcium for Sodium ions, thus reducing acidification level in the soil and remedying resultant yield loss often associated with the unwanted effects of irrigation.

CHARACTERISATION. The mandatory first step in the decision-making process for determining the suitability of phosphogypsum (PG) for particular types of reuse or recycling is characterisation. Characterisation requires taking samples from a predefined series of locations whether at the filter or the stacks and an analysis of the appropriate biological, chemical, physical and radiological properties to fully characterize the PG for the use for which it is intended.

CIRCULAR ECONOMY. An alternative to a traditional linear economy (make, use, dispose) in which we keep resources in use for as long as possible, extract the maximum value from them whilst in use, then recover and regenerate products and materials at the end of each service life.¹¹¹

CONTAMINATION. Radioactive substances on surfaces, or within solids, liquids or gases (including the human body), where their presence is unintended or undesirable, or the process giving rise to their presence in such places.

105. For FAO definition see <http://www.fao.org/3/Y1899E/y1899e05.htm>. See also Otto Spaargaren ISRIC – World Soil Information, Wageningen The Netherlands, https://esdac.jrc.ec.europa.eu/events/SummerSchool_2004/files/Spar_antr.pdf

106. See <https://sites.google.com/site/dinpuithai/Home/taxonomy/i-mollisols/if/if>

107. <https://corporatefinanceinstitute.com/resources/knowledge/other/carbon-credit/>

108. https://www.usgs.gov/faqs/what-carbon-sequestration?qt-news_science_products=0#qt-news_science_products

109. <https://science.howstuffworks.com/environmental/green-science/carbon-trading.htm>

110. For a summary of CEC see <http://soilquality.org.au/factsheets/h1-cations-and-cation-exchange-capacity-queensland>

111. <http://www.wrap.org.uk/about-us/about/wrap-and-circular-economy>

- Contamination does not include residual radioactive material remaining at a site after the completion of decommissioning [82].

CO-PRODUCT. The result of a single chemical reaction from which two different products are formed as, for example, phosphoric acid and phosphogypsum. (see IAEA definition of PG as a “co-product” of making phosphoric acid by the “wet process”).

COST BENEFIT ANALYSIS. A process used by governments, businesses and a range of organisations to analyse decisions. The analyst sums the benefits of a situation or action and then subtracts the costs associated with taking that action.¹¹²

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DECONTAMINATION. The complete or partial removal of contamination by a deliberate physical, chemical or biological process.

- This definition is intended to include a wide range of processes for removing contamination from people, equipment and buildings, but to exclude the removal of radionuclides from within the human body or the removal of radionuclides by natural weathering or migration processes, which are not considered to be decontamination [82].

ENVIRONMENTAL FULL-COST ACCOUNTING. A method of cost accounting that traces direct costs and allocates indirect costs by collecting and presenting information about the possible environmental, social and economic costs and benefits or advantages – in short, about the “triple bottom line” – for each proposed alternative.¹¹⁴

EXEMPTION. The determination by a regulatory body that a source or practice need not be subject to some or all aspects of regulatory control on the basis that the exposure due to the source or practice is too small to warrant the application of those aspects [82].

EXPOSURE. The act or condition of being subject to irradiation. (IAEA Note: *Exposure* should not be used as a synonym for *dose*. *Dose* is a measure of the effects of *exposure*.)

Exposure can be divided into categories according to its nature and duration (see *exposure situations*) or according to the source of the exposure, the people exposed and/or the

circumstances under which they are exposed.

EXPOSURE SITUATION. Exposure situations are classified as follows:

- **Acute exposure.** Exposure received within a short period of time. Normally used to refer to exposure of sufficiently short duration that the resulting doses can be treated as instantaneous (e.g. less than an hour)
- **Chronic exposure.** Exposure persisting in time
- **Existing.** Exposure already present before decision on control is made. (Retrospective)
- **Planned.** Applied as part of an intentional, planned, controlled situation or process. (Prospective)
- **Emergency.** Unexpected, uncontrolled or uncontrollable situation. (Reactive).

FEW NEXUS. The Food-Energy-Water nexus has gained increased attention against the background of the Vision 2030 call for balanced integrated management of resources. PG use as a secondary resource touches all three and is referenced as a paradigmatic case in UN document [79].

FLUE-GAS DESULPHURISATION. FGD technology is based on a chemical reaction that occurs when the warm exhaust gases from the coal-fired boiler come into contact with limestone. This reaction removes 92% of the sulphur dioxide from the flue gas and converts the limestone into Calcium Sulphite.

GRADED APPROACH. A structured method by which the stringency of control to be applied to a product or process is commensurate with the risk associated with a loss of control [3] (see Fig. 5).¹¹⁵

GREEN CHEMISTRY/GREEN ENGINEERING. The invention, design and application of chemical products and processes to reduce or to eliminate the use and generation of hazardous substances.¹¹⁶

INTERIM STORAGE AREA. An area designated by or agreed with the Regulator for the storage of PG pending use longer-term, typically requiring no liner and low intensity environmental impact monitoring. This may include the option to use the stored PG resources as anthrosol for the promotion of biodiversity but also commercial tree planting.

INTERIM STORAGE FACILITY. An alternative term in PG

112. <https://www.investopedia.com/terms/c/cost-benefitanalysis.asp>

113. https://www.va.gov/PROPATH/artifact_library/cost_benefit_analysis_template.docx

114. See https://en.wikipedia.org/wiki/Environmental_full-cost_accounting

115. For the IAEA description of the graded approach see <https://www.iaea.org/publications/10643/use-of-a-graded-approach-in-the-application-of-the-management-system-requirements-for-facilities-and-activities>

116. For an overview of Green Chemistry see www.acs.org/content/acs/en/greenchemistry/what-is-greenchemistry/principles/12-principles-of-green-chemistry.html, and www.incaweb.org/research/green_chemistry/

management for a “stack” where storage is for use not disposal.

<https://web.unep.org/uneppmap/>

INTERVENTION. Any actions intended to reduce or avert exposure or the likelihood of exposure to sources which are not part of a controlled practice (or an exempt practice) or which are out of control as a consequence of an accident.

LIFE-CYCLE ASSESSMENT. An environmental accounting and management approach that considers all the aspects of resource use and environmental releases associated with an industrial system from cradle to grave. Specifically, it is a holistic view of environmental interactions that covers a range of activities, from the extraction of raw materials from the Earth and the production and distribution of energy, through the use, and reuse, and final disposal of a product. LCA is a relative tool intended for comparison and not absolute evaluation, thereby helping decision makers compare all major environmental impacts when choosing between alternative courses of action.¹¹⁷

LONDON CONVENTION. The IMO “Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972”, the “London Convention” for short, is one of the first global conventions to protect the marine environment from human activities. It has been in force since 1975.¹¹⁸

- **London Protocol.** In 1996, the IMO London Protocol was agreed to further modernize the London Convention and, eventually, replace it. Under the London Protocol all dumping of wastes to sea is prohibited, except for possibly acceptable wastes on the so-called “reverse list”.

www.imo.org/OurWork/Environment/LCLP/Pages/default.aspx

- **OSPAR Convention.** The Convention for the Protection of the Marine Environment of the North-East Atlantic, includes regulation of disposal of PG to NE Atlantic Waters.

<https://www.ospar.org/convention>

- **Barcelona Convention and Protocols.** The Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean, originally the Convention for Protection of the Mediterranean Sea against Pollution, and often simply referred to as the Barcelona Convention, is a regional convention adopted in 1976 to prevent and abate pollution from ships, aircraft and land-based sources in the Mediterranean Sea. PG discharge into the Mediterranean is regulated under this Convention.

MATERIALS FLOW ANALYSIS. An analytical method to quantify **flows** and **stocks** of materials or substances in a defined system, also referred to as substance **flow analysis (SFA)**, (Fig. 3).¹¹⁹ It is of particular significance to PG as it illustrates the need to change the long-standing linear economy practice of PG “discharge” to outside the system boundaries as “waste” to retaining these resources within a circular economy system boundary, as a co-product [2], reusable raw material or secondary resource, not as a waste.

NORM (Naturally Occurring Radioactive Materials)

Radioactive material containing no significant amounts of radionuclides other than naturally occurring radionuclides, typically ²³⁸U and ²²⁶Ra.

- The exact definition of ‘significant amounts’ would be a regulatory decision.
- Material in which the activity concentrations of the naturally occurring radionuclides have been changed by a process is included in naturally occurring radioactive material.
- *Naturally occurring radioactive material* or NORM should be used in the singular unless reference is explicitly being made to various materials [82].

PATHWAY (EXPOSURE). A route by which radiation or radionuclides can reach humans and cause exposure.

PHOSPHOGYPSUM. Calcium sulphate. A co-product with phosphoric acid of the wet process production of phosphate fertilizers.

PHOSPHOGYPSUM RULE. Promulgated in 1989 and revised in 1992 the United States Environmental Protection Agency regulates phosphogypsum under the Phosphogypsum Rule [13].

PRACTICE. Any human activity that introduces additional sources of exposure or exposure pathways or extends exposure to additional people or modifies the network of exposure pathways from existing sources, so as to increase the exposure or likelihood of exposure of people or the number of people exposed.

QUALITY PROTOCOL. A technical and scientific reference document compiled to explain why, how and when a waste-derived material can be regarded as a non-waste product and no longer subject to waste controls within a given regulatory regime.¹²⁰ In regulatory regimes where PG is classed according

117. M. A. Curran, in Encyclopedia of Ecology, 2008

118. For the International Maritime Organization see www.imo.org/OurWork/Environment/LCLP/Pages/default.aspx

120. See [image source](#)

120. For Quality Protocol format and Table of Contents guidance See <https://www.gov.uk/government/collections/quality-protocols-end-of-waste-frameworks-for-waste-derived-products>

to IAEA advice as a co-product (ie not as a waste) the Quality Protocol may still be highly advisable as it will set out by type of use and according to the specific characterisation of the PG or PG-derived product to be used.

RADIOACTIVITY. The emission of particulate or electromagnetic radiation as a result of decay of the nuclei of unstable elements, a property of all chemical elements of atomic number above 83. Scientifically, something is described as radioactive if it exhibits the phenomenon of radioactivity or if it contains any substance that exhibits radioactivity. Scientifically, therefore, virtually any material (including material that is considered to be waste) is radioactive. However, it is common regulatory practice to define terms such as radioactive material and radioactive waste in such a way as to include only that material or waste that is subject to regulation by virtue of the radiological properties it exhibits or any radiological risk or hazard that it poses [82].

RADON. A radioactive, colourless, odourless, tasteless noble gas associated with phosphate mining and with the stacking of PG.

REMEDICATION. Any measures that may be carried out to reduce the radiation exposure due to existing contamination of land areas through actions applied to the contamination itself (the source) or to the exposure pathways to humans.

- Complete removal of the contamination is not implied [82].

REUSABLE (SECONDARY) RAW MATERIAL. 'Secondary raw materials' are recycled materials that can be used in manufacturing processes instead of or alongside virgin raw materials.¹²¹

RESOURCE. Naturally occurring materials for which there is a reasonable prospect of economic use valorisation as:

- Primary Resource
- Secondary Resource
- Anthropogenic Resource
- Conservation.

RESOURCE USE EFFICIENCY (fertilizer, water etc) is the output of any crop or anything else per unit of the resource applied under a specified set of soil

and climatic conditions.¹²²

STACKING. The process of separation of PG from PA at the filter and its disposal in "stacks"

- **Dry stacking.** The process of separating PG from PA at the filter as a "dry" (low moisture content) residue and its transportation by belt-conveyor to its storage or disposal point.

- **Wet stacking.** The process of separating PG from PA at the filter as a "wet" slurry residue and its transportation by pipeline to a storage or disposal point where the PG in suspension is allowed to settle out from the process water for stacking while the process water is recovered and returned to the production circuit.

SOIL. The natural medium for the growth of plants [...] consisting of layers (soil horizons) that are composed of weathered mineral materials, organic material, air and water (FAO).¹²³

- **Soil ameliorant.** A mineral or organic material that is applied to improve the quality and structure of the soil and thereby improve plant growth.

- **Soil amendment.** A materials added to a soil to improve its physical properties, such as water retention, permeability, water infiltration, drainage, aeration and structure. The goal is to provide a better environment for roots. To do its work, an amendment must be thoroughly mixed into the soil. If it is merely buried, its effectiveness is reduced, and it will interfere with water and air movement and root growth.¹²⁴

- **Soil capping.** A hard crust on the soil surface that severely limits permeability.¹²⁵

- **Soil fertility.** The ability of a soil to produce the required or optimum level of yield and quality from a given crop, at a given time and under given growing conditions, assuming appropriate, measurable inputs.

- **Soil salinity.** The amount of dissolved salts in the soil solution (the aqueous phase in the soil). The process of accumulating soluble salts in the soil is known as **salinization**. Salts in the soil have an important effect on the functions and management.¹²⁶ Soil salinity is the term used to designate a condition in which the soluble salt content of the soil reaches a level harmful to crops [83].

- **Soil sodicity.** A term given to the amount of sodium held in a soil. Sodium is a cation (positive ion) that is held loosely on clay particles in soil.¹²⁷

121. Secondary Raw Materials, EU definition, see <http://www.europarl.europa.eu/legislative-train/theme-new-boost-for-jobs-growth-and-investment/file-strategy-for-secondary-raw-materials>

122. Definition of Resource Use Efficiency (RUE), see <http://www.hillagric.ac.in/edu/coa/agronomy/lect/agron-4711/Lecture%208%20RUE%20and%20Optimization%20techniques.pdf>

123. Food and Agriculture Organization, <http://www.fao.org/soils-portal/about/all-definitions/en/>

124. See <https://extension.colostate.edu/topic-areas/yard-garden/choosing-a-soil-amendment/>

125. For soil capping see <http://www.holisticresults.com.au/green-participant-area/understanding-the-four-ecosystem-processes/2-1-1-soil-capping>

126. See <https://www.sciencedirect.com/topics/earth-and-planetary-sciences/soil-salinity>

127. See https://www.dpi.nsw.gov.au/_data/assets/pdf_file/0009/127278/Sodic-soil-management.pdf

SOURCE. Anything that may cause *radiation exposure* — such as by emitting *ionizing radiation* or by releasing *radioactive substances or material* — and can be treated as a single entity for protection and safety purposes.

- **Natural source.** A naturally occurring source of radiation, such as the sun and stars (sources of cosmic radiation) and rocks and soil (terrestrial sources of radiation).

SUSTAINABILITY. The preservation of the environment's ability to meet both present and future needs.

SUSTAINABLE DEVELOPMENT. Development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts:

- the concept of *needs*, in particular the essential needs of the world's poor, to which overriding priority should be given; and
- the idea of *limitations* imposed by the state of technology and social organization on the environment's ability to meet present and future needs [81].

VALORISATION. The economic use of a resource across its whole lifecycle.

VERTISOLS. Clayey soils, which have deep, wide cracks on some occasions during the year and slickensides within 100 cm of the soil surface. They shrink when dry and swell when moistened. **Vertisols** make up a relatively homogenous order of soils because of the amount and kind of clay that is common to them.¹²⁸

WASTE (EU). “Any substance or object which the holder discards or intends to discard”.

WASTE (IAEA). “Material for which no further use is foreseen”.

- **Exempt waste.** Waste that is released from *regulatory control* in accordance with *exemption principles*.

- **Mixed waste.** Radioactive waste that also contains non-radioactive toxic or hazardous substances.

- **NORM waste.** Naturally occurring radioactive material for which no further use is foreseen.

WASTE HIERARCHY. The EU Waste Framework Directive (2008, amended 2018)¹²⁹ establishes a strategy for prioritising management of “waste” in a hierarchical form shown as follows¹³⁰ (Fig. 120):



Fig. 120. The EU Waste Hierarchy

1. Prevention
2. Re-use
3. Recycling
4. Recovery (or reprocessing, including energy recovery from waste)
5. Disposal

Of these the least favoured option is disposal.

WATER EFFICIENCY. A means of reducing water wastage by measuring the amount of water required for a particular purpose and the amount of water used or delivered. Water efficiency differs from water conservation in that it focuses on reducing waste, not restricting use.¹³¹

128. See <https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/vertisols>

129. See <https://legislationupdateservice.co.uk/directive-eu-2018-851-amending-directive-2008-98-ec-on-waste/>

130. See <https://ec.europa.eu/environment/waste/framework/>

131. See https://en.wikipedia.org/wiki/Water_efficiency

APPENDIX 1: THE IFA PG NORM WORKING GROUP

Until 2012 Phosphogypsum was not identified by IFA members as an issue in its own right but was dealt with ad hoc through a NORM Task Force which met only infrequently. There was also understandable reticence among IFA member companies about discussing PG openly given the concerns about radioactivity which were the reasons given by the US Environmental Protection Agency in 1989 in mandating the practice of stacking PG and making its use largely impossible.

But when the preliminary findings of IAEA SR78 [2] were conveyed to IFA in 2011 by members of the SR78 drafting team, Luc Maene, then IFA Director General, proposed to host a special meeting of the IFA NORM Task Force dedicated to PG with the new IAEA findings at the centre of the meeting agenda. The meeting was held as a supernumerary Workshop preliminary to the 2012 Annual Technical Symposium in Tashkent. It was well attended and included presentations on SR78 from an IAEA representative.

As a result of the success of the meeting in attracting IFA member company participation and interest, and taking into account the game-changing nature of SR78 in regard to reclassifying PG as a co-product, the NORM Task Force added PG to its remit and name and became a standing Working Group. So began a cycle of annual meetings held on the day immediately before the start of the annual Technical or HSE Symposia. Annual meetings have been held since 2013 as follows:

1. 2013 - Santiago, Chile
2. 2014 - Amsterdam, Netherlands
3. 2015 - Vancouver, Canada
4. 2016 - New Delhi, India
5. 2017 - Amman, Jordan
6. 2018 - Madrid, Spain
7. 2019 - New Orleans, United States
8. 2020 - New York, United States

In addition to annual meetings a number of significant special meetings have been held on PG, as listed below. Of these in 2007 and 2008 IAEA sponsored two meetings held at the Florida Industrial and Phosphate Research Institute, Florida, one to review the scope of SR78, the other the particular issue of PG use in road construction. In 2007 the decision was taken to include in the scope of SR78 an extensive chapter on PG, which had not till then been included in the terms of reference of the report. In 2008 the

meeting had the opportunity to visit one of the pilot roads built in central Florida using local PG and to inspect first-hand the performance of the road and all the environmental monitoring that had been in place since its construction in 1986 which FIPR staff were tasked to undertake.

SPECIAL MEETINGS

2007 – Scope review, IAEA SR78, joint meeting IAEA (funder) and FIPR (host and Stack Free by '53 project team), Bartow, Florida, USA

2008 – PG and roads, joint meeting IAEA (funder) and FIPR (host and Stack Free by '53 project team), Bartow, Florida, USA

2013 – Scoping meeting, IFA Phosphogypsum Report, Istanbul, PG NORM Working Group, hosted by Toros Agri, Istanbul, Turkey

2014 – Arab Fertilizer Association – First PG Workshop, Tunis, Tunisia

2018 – PG and the Circular Economy, Prayon, Engis, Belgium.

Each of these special meetings has had decisive impact on the nature and level of the industry's commitment to finding a sustainable, environmentally and economically viable solution for PG. But from an industry perspective what is perhaps most striking is that while the first two special meetings (2007 and 2008) were led by IAEA and FIPR, thereafter it has been industry itself leading the way, starting with the "tipping point" meeting in Istanbul, September 2013. It is no coincidence that this meeting took place under the benevolent sponsorship of Esin Mete in her role as CEO of Toros Agri and was the prelude to her January 2014 landmark speech. In like manner, a second tipping point was reached at the March 2018 meeting hosted by Prayon and Aleff Group at which the connection was clearly made between the industry's future approach to PG as a resource and its wider understanding of how to begin the transition process to a circular economy.

APPENDIX 2: SAMPLE MATERIAL SAFETY DATA SHEET, PHOSPHOGYPSUM¹³²



Material Safety Data Sheet

NFPA Classification	DOT / TDG Pictograms	WHMIS Classification	PROTECTIVE CLOTHING
Health Flammability Reactivity Specific Hazard			

Section I. Chemical Product and Company Identification			
PRODUCT NAME/TRADE NAME		Type 65 - Florida Phosphogypsum	
SYNONYM	Florida Phosphogypsum	MSDS NUMBER:	14060
CHEMICAL NAME	Calcium sulfate, dihydrate	REVISION NUMBER	4.5
CHEMICAL FAMILY	A sulfate salt composed mainly of calcium sulfate with trace amounts of barium sulfate, calcium fluoride and oxides of aluminum and silicon. (Salt.)	MSDS prepared by the Environment, Health and Safety Department on: March 28, 2001	
CHEMICAL FORMULA	CaSO ₄ .2H ₂ O	24 HR EMERGENCY TELEPHONE NUMBER: Transportation: 1-800-792-8311 Medical: 1-888-670-8123	
MATERIAL USES	Agricultural industry: Soil conditioner. Industrial applications: Retarder for Portland cement. Soil neutralizer. Mining industry: Mine tailings flocculant.		
MANUFACTURER		SUPPLIER	
Agrium North American Wholesale 13131 Lake Fraser Drive, S.E. Calgary, Alberta, Canada T2J 7E8		Agrium North American Wholesale 13131 Lake Fraser Drive, S.E. Calgary, Alberta, Canada, T2J 7E8 Agrium U.S. Inc. Suite 1700, 4582 South Ulster St. Denver, Colorado, U.S.A., 80237	

Section II. Hazardous Ingredients								
NAME	CAS #	Exposure Limits (ACGIH)						% by Weight
		TLV-TWA mg/m ³	TLV-TWA ppm	STEL mg/m ³	STEL ppm	CEIL mg/m ³	CEIL ppm	
crystalline silica	14808-60-7	0.1						0.24
calcium sulfate, dihydrate	10101-41-4	10						86 - 92
Calcium fluoride	7789-75-5	2.5						0.9
TOXICOLOGICAL DATA ON INGREDIENTS		The minimum or maximum tolerated human exposure to this agent has not been delineated. TOXICITY VALUES - Gypsum A. DIHYDRATE: TDLo - (IP) RAT: 450 mg/kg TCLo - (INHL) HUMAN: 194 g/m ³						

Continued on next page

132. This Agrium PG Material Safety Data Sheet (MSDS) (2001) is reproduced for reference only. For long it was the only published MSDS issued by the phosphate industry. It is now being replaced by the more modern standard Safety Data Sheet (SDS). Producers who are valorising PG as a co-product will need to publish an SDS of the PG they are using and/or selling. For details of the 16-part SDS format current as of date of release of this Report see <https://www.osha.gov/Publications/OSHA3514.html>

Section III. Hazards Identification.

POTENTIAL ACUTE HEALTH EFFECTS	This product may irritate eyes and skin upon prolonged or repeated contact. Inhaled dust may be irritating to the respiratory tract.
POTENTIAL CHRONIC HEALTH EFFECTS	Contains crystalline silica (quartz). Prolonged or repeated overexposures by inhalation may cause progressive and permanent lung damage. Crystalline silica is considered a human carcinogen by IARC, Reasonably anticipated to be Carcinogenic by NTP, and a Suspected Human Carcinogen by ACGIH. Contains trace quantities of naturally occurring radioactive materials (radium-226). Consult Section 16, Other Information, Special Considerations, for further information on this subject.

Section IV. First Aid Measures

EYE CONTACT	May cause eye irritation due to mechanical action. Immediately flush eyes with running water for at least 15 minutes, keeping eyelids open. Obtain medical attention if irritation persists.
MINOR SKIN CONTACT	May cause skin irritation. Wash contaminated skin with soap and water. Cover dry or irritated skin with a good quality skin lotion. If irritation persists, seek medical attention.
EXTENSIVE SKIN CONTACT	No additional information.
MINOR INHALATION	Inhalation of dust may produce respiratory tract irritation, characterized by burning, sneezing and coughing. Remove individual to fresh air and allow to rest. Obtain medical assistance if breathing remains laboured.
SEVERE INHALATION	In emergency situations use proper respiratory protection to evacuate affected individuals to a safe area as soon as possible. Loosen tight clothing around the person's neck and waist. Oxygen may be administered if breathing is difficult. If the person is not breathing, perform artificial respiration. Obtain immediate medical attention.
SLIGHT INGESTION	Have conscious person drink several glasses of water or milk. Induce vomiting. Lower the head so that the vomit will not reenter the mouth and throat. NEVER give an unconscious person anything to drink. Obtain medical attention.
EXTENSIVE INGESTION	No additional information.

Section V. Fire and Explosion Data

THE PRODUCT IS	Non-flammable.
AUTO-IGNITION TEMPERATURE	Not applicable.
FLASH POINT	Not applicable.
FLAMMABILITY LIMITS	Not applicable.
PRODUCTS OF COMBUSTION	Not applicable.
FIRE HAZARD IN THE PRESENCE OF VARIOUS SUBSTANCES	Not applicable.
EXPLOSION HAZARD IN THE PRESENCE OF VARIOUS SUBSTANCES	Does not present any risk of explosion.
FIRE FIGHTING MEDIA AND INSTRUCTIONS	Non-flammable.
SPECIAL REMARKS ON FIRE HAZARDS	When exposed to heat, phosphogypsum loses water of hydration forming calcium sulfate hemihydrate (plaster of paris).
SPECIAL REMARKS ON EXPLOSION HAZARDS	No additional remark.

Continued on next page

Section VI. Accidental Release Measures

SMALL SPILL	Use appropriate tools to put the spilled solid in a suitable container for intended use or disposal. Ensure disposal complies with local regulations.
LARGE SPILL	Prevent additional discharge of material, if possible to do so without hazard. Keep spills from entering sewers, wells, watercourses, etc. Product will promote algae growth and may degrade water quality and taste. Notify downstream water users. Sulfate in potable drinking water should be maintained below 500mg/L (Canada). Recover and place in suitable containers for recycle, reuse, or disposal. Ensure disposal complies with local regulations. Will dissolve and disperse in water. Reclaiming material may not be viable.

Section VII. Handling and Storage

PRECAUTIONS	Avoid contact with skin and eyes. Do not breathe dust in concentrations which exceed specified occupational exposure limits. After handling, and prior to eating, drinking or using smoking materials, always wash hands thoroughly with soap and water. Use process enclosures, local exhaust ventilation, or other engineering controls to keep airborne levels below recommended exposure limits.
STORAGE	Keep in a well-ventilated location. Keep out of reach of children.

Section VIII. Exposure Controls/Personal Protection

ENGINEERING CONTROLS	Store and use only in well ventilated areas. If user operations generate dust, supply adequate general ventilation to keep exposure to airborne contaminants below the applicable exposure limits.
PERSONAL PROTECTION	The selection of personal protective equipment varies, depending upon conditions of use. Wear appropriate respiratory protection for dust/mist when ventilation is inadequate. A NIOSH/MSHA approved dust respirator with P-100 filter cartridges may be used under conditions where airborne concentrations may exceed occupational exposure limits. Protection provided by air purifying respirators may be limited. A positive pressure supplied air respirator should be used if concentrations are unknown or under any other other circumstances where air purifying respirators may be inadequate. Where skin and eye contact may occur as a result of brief periodic exposures, wear long sleeved clothing, coveralls, chemical resistant gloves, and safety glasses with side shields.
PERSONAL PROTECTION IN CASE OF LARGE RELEASE	No additional remarks.
EXPOSURE LIMITS	ACGIH TLV-TWA: 10 mg/m ³ , as Particulates Not Otherwise Classified (nuisance particulates). Federal and Provincial standards may vary by jurisdiction. Consult authorities for local acceptable exposure limits.

Section IX. Physical and Chemical Properties

PHYSICAL STATE AND APPEARANCE	Solid. (Solid crystalline powder.)		
MOLECULAR WEIGHT	136.14	COLOR	White to yellowish.
pH (10% SOLN/WATER)	4	ODOR	Odorless.
BOILING POINT	Decomposes.	ODOR THRESHOLD	Not applicable.
MELTING POINT	1450°C (2642°F)	TASTE	Saline. (Slight.)
CRITICAL TEMPERATURE	Not applicable.	VOLATILITY	Non-volatile solids, but contains 6 - 12 wt% moisture.
SPECIFIC GRAVITY g/cc	2.96 (Water = 1)	SOLUBILITY	Very slightly soluble in cold water, hot water.
BULK DENSITY kg/m³ ; lbs/ft³	Loose: 888 kg/m ³ , 55.4 lbs/ft ³ ; Tapped: 1130 kg/m ³ , 70.5 lbs/ft ³ .	DISPERSION PROPERTIES	Easily dispersed in any proportion in cold water and hot water.
VAPOR PRESSURE	Not applicable.	WATER/OIL DIST. COEFF.	Not available.
VAPOR DENSITY	Not applicable.		

Continued on next page

Section X. Stability and Reactivity Data

STABILITY	The product is stable.
INSTABILITY TEMPERATURE	Not applicable.
CONDITIONS OF INSTABILITY	No additional remark.
INCOMPATABILITY WITH VARIOUS SUBSTANCES	Very slightly to slightly reactive with metals, alkalis. Non-reactive with oxidizing agents, reducing agents, combustible materials, organic materials, acids, moisture.
CORROSIVITY	Slightly corrosive to copper, steel, aluminum, zinc. Non-corrosive to fibreglass, stainless steel (304 or 316).
SPECIAL REMARKS ON REACTIVITY	No additional remark.
SPECIAL REMARKS ON CORROSIVITY	Slightly corrosive to ferrous metals on prolonged contact. Contact your sales representative or a metallurgical specialist to ensure compatibility with system equipment.

Section XI. Toxicological Information

SIGNIFICANT ROUTES OF EXPOSURE	Ingestion. Inhalation.
TOXICITY TO ANIMALS	LD50: Not available. LC50: Not available.
SPECIAL REMARKS ON TOXICITY TO ANIMALS	No additional remark.
OTHER EFFECTS ON HUMANS	Slightly dangerous in case of eye or skin contact (irritant). Dangerous in case of overexposure by ingestion or inhalation.
SPECIAL REMARKS ON CHRONIC EFFECTS ON HUMANS	No additional remark.
SPECIAL REMARKS ON OTHER EFFECTS ON HUMANS	ACGIH TLV value for calcium sulfate, based on total dust containing no asbestos and <1% crystalline silica.

Section XII. Ecological Information


ECOTOXICITY	No additional remark.
BOD and COD	Not available.
PRODUCTS OF DEGRADATION	Some metallic oxides.
TOXICITY OF THE PRODUCTS OF DEGRADATION	The products of degradation are less toxic than the product itself.
SPECIAL REMARKS ON THE PRODUCTS OF DEGRADATION	No additional remark.

Continued on next page





Section XIII. Disposal Considerations

WASTE DISPOSAL OR RECYCLING	Recover and place material in a suitable container for intended use or disposal. Call for assistance on disposal.
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Section XIV. Transport Information

DOT / TDG CLASSIFICATION	Not controlled under TDG (Canada).
PIN	Not applicable (PIN and PG).
SPECIAL PROVISIONS FOR TRANSPORT	Not applicable.
DOT (U.S.A) (Pictograms)	

Section XV. Other Regulatory Information and Pictograms

OTHER REGULATIONS	CANADIAN ENVIRONMENTAL PROTECTION ACT (CEPA): This product is on the Domestic Substances List (DSL), and is acceptable for use under the provisions of CEPA.		
OTHER CLASSIFICATIONS	HCS (U.S.A.)	Not controlled under the HCS (United States).	
	DSCL (EEC)	Not controlled under DSCL (Europe).	
National Fire Protection Association (U.S.A.)	Hazards presented under acute emergency conditions only:		Fire Hazard Reactivity Specific Hazard
TDG (Pictograms - Canada)			
DSCL (Europe) (Pictograms)			
ADR (Europe) (Pictograms)			

Continued on next page

Section XVI. Other Information

REFERENCES	<ul style="list-style-type: none"> -American Conference of Governmental Industrial Hygienists, Threshold Limit Values for Chemical Substances, 2000. -Canadian Centre for Occupational Health and Safety CCInfo Disk. -Corrosion Data Survey, Sixth Edition, 1985, National Association of Corrosion Engineers. - Guidelines for the Handling of Radioactive Materials in Western Canada, 1995, Western Canada NORM Committee - Canadian Guidelines for the Management of Naturally Occurring Radioactive materials (NORM), 1st Ed. January, 2000
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OTHER SPECIAL CONSIDERATIONS	<p>Florida phosphogypsum contains trace but measurable quantities of radioactive substances (typical analyses: uranium-238: 0.14 Bq/g, radium-226: 0.84 Bq/g). The Canadian NORM Working Group of the Federal Provincial Territorial Radiation Protection Committee, has established an investigation threshold of 0.3 Bq/g for material containing Ra-226. Dose assessments conducted by both the PATHRAE and RESRAD risk assessment methodology indicate that the material meets the criterion for Unrestricted use for soil remediation, tailings flocculation and manure conditioning, based on the latest criterion of the International Commission for Radiological Protection (ICRP). These levels of activity in phosphogypsum are considered exempt by the state of Louisiana, and are acceptable for research purposes by the US EPA.</p> <p>One of the radioactive decay products produced is radon gas. This gas may build up in the headspace of closed storage containers or in areas of poor ventilation. The handling and use of phosphogypsum should therefore be conducted under good general ventilation conditions (minimum recommended value: 2 air changes per hour). Further information on the safe handling of phosphogypsum may be obtained in the document, Guidelines for the Handling of Radioactive Materials in Western Canada, prepared by Western Canada NORM Committee and available through Alberta Labour Occupational Health and Safety Division, British Columbia Ministry of Health Radiation Protection Service, or Saskatchewan Labour Occupational Health and Safety Branch.</p>
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FOR FURTHER SAFETY, HEALTH, OR ENVIRONMENTAL INFORMATION ON THIS PRODUCT, CONTACT	AGRIUM Environment, Health and Safety Department Telephone (780) 998-6134 or Fax (780) 998-6143
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NOTICE TO READER

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REFERENCES

1. INTERNATIONAL FERTILIZER INDUSTRY ASSOCIATION, Phosphogypsum: Sustainable Management and Use, (eds.) Johnston, AE, Birky, BK, Hilton, J, Paris (2016).
2. INTERNATIONAL ATOMIC ENERGY AGENCY, Radiation Protection and Management of NORM Residues in the Phosphate Industry, Safety Reports Series No. 78, IAEA, Vienna (2013).
3. INTERNATIONAL ATOMIC ENERGY AGENCY, Use of a Graded Approach in the Application of the Management System Requirements for Facilities and Activities, IAEA-TECDOC-1740, IAEA, Vienna (2014).
4. WITHERS, PJA, ELSEER, JJ, HILTON, J, OHTAKE, H, SCHIPPER WJ, VAN DIJK, KC, Greening the global phosphorus cycle: how green chemistry can help achieve planetary P sustainability, Green Chem., (2015), 17, 2087.
5. ALEFF GROUP, Phosphogypsum Interim Storage Facilities: Good Management Practices and End of Life/ End of Waste Guidance, Report for Fertilizers Europe Member Companies, London and Brussels, (2019).
6. HILTON, J, "Phosphogypsum – management and opportunities for use: Resolving a conflict between negative externality and public good", Proc. No. 587, International Fertiliser Society, Leek, UK, (2006).
7. REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003, Brussels (2019).
<https://data.consilium.europa.eu/doc/document/PE-76-2018-INIT/en/pdf>
8. MURALIKRISHNA, IV, MANICKAM, V, Environmental Management: Science and Engineering for Industry, (2017).
<https://www.sciencedirect.com/book/9780128119891/environmental-management>
9. INTERNATIONAL STANDARDS ORGANISATION, ISO 14040:2006, Environmental management — Life cycle assessment - Principles and framework (2006, reconfirmed 2016) <https://www.iso.org/standard/37456.html>
10. COMISSÃO NACIONAL DE ENEGRIA NUCLEAR, Resolução No. 171 De 30 De Abril 2014.
http://memoria.cnem.gov.br/Doc/pdf/Legislacao/RS_CNENCD_171_2014.pdf
11. CENTRAL POLLUTION CONTROL BOARD, Guidelines for Management and Handling of Phosphogypsum, Hazardous Waste Management Series: HAZWAMS (2015).
http://www.indiaenvironmentportal.org.in/files/file/Final_Draft_Guidelines_for_Phosphogypsum.pdf
12. UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE, Specifications for the application of the United Nations Framework Classification for Resources to Anthropogenic Resources Done in Geneva, 28 September 2018.
https://www.unece.org/fileadmin/DAM/energy/se/pdfs/UNFC/Anthropogenic_Resources/UNFC_Antropogenic_ResourceSpecifications.pdf
13. UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, National Emissions Standard for Hazardous Air Pollutants (NEHSAP) Subpart R, National Emission Standards for Radon Emissions from Phosphogypsum Stacks (revised 1992), EPA, Washington, DC (1992).
14. ALCORDO, IS, RECHCIGL, JE, Phosphogypsum in Agriculture: A Review, in Spark, DL, (ed.) Advances in Agronomy 49:55-118. Academic Press, New York (1993).
15. ABRIL, JM, GARCÍA-TENORIO, R, ENAMORADO, SM, HURTADO, LA, DELGADO, A, The cumulative effect of three decades of phosphogypsum amendments in reclaimed marsh soils from SW Spain: 226Ra, 238U and Cd contents in soils and tomato fruit, Sci. Total Environ. 403 (2008) 80–88.

16. SYCHEV, VG, AKANOVA, NI, LOKTIONOV, MY, SHEUDZHEN, AK, VIZIRSKAYA, MM, SEREGIN, MB, BONDAREVA, TN, Ministry of Agriculture of the Russian Federation, Russian Academy of Agricultural Sciences, D.N. Pryanishnikov State Scientific Institution All-Russia Research Institute of Agrochemistry, Scientific and Practical Recommendations for Application of Neutralized Phosphogypsum as Chemical Ameliorant and Sulfur-rich Fertilizer, Moscow (2012).
17. AKANOVA, NI, Phosphogypsum neutralized - promising product for agriculture intensification. In materials of workshops of JSC "MCC" EuroChem fertility. 2013 No. 1 (70), 2-7.
18. ANGELS, LI, LEVIN, BV, CHERNENKO, YD, Phosphate raw materials, M.: Nedra, (2000).
19. BAYBEKOV, RF, SHILNIKOV, IA, AKANOVA, NI, SHEUDZHEN, AK, Scientific-practical recommendations on phosphogypsum as chemical ameliorant and sulphur-containing fertilizer, Moscow: VNIIA, (2012).
20. MELNIK, OA, SLAVGORSKAYA, DA, The effect of industrial and agricultural waste on plant productivity and yield quality, Ecological Bulletin of the North Caucasus, (2010), Vol.6, No. 4, 30-33.
21. ZINKOVSKAYA, TS, "The effect of the phosphate rock and phosphogypsum combined use on acidic soils", in Problems of Recultivation of Household, Industrial and Agricultural Waste, Krasnodar, (2010) 161-163.
22. LOKTIONOV, MY, Ecological aspects of neutralized phosphogypsum agricultural use on meadow black soil in Krasnodar region, Abstract, PhD thesis, (2013).
23. KIZINYOK, SV, Ways to increase fertilizers efficiency in rice growing systems, Abstract. Doct. Thesis, (2013).
24. CHUAN, L, Use of Phosphogypsum in Agriculture in China, Review Papers, International Fertilizer Industry Association, Paris, (2016).
25. CHEKMAREV, PA, The report of the crop-production and chemical plant protection Department Director, Russian Ministry of Agriculture, All-Russian agrarian meeting, March 10, 2015.
26. BELJUCHENKO, IS, DOBRYDNEV, EP, MERAVYEV, EI, Environmental features of phosphogypsum and perspectives of its application in agriculture, Problems of reclamation of household, industrial and agricultural waste, (2010).
27. FEDOTOVA, LS, TIMOSHINA, NA, KNYAZEVA, EB, TROSHINA, AA, "Phosphogypsum for agriculture - an effective ameliorant to increase soil fertility and potato productivity", in Conference Proceedings, «Ecological problems of economic agents» - Penza, (2015), 200-208.
28. SHEUDJEN, AH, ONOSHENKO, LM, BONDAREVA, TN, ESIPENKO, SV, "Neutralized phosphogypsum as a highly effective multicomponent fertilizer for cereal crops", Proceedings of Kuban State Agrarian University, Krasnodar, (2015), 144-148.
29. CAIRES, EF, INAGAKI, TM, GUIMARÃES, AM, Phosphogypsum: Agricultural Uses in Southern Brazil, International Fertilizer Industry Association, Paris, (2016).
30. SHUGLYA, ZM, Sulphur deficiency identification and the efficiency of phosphogypsum application on sod-podzolic soils of the USSR, Abstract, PhD thesis, Zhodino, (1969).
31. ZHANG, J, WANG, F, Regional temperature response in Central Asia to national committed emission reductions. International Journal of Environmental Research and Public Health 16, 2661 (2019).
32. QADIR, M, QUILLÉROU, E, NANGIA, V, MURTAZA, G, SINGH, M, THOMAS, RJ, DRECHSEL, P, NOBLE, AD, Economics of salt-induced land degradation and restoration. Natural Resources Forum 38: 282-295 (2014).
33. MIRZABAEV, A, GOEDECKE, J, DUBOVYK, O, DJANIBEKOV, U, BAO LE, Q, AW-HASSAN, A, Economics of land degradation in Central Asia, 261-290, in: Nkonya E., Mirzabaev A., von Braun J. (eds) Economics of Land Degradation and Improvement – A Global Assessment for Sustainable Development, Springer (2015).

34. CAI X, MCKINNEY, DC, ROSEGRANT, MW, Sustainability analysis for irrigation water management in the Aral Sea region. *Agricultural Systems* 76: 1043-1066 (2003).
35. QADIR, M, SCHUBERT, S, OSTER, JD, SPOSITO, G, MINHAS, PS, CHERAGHI, SAM, MURTAZA, G, MIRZABAEV, A, SAQIB, M, High-magnesium waters and soils: Emerging environmental and food security constraints. *Science of the Total Environment* 642: 1108-1117 (2018).
36. VYSHPOLSKY, F, MUKHAMEDJANOV, K, BEKBAEV, U, IBATULLIN, S, YULDASHEV, T, NOBLE, AD, MIRZABAEV, A, AW-HASSAN, A, QADIR, M, Optimizing the rate and timing of phosphogypsum application to magnesium-affected soil for crop yield and water productivity enhancement. *Agricultural Water Management* 97: 1277–1286 (2010).
37. VYSHPOLSKY, F, QADIR, M, KARIMOV, A, MUKHAMEDJANOV, K, BEKBAEV, U, PARODA, R, AW-HASSAN, A, KARAJEH, F, Enhancing the productivity of high-magnesium soil and water resources through the application of phosphogypsum in Central Asia. *Land Degradation & Development* 19: 45-56 (2008).
38. QADIR, M, NOBLE, AD, CHARTRES, C, Adapting to climate change through improving water productivity of soils in dry areas. *Land Degradation and Development* 24: 12-21 (2013).
39. NICHOL, C, Afforestation and beneficial use of phosphogypsum *in situ*. Presented at the IFA PG/NORM Working Group 7th Annual Meeting, 8 April 2019, New Orleans, USA (2019).
40. YADAV, RK, DATTA, A, DAGAR, JC, Future Research Needs: Way Forward for Combating Salinity in Climate Change Scenario. In: Dagar, J, Yadav, R, Sharma, P, (eds) *Research Developments in Saline Agriculture*. Springer, Singapore (2019).
41. AULA, L, DHILLON, JS, OMARA, P, WEHMEYER, GB, FREEMAN, KW, RAUN, WR, World Sulfur Use Efficiency for Cereal Crops, *Agron. J.* (2019) Vol. 111 No. 5, 2485-2492.
42. MESSICK, DL, FAN, MX, BREY, CD, Global sulfur requirement and sulfur fertilisers, *Landbauforsch. Völkenrode*, (2005) 283:97–104.
43. THE SULPHUR INSTITUTE, Sulphur – the fourth major plant nutrient (2018). <https://www.sulphurinstitute.org/fertilizer/> (accessed 27 Oct. 2018).
44. ZHAO, FJ, MCGRATH, SP, HAWKESFORD, MJ, Sulphur nutrition and the sulphur cycle. Institute of Arable Crops, Research report 2000–2001. Rothamsted Experimental Station, UK (2001).
45. RANDALL, PJ, SPENCER, K, FRENEY, JR, Sulfur and nitrogen fertilizer effects on wheat: Concentrations of sulfur and nitrogen and the nitrogen to sulfur ratio in grain, in relation to the yield response, *Aust. J. Agric. Res.* 32:203–212. doi:10.1071/AR9810203, (1981).
46. JÄRVAN, M, EDESI, L, ADAMSON, A, LUKME, L, AKK, A, The effect of sulphur fertilization on yield, quality of protein and baking properties of winter wheat, *Agron. Res. (Tartu)* 6:459–469, (2008).
47. KLIKOCKA, H, CYBULSKA, M, NOWAK, A, Efficiency of fertilization and utilization of nitrogen and sulphur by spring wheat. *Pol. J. Environ. Stud.* 26:2029–2036. doi:10.15244/pjoes/69942 (2017).
48. BISWAS, BC, SARKAR, MC, TANWAR, NPS, DAS, S, KALWE, SP, Sulphur Deficiency in Soils and Crop Response to Fertiliser Sulphur in India, *Fertiliser News*, Vol 49 (10) October 2004.
49. PAGE, AL, CHANG, AC, ADRIANO, DC, Deficiencies and toxicities of trace elements. In *Agricultural Salinity Assessment and management*, in Tanji KK (ed.). *Manuals and Reports on Engineering Practices* No. 71. American Society of Civil Engineers: New York (1990) 138–160.
50. IVUSHKIN, K, BARTHOLOMEUS, H, BREGT, AK, PULATOV, A, DE SOUSA, L, Remote Sensing of Environment, Volume 231, 15 September 2019, 111260.

51. ZAMAN, M, SHAHID, SA, HENG, L, Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques, Springer Open, International Atomic Energy Agency, Vienna (2018).
52. IABROL, IP, YADAV, JSP, MASSOUD, FI, Salt-Affected Soils and their Management, FAO SOILS BULLETIN 39, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS Rome, (1988).
53. SMITH, PA, THEYS, T, "Gypsum, a Profitable, Saleable Product?", IFA Technical Conference, New Orleans, (2000).
54. DAVISTER, A., Phosphogypsum: a waste (more or less harmful) or a resource? (1998). Paper to the IFA Technical Conference, Marrakech, September 1998.
55. NASH, J, Non-cooperative Games, The Annals of Mathematics, Second Series, Vol. 54, No. 2, (Sep., 1951), pp. 286-295.
56. RUTHERFORD, PM, DUDAS, MJ, AROCENA, JM, Radium in phosphogypsum leachates, J Environ. Qual. 24 (1995) 307-314.
57. AROCENA, JM, RUTHERFORD, PM, DUDAS, MJ, Heterogeneous distribution of trace elements and fluorine in phosphogypsum by-product, Sci. Total Environ. 162 2-3 (1995) 149-60.
58. RUTHERFORD, PM, DUDAS, MJ, AROCENA, JM, Heterogeneous distribution of radionuclides, barium and strontium in phosphogypsum by product, Sci. Total Environ. 180 3 (1996) 201-209.
59. HILTON, J, BIRKY, BK, JOHNSTON, AE, "The 'constructive regulation' of phosphates and phosphogypsum: A new, evidence-based approach to regulating a NORM industry vital to the global community", Proceedings, IRPA 12, Buenos Aires, (2008).
60. LI, S, Defining the Future: Outlook of China Petroleum and Chemical Industry on 2030 & Beyond, Translated NIE, Z, LI, H, Chemical Industry Press, Beijing, (2018).
61. USHAKOV, VV, OLKHOVIKOV, VM, (eds), Construction of Automobile Roads (— M; — Knorus, — 2020—572 p.
62. ISACHENKO, S, KODZOEV, M-B, APPLICATION OF INNOVATIVE MATERIALS FOR ROAD CONSTRUCTION, — Bulletin of Science and Practice (scientific journal) T. 4. N°3. 2018 r.
63. KRYZHANOVSKY, IM, GLUKHOVTSEV, IN, KOZHUSHKO, VM, The loading capacity of the phosphogypsum base layers. Proceedings of Soyuzdornii "Problems of the use of phosphogypsum in road construction", Balashikha, 1986 (in Russian). (И.М. Крыжановский, И.Н. Глуховцев, В.М. Кожушко. Несущая способность слоев оснований из фосфогипса. Труды Союздорнии «Вопросы применения фосфогипса в дорожном строительстве», Балашиха, 1986г.)
64. REBINDER, PA, Surface phenomena in disperse systems. Physico-chemical mechanics (Nauka, Moscow, 1979), 469 p.
65. SHRIVASTAVA, LK, KUMAR, A, SENGHER, SS, MISHRA, VN, PANDA, A, Influence of zyppite on productivity and nutrient uptake of chickpea (*Cicer arietinum* L.) crop under rainfed condition Chhattisgarh plain region, Legume Research, 41(1) 2018: 95-101 (2017).
66. PINGOLIYA, KK, DOTANIYA, ML, MATHUR, AK, Role of phosphorus and iron in chickpea (*Cicer arietinum* L.). Lap Lambert Academic Publisher, Germany (2013).
67. SHUKLA, M, PATEL, RH, VERMA, R, DEEWAN, P, DOTANIYA, ML, Effect of bio-organics and chemical fertilizers on growth and yield of chickpea (*Cicer arietinum* L.) under middle Gujarat conditions. Vegetos. 26:183-187. DOI: 10.5958/ j.2229 4473.26.1.026 (2013).
68. KUMBHARE, NV, DUBEY, SK, NAIN, MS, BAHAL, R, Micro analysis of yield gap and profitability in pulses and cereals. Legume Research, 37: 532-536. DOI: 10.5958/0976-0571.00671.7 (2014).

69. DOTANIYA, ML, DATTA, SC, BISWAS, DR, MEENA, HM, KUMAR, K, Production of oxalic acid as influenced by the application of organic residue and its effect on phosphorus uptake by wheat (*Triticum aestivum* L.) in an Inceptisol of north India. *National Academic Science Letter*, 37:401-405. DOI: 10.1007/s40009-014-0254-3 9 (2014).
70. DOTANIYA, ML, MEENA, VD, Rhizosphere effect on nutrient availability in soil and its uptake by plants - A review. *Proceedings of National Academic Science, India Sec. B: Biological Science*, DOI: 10.1007/s40011-013-0297-0 (2013).
71. DOTANIYA, ML, DATTA, SC, Impact of bagasse and press mud on availability and fixation capacity of phosphorus in an Inceptisol of north India. *Sugar Tech.* 16:109-112. DOI: 10.1007/s12355-013-0264-3, (2013).
72. GOVERNMENT OF INDIA MINISTRY OF MINES INDIAN BUREAU OF MINES, Indian Minerals Yearbook 2016 (Part-III : Mineral Reviews) 55th Edition GYPSUM (FINAL RELEASE) February, 2018.
<http://ibm.gov.in/writereaddata/files/05152018164638Gypsum%202016.pdf>
73. LLOYD, GM, Jr., (ed.), By-products of Phosphate Industries, Proc. 3rd Workshop Orlando, FL, 1986, Publication 01-031-046, Florida Institute of Phosphate Research, Bartow, FL (1986).
74. BORRIS, DP, BOODY, PW, (Eds), Phosphogypsum (Proc. Int. Symp. Lake Buena Vista, FL, 1980), Publication 01-001-017, Florida Institute of Phosphate Research, Bartow FL, (1980).
75. CHANG, WF, CHIN, DA, HO, R, Phosphogypsum for Secondary Road Construction, Publication 01-033-077, Florida Institute of Phosphate Research, Bartow FL, (1989).
76. ROSSITER, J, LLOYD, GM, "Phosphogypsum to sulphuric acid: Demonstration plant report", paper presented at AIChE Joint Meeting, Clearwater Beach FL, (1989).
77. CHANG, WF, LLOYD, GM, Jr., (eds), Proceedings of the Third International Symposium on Phosphogypsum, 3 Vols. FIPR Publications 01-060-083v1, 01-060-083v2, 01-060-083SuppFinal (1990). <http://fipr.state.fl.us/wp-content/uploads/2014/12/01-060-083v1Final.pdf>, <http://fipr.state.fl.us/wp-content/uploads/2014/12/01-060-083v2Final.pdf>, <http://fipr.state.fl.us/wp-content/uploads/2014/11/01-060-083suppFinal.pdf>
78. SHUKLA, AK, BEHRA, SK, All India Coordinated Research Project on Micro- and Secondary Nutrients and Pollutant Elements in Soils and Plants: Research Achievements and Future Thrusts, *Indian Journal of Fertilisers* 15(5), 522-543 (May 2019).
79. HILTON, J, Transforming our world's natural resources: A step change for the United Nations Framework Classification for Resources? ECE/ENERGY/GE.3/2018/7, United Nations, Geneva (2018).
80. HAZELTON PA, MURPHY BW, Interpreting Soil Test Results: What Do All the Numbers Mean? CSIRO Publishing: Melbourne (2007).
81. BRUNDTLAND G. (ed) Our Common Future. The World Commission on Environment and Development, Oxford University Press, Oxford (1987).
82. EUROPEAN COMMISSION, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, WORLD HEALTH ORGANIZATION, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, General Safety Requirements, IAEA Safety Standards Series No. GSR Part 3, (Vienna 2014).
83. CHILDS, SW, HANKS, RJ, *Soil Sci. Soc. Am. Proc.*, 39 (1975), 617-622.

